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An improved axiomatic design approach in distributed resource environment, part 1: Toward Functional Requirements to Design Parameters transformation

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Abstract

How to transform Functional Requirements (FRs) into Design Parameters (DPs) plays a key role in using the Axiomatic Design (AD) theory. However, the AD theory does not provide such an approach to support the transformation from FRs to DPs. As the meantime, there is a trend to use internet-based knowledge service in a distributed resource environment to efficiently generate a design concept. The authors aim at developing an improved axiomatic design approach. This approach consists of two parts, part 1 built a new model for the transformation from FRs to DPs in a distributed resource environment; part 2 proposed an achieving algorithm for the generation of Function unit chain sets (FUCSs). The studies are based on a hypothesis that almost all of the FRs can be met by a function unit set. The DPs of each Function Unit (FU) are provided by knowledge service suppliers. In such a distributed resource environment, designers only need to search function units via their inputs and outputs and integrate them into a concept solution to meet a functional requirement. This paper firstly defined the basic definitions of Functional Requirements (FRs), Functions (Fs), Function Units (FUs), Function unit sets (FUSs), Function unit chain sets (FUCSs) and Design Parameters (DPs), then described the transformation process in detail, thirdly, proposed principle forms for calculating the outputs in FUSs, finally, used a case study to illustrate the proposed approach by analyzing the design process of a friction-abrasion testing machine.

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Keywords: functional requirement; design parameter; function unit; function unit set; distributed resource environment

1. Introduction

Designing a competitive product is a challenge for designers. Because it is hard for designers to follow a standard procedure to design different products with the incomplete knowledge. Therefore, how to effectively design and acquire enough knowledge to perform the design process requires more researches to develop new design models and methods. In step of conceptual design, the key issue is the transformation from Functional Requirements (FRs) or function (F) in function domain to structure (S) or design parameters (DPs) in physical domain. To finish this transformation, many efforts have been taken.

In design community, quite a few researchers focused on developing systematic methods to guide the whole design process. For example, Gero et al. described a design process by three variables: Function variables to answer the question about what it's for, behavior variables to answer the question about what it does, and structure variables to answer the question about what it is. The relationship between function variables and structure variables in design process was analyzed in the reference [1]. Pahl and Beitz decomposed a design process into four steps to finish the transformation from function to structure: firstly, define sub-functions, secondly, combine several physical effects in order to fulfill the sub-functions, then, obtain the physical principles of the sub-functions, finally, find out the solution principles [2]. Their research was the foundation of modern engineering design. Suh proposed that the world of design have four domains: customer domain, functional domain, physical domain and process domain. Customer domain consists of Customer Needs (CNs). In functional domain, Customer

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Needs must be transformed to Functional Requirements (FRs). In physical domain, designers need to find Design Parameters (DPs) to satisfy FRs. In process domain, production process should be described by Process Variables (PVs). In his research, product design is a mapping process from customer domain to process domain [3].

Others made efforts to find more concrete design methods or tools that assist design process. For example, Kalyanasundaram et al. proposed a function-based approach to support conceptual task of combining two existing single-state products into an integrated product that provides multiple functions. Function sharing matrix, based on quantified function structure similarity, is proposed and applied to define component sharing matrix that can guide integration product design [4]. Tang et al. described kinematic function using function units and trees so that computer can easily recognize and make automatic selections and combinations among many different types of mechanisms [5]. Yeh et al. used QFD and TRIZ method to analyze the design process of a notebook [6]. Madden et al. presented additive manufacturing (AM) as a compelling solution to critical design improvements and substantially reduced prototyping cost and time [7]. Suh. proposed Axiomatic Design (AD) which concludes two basic axioms: independent axiom, i.e. the independence of Functional Requirements must be maintained, and information axiom, which means among those designs that has the highest probability of success is the best design [8-11]. The AD theory had gotten a good development. Kulak, O. provided a recognizable overview of literature on AD principles covering 63 papers from 1990 to 2009, and classified it into four main groups, namely the type of the axiom, the application area, the method, and the evaluation type [12]. However, strictly following these axioms is not always available, especially in the design of integration product [13]. Besides, Suh used design matrices to describe the relationship between FRs in functional domain and DPs in physical domain. The selection of DPs is directly related to the detail design. Finding a proper DP to satisfy a FR is dependent on individual knowledge of designers. Different designers using the same axioms may result in products of different quality [14]. That limits AD's development to some extent.

In fact, the researches mentioned above all have a premise that designers have already gotten all related knowledge and experiences. But as the design becomes more and more complicated, it's difficult for only one designer or one company to be equipped with all related knowledge for product design [15]. To stay competitive in a dynamic market, it's time to do collaborative product design in a distributed resource environment, which means designers should make full use of outer resources to finish the transformation from FRs in functional domain to DPs in physical domain [16-17]. Because resources and experts are geographically distributed, the web-based collaborative design will be an effective way to contact these related resources and experts [18]. However, how to find these related resources quickly and connect them in the right order in the premise that we are not familiar with these resources still lacks a good approach.

This paper aims at developing a method to do the transformation from FRs to DPs in a distributed resource environment. Because of the development of the Internet and the designer's behavior changes on the Internet, a new method for design is proposed which can get full use of the resources distributed on the Internet and lighten the designer's burden. The outline of the article is as follows: in section 2 the basic definitions of Functional Requirements (FRs), Functions (Fs), Function Units (FUs), Function unit sets (FUSs), Function unit chain sets (FUCSs) and Design Parameters (DPs) are defined. Section 3 describes the new model from FRs to DPs in detail that includes the new design process, the searching method from F to FUS, and principle forms of computing outputs in a FUS. Then section 4 uses a case study to illustrate the proposed approach by analyzing the design process of a friction-abrasion testing machine. Finally, the article is concluded and the future works are depicted in section 5.

2. Basic Definitions

Product design in this paper is regarded as system design in the AD theory which consists of sub-system, hardware, software and people [10]. Some basic definitions must be clearly discussed.

Functional Requirement (FR): FR is defined as the minimum set of independent requirements that completely characterizes the function needs of the product (adapted from [10]). It is described by natural language [19]. Not all products are market-oriented. Hence we used FR in this paper instead of CN. In AD theory, CN and FR are all described by natural language, and the transformation process from CN to FR is depicted in the reference [20].

Function (F): FR can be satisfied by F in functional domain. F is defined with inputs and outputs [5, 21, 22]. The transformation from FR to F is implemented by designers [23]. This paper proposed the definition of Function with inputs and outputs to normalize the description of FR and then easily recognized by computer. Here, each input or output has its name and features, and every feature can be described by its name, its value range and its unit, as shown in Fig.1.The name of each input or output can be described by some keywords which will be mentioned in part 2.

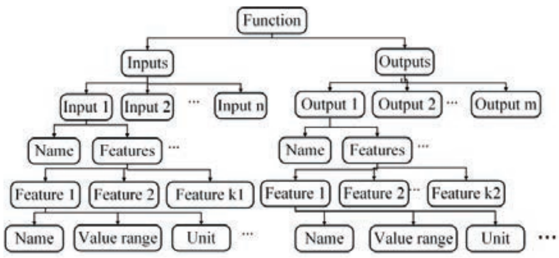

Fig.1 Representation of function

Function unit(FU): FU is a physical structure to meet a specific F. It might be an existing product or an existing design. A FU can be divided into several FUs when the designer knows its structure [24]. A FU is a set of DPs provided by a knowledge service supplier. In this study, a function unit is defined by three characters: name (N), inputs, and outputs. And transform matrix(TM) is dependent on the relationship between inputs and outputs, as shown in Fig.2. The TM matrix has no relationship with the design matrix [A] in AD theory. The design matrix [A] in AD theory reflects the relationship between FRs in functional domain and DPs in physical domain, while the TM matrix reflects the relationship between inputs and outputs of a FU in physical domain. In a FUS, if we get all original inputs and TMs, all outputs can be calculated. A FU, distributed on the Internet, is provided by a knowledge service supplier who knows all DPs about the FU. Hence, if one FU is chosen, all its DPs can be obtained by consulting its knowledge service supplier.

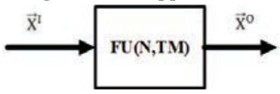

Fig.2 Representation of a function unit

In Fig.2, N is the function unit name, $\vec{X}^I$ is the input of the function unit, and $\vec{X}^O$ is the output of the function unit. TM is the transform matrix that reflects the effects of inputs on outputs. TM is shown in formula (1). The relationship among the three variables is $\vec{X}^O = TM \times \vec{X}^I$. As a function unit may have multiple inputs and outputs, $\vec{X}^I$、$\vec{X}^O$ are column vectors, i.e. $\vec{X}^I = [X_1^I, X_2^I, \ldots, X_m^I]^T, \vec{X}^O = [X_1^O, X_2^O, \ldots, X_n^O]^T$. Where, m is the number of inputs, and n is the number of outputs. X_i^I (i=1, 2, … , m) is called an element in $\vec{X}^I$. X_i^O (i=1,2,…,n) is called an element in $\vec{X}^O$.

$$TM = \begin{bmatrix} \frac{\partial X_1^O}{\partial X_1^I} & \cdots & \frac{\partial X_1^O}{\partial X_m^I} \\ \vdots & \ddots & \vdots \\ \frac{\partial X_n^O}{\partial X_1^I} & \cdots & \frac{\partial X_n^O}{\partial X_m^I} \end{bmatrix} \quad (1)$$

Function unit set (FUS): To meet one F might need more than one FU. Therefore, it needs to find more related function units and connected them in the right order to meet the given F. The ordered integration of function units is a function unit set. The integration means linking two or more FUs in a certain structure to form an FUS which can realize the F.

Function unit chain set (FUCS): When the FUs are connected one by one like a chain, the function unit set can be called a function unit chain set (FUCS).

Design parameter (DP): DP is the key physical variables in the physical domain that characterizes the design satisfying the specific F [10]. For a given F transformed from FR by designers, once the FUS is found out, the DPs are certain and can be provided by knowledge service suppliers.

3. The new model

3.1. The new design process

In axiomatic design theory, FRs have a hierarchical structure according to their abstraction levels. And the design process is zigzagging, as shown in Fig. 3(a) [14]. If a FR can't find a suitable DP, the FR should be resolved into sub-FRs and designers have to find suitable sub-DPs to satisfy the sub-FRs. The zigzagging process will be completed when all FRs at the bottom have found corresponding DPs. By combining all FRs at the bottom of the structure, the topmost FR can be achieved. The relationship between FR and DP is one-to-one. However, finding a proper DP to satisfy each FR relies on the knowledge and experiences grasped by designers. That makes the design become a difficult thing.

In this study, a hypothesis is put forward that there are enough knowledge services on the Internet and they can provide any kind of function unit or the knowledge service for the function you need. Then a new design process model for the transformation from FRs to DPs was built, as show in Fig. 3(b). As can been seen, the process of FRs to DPs is transformed to the processes of FRs to Fs, Fs to FUSs and FUSs to DPs. Here, FRs are satisfied by Fs. when FUSs are found, DPs can be known by consulting knowledge service supplier. The design process is still zigzagging. When an F can't find a suitable FUS, the corresponding FR should be broken up into sub-FRs presented by sub-Fs and designers need to find sub-FUSs to meet sub-Fs. The process will be finished when all Fs at the bottom have searched for realizable FUSs. The relationship between F and FUS is one-to-one, while the relationship between F and DP is one-to-more. This is because one FR might be met by many DPs rather than one DP. Only when the FR is sufficiently detailed, can one DP meet the FR. The independent axiom emphasize the independent of FRs, i.e., one DP just influence one FR. In this paper, one FUS (the set of DPs) only influence one FR when it satisfies the independent axiom.

In conclusion, conventional AD finishes the transformation from FRs to DPs using the knowledge the designer mastered. And the descriptions of FR and DP use natural language. However, the proposed method finishes the transformation from FRs to DPs using the knowledge distributed on the Internet. And the description of FR and DP is transformed to the description of F (Function) and FUS (Function unit set) which is standard and easy to be recognized by computer. According to the law that design is based on existing knowledge [25] and the hypothesis proposed, after a FR is well represented by F in function domain, the corresponding FUS can be found via their inputs and outputs in a distributed resource environment. The procedures about how to find a suitable FUS to meet the F will be depicted in section 3.2.

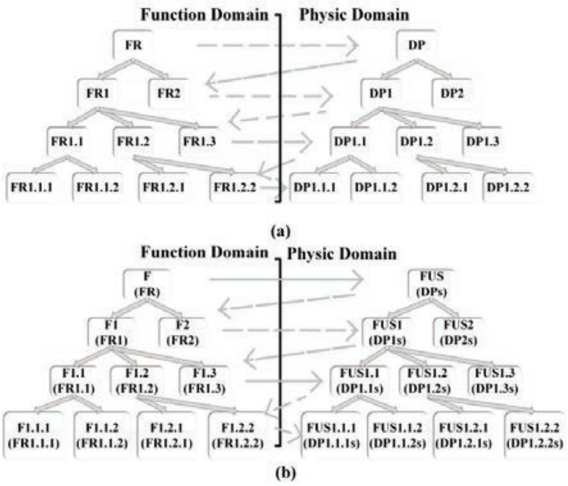

Fig.3 Design process models: (a): Suh's model. (b): The new model.

3.2. The searching process from F to FUS

Step 1: Search a simple FUS to satisfy aim inputs and aim outputs.

FR is described by natural language and it can be satisfied by F, i.e. inputs and outputs. In the beginning of designing a product, the designer just needs to consider the aim inputs and the aim outputs of the product. The inputs and outputs that he wants to get are called the aim inputs and the aim outputs. It is different from other necessary inputs and outputs. According to the aim inputs and the aim outputs, we can find a function unit set whose inputs of the 1st FU include the aim inputs and outputs of the last FU include the aim outputs. This is a function unit chain set. The function units in the middle of chain set are found by matching one or more elements in their outputs and inputs. The searching algorithm is discussed in part 2. The structure of the function set is like Fig. 4. The connection points (C_{1-2} , C_{2-3}) are used to connect the outputs of the former function unit and the inputs of the latter function unit. And there must be one or more elements that have the same name and matched features in the outputs of former function unit and the inputs of latter function unit.

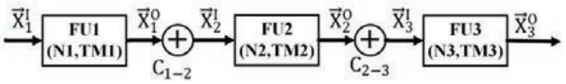

Fig.4 The function unit set satisfying aim inputs and outputs

Step 2: Complete the function unit set until that all inputs can be given.

After getting the function chain unit set that satisfies the aim inputs and the aim outputs, we used again a method of matching inputs and outputs to complete the function unit chain set, i.e. ensure all original inputs of function units can be given so that we can get the aim outputs. It means at the connecting point C_{i-j} , every element in $\vec{X}_j^I$ can find an element in $\vec{X}_i^O$ that have the same name and matched features. If any element X_{j-x}^I in $\vec{X}_j^I$ can't find a matching one, increase a new input $\vec{X}_{new}^I$ that have the same name and matched features as X_{j-x}^I. $\vec{X}_{new}^I$ might come from outside, as shown in Fig. 5(a), or come from any FU in the chain set, see Fig. 5(b). Here, B_1 is a branch point, used to pick required outputs from an FU, therefore, $\vec{X}_{new}^I \in \vec{X}_1^O$. The computing form is $\vec{X}_{new}^I = BM1 \times \vec{X}_1^O$. BM1 is a branch matrix that will be depicted in section 3.3.

After the matching process, we can get a complete function unit set. Then if we get all inputs and transform matrixes in the function unit set, we can calculate outputs of each function unit in principle. The principle forms will be introduced in the next section.

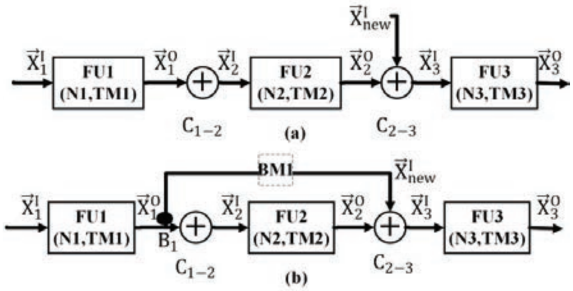

Fig.5 Add a new input $\vec{X}_{new}^I$: (a) $\vec{X}_{new}^I$ comes from outside. (b)$\vec{X}_{new}^I$ comes from a FU in the chain set

3.3. Principle forms of computing outputs in a complete function unit set

Computing outputs of each function unit in a complete function unit set needs finish a transformation from diagram to formulas. In this section, basic solution principle forms are defined below.

Principle 1: For one function unit, as shown in Fig. 6(a). The corresponding formula is

$$\vec{X}_1^O = TM1 \times \vec{X}_1^I \qquad (2)$$

Principle 2: For two function units connected in series, as shown in Fig. 6(b). The corresponding formula is

$$\vec{X}_2^O = TM2 \times \vec{X}_2^I = TM2 \times TM1 \times \vec{X}_1^I \qquad (3)$$

Principle 3: For two function units connected in parallel, as shown in Fig. 6(c). The principle form is different from the traditional one. Because $\vec{X}_1^O$ and $\vec{X}_2^O$ might be with different characters, like load and hot air. The corresponding formula is

$$\vec{X}^O = \begin{bmatrix} \vec{X}_1^O \\ \vec{X}_2^O \end{bmatrix} = \begin{bmatrix} TM1 \times \vec{X}_1^I \\ TM2 \times \vec{X}_2^I \end{bmatrix} \qquad (4)$$

Principle 4: For a branch point B_1, as shown in Fig. 6(d). If $\vec{X}_1^O = [X_{11}^O \ X_{12}^O \ \ldots \ X_{1n}^O]^T$, the vector $\vec{X}^O$ after the branch point will belong to $\vec{X}_1^O$, i.e. $\vec{X}^O \in \vec{X}_1^O$. Their relationship is

$$\vec{X}^O = BM1 \times \vec{X}_1^O \qquad (5)$$

Here, BM1 is a branch matrix which consists of parameters 0 and 1. The form of BM1 is $BM1 = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{bmatrix}$. Here, n is the number of outputs of the function unit. And m is the desirable number of outputs. The function of branch matrix is selecting part elements from all elements. For example, if $\vec{X}_1^O=\begin{bmatrix}X_{11}^O\\X_{12}^O\\X_{13}^O\end{bmatrix}$, BM1=$\begin{bmatrix}1&0&0\\0&1&0\end{bmatrix}$, then $\vec{X}^O=BM1\times\vec{X}_1^O=\begin{bmatrix}X_{11}^O\\X_{12}^O\end{bmatrix}$.

By using four principles above, the outputs of each function unit can be presented mathematically.

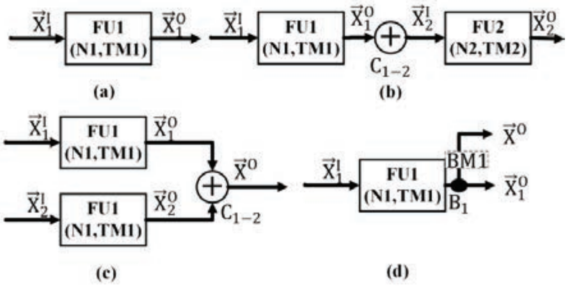

Fig.6 Different structure diagrams of a FUS

4. An illustrative case

When a designer begins to design a new friction-abrasion testing machine, the first things to do are recognizing the Functional Requirements in natural language and trying to transform them into Fs defined with inputs and outputs.

Here, the FRs are 1) doing friction-abrasion experiment of two surfaces with reciprocating translational motion under normal load at a high temperature, 2) getting friction and other relative information. Suppose that the FRs can't be satisfied by existing machines and the designer want to design a new machine, the FUS can't be found. Hence, the designer needs to break up the FRs into sub-FRs presented by sub-Fs, and then try to find sub-FUSs to meet these sub-Fs. There are four sub-FRs, i.e., FR1 (making relative reciprocating motion of two surfaces), FR2 (applying load on two surfaces), FR3 (rising temperature of two surfaces) and FR4 (getting reciprocating motion, load, temperature and friction information). The sub-FRs should be presented by sub-Fs defined with aim inputs $\vec{X}_A^I$ and aim outputs $\vec{X}_A^O$. The aim inputs and outputs of F1-F4 are shown in Table 1.

Based on $\vec{X}_{A1}^I$ and $\vec{X}_{A1}^O$, we can find an FUS1 to meet the F1. The process is divided into two steps.

Step 1: Search a simple FUS that satisfies the aim inputs $\vec{X}_{A1}^I$ and the aim outputs $\vec{X}_{A1}^O$

We can find an FUS like Fig. 7 by an algorithm. The algorithm for searching the FUS1 is published in part 2. The representations of FU1 and FU2 are shown in Table 2. In this FUS, $\vec{X}_1^I$ includes the aim inputs $\vec{X}_{A1}^I$ and $\vec{X}_2^O$ includes the aim outputs $\vec{X}_{A1}^O$. In Fig. 7, C_{A1-1} is a connecting point used to connect the aim inputs $\vec{X}_{A1}^I$ and the input $\vec{X}_1^I$, C_{1-2} is used to connect the output $\vec{X}_1^O$ and the inputs $\vec{X}_2^I$ and C_{2-A1} is used to connect the output $\vec{X}_2^O$ and the aim output $\vec{X}_{A1}^O$. At these connecting points, there must be at least one element that has the same name and matched features in former outputs and latter inputs.

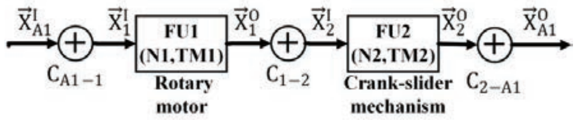

Fig.7 The FUS satisfying the aim inputs $\vec{X}_{A1}^I$ and outputs $\vec{X}_{A1}^O$

Step 2: Complete the function unit set until that all original inputs can be given

By matching outputs and inputs at the connecting point C_{A1-1}, we find that an element X_{1-2}^I in $\vec{X}_1^I$ can't be given directly. So we add the FU3 whose output X_{3-1}^O can match the element X_{1-2}^I and the inputs can be given directly. The presentation of the FU3 is shown in Table 2. The function unit structure diagram of the FUS1 is shown in Fig. 8(a). The function unit structure diagram presents the relations of FUs in physical domain to realize the Fs. It is in physical domain and helps for making the steps from functional to physical easier. So far the process from FR1 to FUS1 is finished.

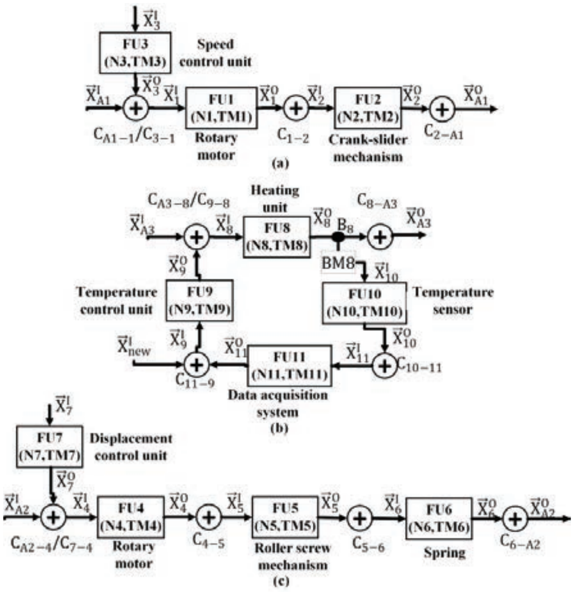

Fig.8 Function unit structure diagrams of FUS1-FUS3: (a) FUS1;(b) FUS3; (c) FUS2

By using the same method, we find the FUS2 and FUS3 to meet the F2 and the F3. The function unit structure diagrams are shown in Fig. 8(b) and Fig. 8(c). The presentations of FU4-11 are shown in Table 2. C_{A2-4}/C_{7-4}, C_{4-5}, C_{5-6}, C_{6-A2}, C_{A3-8}/C_{9-8}, C_{8-A3}, C_{10-11} C_{11-9}/C_{n-9} are connecting points and B_8 is a branch point. BM8= [1].

However, a suitable FUS4 can't be found to meet the F4. So we need to break up FR4 to sub-FR4s, i.e., FR4.1（getting reciprocating motion information）, FR4.2 (getting load information), FR4.3 (getting temperature information) and FR4.4 (getting friction information). Then the FR4.X must be transformed to F4.X defined with inputs and outputs. The aim inputs and outputs of F4.1-F4.4 are shown in Table 3.

Table 1 Representations of F1-F4

Functions	Aim inputs/outputs		Name	Features		
				Name	Value range	Unit
F1	$\vec{X}_{A1}^{I}$	$\vec{X}_{A1-1}^{I}$	Electric energy	Voltage	220	V
	$\vec{X}_{A1}^{O}$	$\vec{X}_{A1-1}^{O}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
F2	$\vec{X}_{A2}^{I}$	$\vec{X}_{A2-1}^{I}$	Electric energy	Voltage	220	V
	$\vec{X}_{A2}^{O}$	$\vec{X}_{A2-1}^{O}$	Load	Load	0-300	N
F3	$\vec{X}_{A3}^{I}$	$\vec{X}_{A3-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{A3-2}^{I}$	Cold air	Temperature	20	°C
	$\vec{X}_{A3}^{O}$	$\vec{X}_{A3-1}^{O}$	Hot air	Temperature	20-200	°C
F4	$\vec{X}_{A4}^{I}$	$\vec{X}_{A4-1}^{I}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
		$\vec{X}_{A4-2}^{I}$	Load	Load	0-300	N
		$\vec{X}_{A4-3}^{I}$	Hot air	Temperature	20-200	°C
	$\vec{X}_{A4}^{O}$	$\vec{X}_{A4-1}^{O}$	Reciprocating motion information	Frequency information	0-20	Hz
		$\vec{X}_{A4-2}^{O}$	Load information	Load information	0-300	N
		$\vec{X}_{A4-3}^{O}$	Temperature information	Temperature information	20-200	°C
		$\vec{X}_{A4-4}^{O}$	Friction information	Friction coefficient information	0-2	Null

Table 2 Presentations of FU1-FU18

FU1	N1	Rotary motor				
	TM1	[X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{1}^{I}$	$\vec{X}_{1-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{1-2}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{1}^{O}$	$\vec{X}_{1-1}^{O}$	Rotary motion	Speed	0-1000	rpm
FU2	N2	Crank-slider mechanism				
	TM2	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{2}^{I}$	$\vec{X}_{2-1}^{I}$	Rotary motion	Speed	0-1000	rpm
	$\vec{X}_{2}^{O}$	$\vec{X}_{2-1}^{O}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
FU3	N3	Speed control unit				
	TM3	[X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{3}^{I}$	$\vec{X}_{3-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{3-2}^{I}$	Rotary motion information	Speed information	0-1000	rpm
	$\vec{X}_{3}^{O}$	$\vec{X}_{3-1}^{O}$	Electric signal	Voltage	0-5	V
FU4	N4	Rotary motor				
	TM4	[X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{4}^{I}$	$\vec{X}_{4-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{4-2}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{4}^{O}$	$\vec{X}_{4-1}^{O}$	Rotary motion	Speed	50	rpm
				Duration	0-50	h
FU5	N5	Roller screw mechanism				
	TM5	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{5}^{I}$	$\vec{X}_{5-1}^{I}$	Rotary motion	Speed	50	rpm
				Duration	0-5	min
	$\vec{X}_{5}^{O}$	$\vec{X}_{5-1}^{O}$	Displacement	Displacement	0-100	mm
FU6	N6	Spring				
	TM6	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{6}^{I}$	$\vec{X}_{6-1}^{I}$	Displacement	Displacement	0-100	mm
	$\vec{X}_{6}^{O}$	$\vec{X}_{6-1}^{O}$	Load	Load	0-300	N
FU7	N7	Displacement control unit				
	TM7	[X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{7}^{I}$	$\vec{X}_{7-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{7-2}^{I}$	Rotary motion information	Duration information	0-5	min
	$\vec{X}_{7}^{O}$	$\vec{X}_{7-1}^{O}$	Electric signal	Voltage	0-5	V
FU8	N8	Heating unit				
	TM8	[X X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{8}^{I}$	$\vec{X}_{8-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{8-2}^{I}$	Cold air	Temperature	20	°C
		$\vec{X}_{8-3}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{8}^{O}$	$\vec{X}_{8-1}^{O}$	Hot air	Temperature	20-200	°C
FU9	N9	Temperature control unit				
	TM9	[X X X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{9}^{I}$	$\vec{X}_{9-1}^{I}$	Electric energy	Voltage	220	V
		$\vec{X}_{9-2}^{I}$	Desirable temperature information	Temperature	20-200	°C
		$\vec{X}_{9-3}^{I}$	Actual temperature information	Temperature	20-200	°C
	$\vec{X}_{9}^{O}$	$\vec{X}_{9-1}^{O}$	Electric signal	Voltage	0-5	V
FU10	N10	Temperature sensor				
	TM10	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{10}^{I}$	$\vec{X}_{10-1}^{I}$	Hot air	Temperature	20-200	°C
	$\vec{X}_{10}^{O}$	$\vec{X}_{10-1}^{O}$	Electric signal	Voltage	0-5	V
FU11	N11	Data acquisition system				
	TM11	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{11}^{I}$	$\vec{X}_{11-1}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{11}^{O}$	$\vec{X}_{11-1}^{O}$	Actual temperature information	Temperature	20-200	°C
FU12	N12	Speed sensor				
	TM12	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{12}^{I}$	$\vec{X}_{12-1}^{I}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
	$\vec{X}_{12}^{O}$	$\vec{X}_{12-1}^{O}$	Electric signal	Voltage	0-5	V
FU13	N13	Data acquisition system				
	TM13	[X]				
	Inputs/outputs		Name	Features		
				Name	Value range	Unit
	$\vec{X}_{13}^{I}$	$\vec{X}_{13-1}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{13}^{O}$	$\vec{X}_{13-1}^{O}$	Reciprocating motion information	Frequency information	0-20	Hz

				Features		
FU14	N14	Force sensor(load)				
	TM14	[X]				
	Inputs/outputs		Name	Name	Value range	Unit
	$\vec{X}_{14}^{I}$	$\vec{X}_{14-1}^{I}$	Load	Load	0-300	N
	$\vec{X}_{14}^{O}$	$\vec{X}_{14-1}^{O}$	Electric signal	Voltage	0-5	V
FU15	N15	Data acquisition system				
	TM15	[X]				
	Inputs/outputs		Name	Name	Value range	Unit
	$\vec{X}_{15}^{I}$	$\vec{X}_{15-1}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{15}^{O}$	$\vec{X}_{15-1}^{O}$	Load information	Load information	0-300	N
FU16	N16	Two surfaces				
	TM16	[X X X]				
	Inputs/outputs		Name	Name	Value range	Unit
	$\vec{X}_{16}^{I}$	$\vec{X}_{16-1}^{I}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
		$\vec{X}_{16-2}^{I}$	Load	Load	0-300	N
		$\vec{X}_{16-3}^{I}$	Hot air	Temperature	20-200	°C
	$\vec{X}_{16}^{O}$	$\vec{X}_{16-1}^{O}$	Friction	Friction	0-600	N
FU17	N17	Force sensor(friction)				
	TM17	[X]				
	Inputs/outputs		Name	Name	Value range	Unit
	$\vec{X}_{17}^{I}$	$\vec{X}_{17-1}^{I}$	Friction	Friction	0-600	N
	$\vec{X}_{17}^{O}$	$\vec{X}_{17-1}^{O}$	Electric signal	Voltage	0-5	V
FU18	N18	Data acquisition system				
	TM18	[X]				
	Inputs/outputs		Name	Name	Value range	Unit
	$\vec{X}_{18}^{I}$	$\vec{X}_{18-1}^{I}$	Electric signal	Voltage	0-5	V
	$\vec{X}_{19}^{O}$	$\vec{X}_{19-1}^{O}$	Friction information	Friction coefficient information	0-2	Null

Table 3 Representations of F4.1-F4.4

Functions	Aim inputs/outputs		Name	Features		
				Name	Value range	Unit
F4.1	$\vec{X}_{A4.1}^{I}$	$\vec{X}_{A4.1-1}^{O}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
	$\vec{X}_{A4.1}^{O}$	$\vec{X}_{A4.1-1}^{O}$	Reciprocating motion information	Frequency information	0-20	Hz
F4.2	$\vec{X}_{A4.2}^{I}$	$\vec{X}_{A4.2-1}^{I}$	Load	Load	0-300	N
	$\vec{X}_{A4.2}^{O}$	$\vec{X}_{A4.2-1}^{O}$	Load information	Load information	0-300	N
F4.3	$\vec{X}_{A4.3}^{I}$	$\vec{X}_{A4.3-1}^{I}$	Hot air	Temperature	20-200	°C
	$\vec{X}_{A4.3}^{O}$	$\vec{X}_{A4.3-1}^{O}$	Temperature information	Temperature information	20-200	°C
F4.4	$\vec{X}_{A4.4}^{I}$	$\vec{X}_{A4.4-1}^{I}$	Reciprocating motion	Stroke	2.5-50	mm
				Frequency	0-20	Hz
		$\vec{X}_{A4.4-2}^{I}$	Load	Load	0-300	N
		$\vec{X}_{A4.4-3}^{I}$	Hot air	Temperature	20-200	°C
	$\vec{X}_{A4.4}^{O}$	$\vec{X}_{A4.4-1}^{O}$	Friction information	Friction coefficient information	0-2	Null

Based on F4.1-F4.4, we can find FUS4.1-FUS4.4 using the method mentioned above, as shown in Fig.9. The presentations of FU12-18 are shown in Table 2.

After getting all FUSs, the function unit structure diagram of friction-abrasion testing machine is depicted in Fig.10. We also can present outputs of each FU via four basic principles in section 3.2. The formulas are presented below. If all inputs are known and transform matrixes can be math mode. The values of all outputs can be calculated using these formulas.

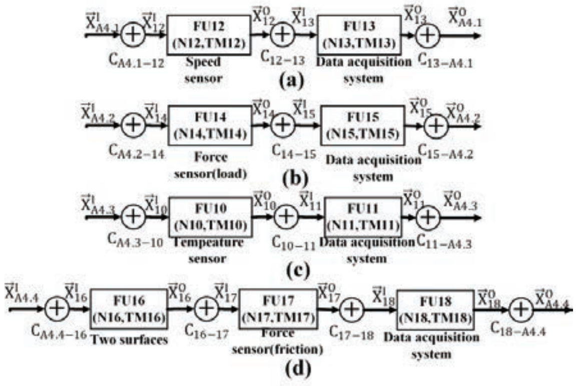

Fig.9 Function unit structure diagrams of FUS4.1-FUS4.4:(a) FUS4.1; (b)FUS4,2; (c)FUS4.3; (d)FUS4.4.

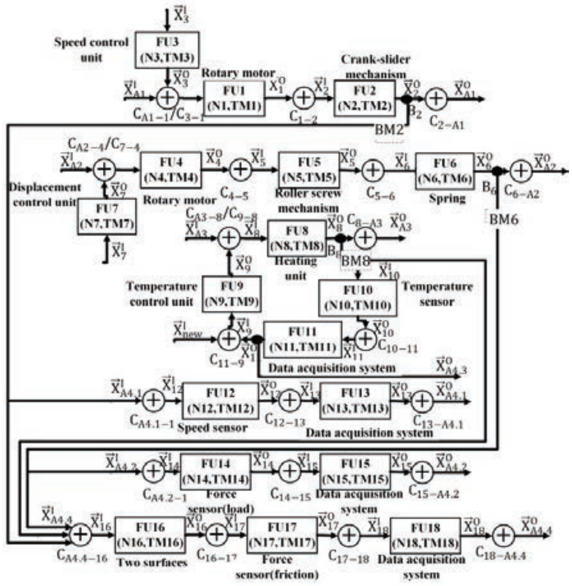

Fig.10 Function unit structure diagram of the friction-abrasion testing machine

$$\vec{X}_1^{O} = TM1 \times \vec{X}_1^{I} = TM1 \times \begin{bmatrix} \vec{X}_{A1}^{I} \\ \vec{X}_3^{O} \end{bmatrix} \quad (6)$$

$$\vec{X}_2^{O}\ (\vec{\mathbf{X}}_{\mathbf{A1}}^{\mathbf{O}}) = TM2 \times \vec{X}_2^{I} = TM2 \times \vec{X}_1^{O} \quad (7)$$

$$\vec{X}_3^{O} = TM3 \times \vec{X}_3^{I} \quad (8)$$

$$\vec{X}_4^{O} = TM4 \times \vec{X}_4^{I} = TM4 \times \begin{bmatrix} \vec{X}_{A2}^{I} \\ \vec{X}_7^{O} \end{bmatrix} \quad (9)$$

$$\vec{X}_5^{O} = TM5 \times \vec{X}_5^{I} = TM5 \times \vec{X}_4^{O} \quad (10)$$

$$\vec{X}_6^{O}\ (\vec{\mathbf{X}}_{\mathbf{A2}}^{\mathbf{O}}) = TM6 \times \vec{X}_6^{I} = TM6 \times \vec{X}_5^{O} \quad (11)$$

$$\vec{X}_7^{O} = TM7 \times \vec{X}_7^{I} \quad (12)$$

$$\vec{X}_8^{O}\ (\vec{\mathbf{X}}_{\mathbf{A3}}^{\mathbf{O}}) = TM8 \times \vec{X}_8^{I} = TM8 \times \begin{bmatrix} \vec{X}_{A3}^{I} \\ \vec{X}_9^{O} \end{bmatrix} \quad (13)$$

$$\vec{X}_9^{O} = TM9 \times \vec{X}_9^{I} = TM9 \times \begin{bmatrix} \vec{X}_{n}^{I} \\ \vec{X}_{11}^{O} \end{bmatrix} \quad (14)$$

$$\vec{X}_{10}^{O} = TM10 \times \vec{X}_{10}^{I} = TM10 \times BM8 \times \vec{X}_8^{O} \quad (15)$$

$$\vec{X}_{11}^{O}\ (\vec{\mathbf{X}}_{\mathbf{A4.3}}^{\mathbf{O}}) = TM11 \times \vec{X}_{11}^{I} = TM11 \times \vec{X}_{10}^{O} \quad (16)$$

$$\vec{X}_{12}^{O} = TM12 \times \vec{X}_{12}^{I} = TM12 \times BM2 \times \vec{X}_{2}^{O} \quad (17)$$

$$\vec{X}_{13}^{O}\ (\vec{\mathbf{X}}_{\mathbf{A4.1}}^{\mathbf{O}}) = TM13 \times \vec{X}_{13}^{I} = TM13 \times \vec{X}_{12}^{O} \quad (18)$$

$$\vec{X}_{14}^{O} = TM14 \times \vec{X}_{14}^{I} = TM14 \times BM6 \times \vec{X}_{6}^{O} \quad (19)$$

$$\vec{X}_{15}^{O}\ (\vec{\mathbf{X}}_{\mathbf{A4.2}}^{\mathbf{O}}) = TM15 \times \vec{X}_{15}^{I} = TM15 \times \vec{X}_{14}^{O} \quad (20)$$

$$\vec{X}_{16}^{O} = TM16 \times \vec{X}_{16}^{I} = TM16 \times \begin{bmatrix} BM2 \times \vec{X}_{2}^{O} \\ BM6 \times \vec{X}_{6}^{O} \\ BM8 \times \vec{X}_{8}^{O} \end{bmatrix} \quad (21)$$

$$\vec{X}_{17}^{O} = TM17 \times \vec{X}_{17}^{I} = TM17 \times \vec{X}_{16}^{O} \quad (22)$$

$$\vec{X}_{18}^{O}\ (\vec{\mathbf{X}}_{\mathbf{A4.4}}^{\mathbf{O}}) = TM18 \times \vec{X}_{18}^{I} = TM18 \times \vec{X}_{17}^{O} \quad (23)$$

In conclusion, Fig. 10 presents the function unit structure diagram of the friction-abrasion testing machine, and formulas (6-23) are used to compute the outputs of each FU. Because the function units are geographically distributed, these results help designers coordinate the relationship between related function units and modify the design when part outputs are undesirable.

Within the context of the hypothesis given before, when the complete function unit structure diagram is got, the DPs can be provided by knowledge service supplier. What designer should do is putting together the DPs and making a layout for the DPs set in the design. The assessment of behavior and structure of the DPs set is out of the scope of this paper. So far the whole process from FRs to DPs is completed. When several function unit structure diagrams are obtained, an optimization process will be carried out according to the second axiom and other consideration that is out of the scope of the paper.

5. Conclusions and future works

The transformation from FR to DP is the key issue in design process. In axiomatic design (AD), finding a suitable DP to satisfy a given FR is mainly dependent on individual knowledge and experience of designers. That induces different designers using the same axiom results in different quality of product and limits the development of AD to some extent. To solve the problem, this paper develops a new model toward the transformation from FR to DP. In this study, designers could make full use of resources distributed on the Internet to complete the transformation. Basic definition (FR, F, FU, FUS, FUCS, DP) are discussed and the searching procedure from FRs to DPs is described. In addition, principle forms to compute outputs of function units in a complete FUS are developed. To verify the proposed method, a case study is used by analyzing the design process of a friction-abrasion testing machine. The advantages of this approach are described below.

（1）Designers can get utmost use of knowledge service distributed on the Internet rather than purely individual knowledge and experience to finish the transformation from FR to DP. This absolutely will lighten the burden of designers and may optimize the quality of design.

（2）By applying this approach, designers can get initial design scheme by function unit structure diagram in the premise that they are not familiar with these function units. It helps to coordinate the relationship between related function units.

（3）After getting all original inputs and transform matrixes(TM), designers can calculate outputs of each function unit. It helps to modify the design when some outputs are undesirable.

（4）This approach can be applied in many fields. Therefore, it is easy to combine different function units in different fields as long as the inputs and outputs of them have the same name and matched features. It is good for product innovation.

The future works will be carried on from the following areas. Firstly, use more cases to validate the effectiveness of the proposed method. Secondly, the descriptions of inputs and outputs use the key words that sets high requirement for the searching algorithm. Hence, the future works will focus on improving the search algorithm to finish the transformation from F to FUS. Finally, we will put it online to provide the knowledge service for designers.

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