Methodology for Creative Machine Design Based on Decomposition-Composition Technique*

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Structuralism as a philosophical and theoretical orientation emerged in the 1950's and boomed in the 1960's. This study attempts to view machine design systems by using structuralist notions as a guide to system thoughts. The method using the concepts of duality, and the decomposition-composition technique is proposed for the creation of new designs.

Key Words: Design Methodology, Creative Machine Design, Duality, Decomposition, Composition

1. Introduction

Machine design is a branch of design. According to design theory literature⁽¹⁾⁻⁽³⁾ machine design can be characterized in two ways. The first is that machine design is a process of symbolic thinking. The designer serves as an information processing unit as a machine does. The way of thinking behind his design task can be treated as a series of code manipulations, these codes being meaningful symbols such as mathematical operators, geometric shapes, characters, and letters. The second is that machine design is a type of communication. It can be treated as communication among designers, producers, managers, and others involved. The medium of communication may be design shapes, performances, manufacturability, and safety considerations. Generally speaking, they are all elements of the design function, taking the form of drawings, models, codes, characters, letters, symbols, etc.

Therefore, these media are representations which act as signifiers in the expression of the designer's thinking. Taking into account these two characteristics, structuralism can then be used to organize these communication codes and to use them in a machine design system.

2. Design with Equivalent Functions

The function of a machine can be represented by its mechanism, in physical terms, as the linkage structure. That is, for any mechanical system, function and structure can be decomposed. For example, most mechanisms which transfer rotation into linear motion have physical structures containing cranks, connecting rods, and pistons. Figure 1(a) is a so-called crank mechanism, where rotary input is transferred into linear motion. However, the crank mechanism is not the sole solution to the rotary-to-linear motion transformation problem. In Figure 1(b), the cam-roller mechanism also performs rotary-to-linear motion transformation. Figure 1(a) and (b) are not equivalent in physical structure but they serve equivalent functions. The question is how a designer can create a new mechanism, but with an equivalent

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function.

3. System and Subsystem

A system usually is comprised of several subsystems. Each subsystem presents its function to the outside world as if it were independent. Unfortunately, this is not entirely true. A subsystem may have its main function, but it cannot work without being integrated with other subsystems. Hence, it has a function or structure. A mechanism with a main function is part of a machine and satisfies a design requirement of the machine system. This mechanism may not be able to satisfy the same requirement when it is moved to another machine system. For example, a bird can

Fig. 1 Equivalent function mechanisms

Fig. 2 A bearing system

Fig. 3 The mutually influencing relationships in a bearing system

be represented as a system which has two wings: they serve as two subsystems which make the bird fly. If a man is equipped with two wings, he cannot fly because the wing subsystems work only when they are matched with the bird's special bone structure and organs. A man does not have the same subsystems as the bird, hence, he cannot fly. That is, a mechanism or a subsystem can be decomposed from a machine or a system for reasons of analysis, but without being integrated into related subsystems, they may not be able to work as before.

4. Concept of Multidecision

When we observe machine systems, we find that almost all are comprised of several subsystems, each of which is a determining factor in the global function of the system. No subsystem is independent, but is in fact mutually affected by other subsystems. A slight change in one subsystem may change the performance of the other subsystems and thus the system as a whole. Figure 2 shows a bearing system containing six subsystems: a shaft, a roller bearing, a lock washer, a locknut, a retaining ring and a bearing housing, as numbered in sequence. Bearing selection may be affected by the shaft loading and rotation speed; the type of bearing also changes the housing assembly, and so on. Any parameter change in one subsystem—such as loading, revolutions per minute, type of machine element—may affect other subsystems. These mutually influencing relationships are illustrated in Figure 3. A machine system is similar in this regard: owing to various mutually influencing relationships, several machine elements may constitute a subassembly and several subassemblies, in turn, construct a machine.

5. Duality and Classification

The notion of duality has been used as a scheme for binary classification. A brief reference to Jakobson's thesis quoted in Leach's work⁽⁴⁾ regarded that voices, concepts and vocabulary used in languages are inevitably dualistic, and that a single element is meaningless when removed from context with its paired reference. Indeed, it is owing to the principle of duality, that language organization develops, explaining, for example, how infants, in their language acquisition, distinguish vowels from consonants, high frequencies from low frequencies, etc.

Greimas' semantic rectangle was introduced in Jameson's work⁽⁵⁾ which presented a complexity of relationships illustrated in Figure 4. Here, $\bar{x}$ represents the inverse of x , $-x$ represents not x , and $-\bar{x}$ represents not inverse x . These relationships can be

abstracted further. If x were to stand for the color black, for example, then $\bar{x}$ would be the inverse of black, in general, white; $-x$ then means not black, and $-\bar{x}$ means not white. In Leach's work⁽⁴⁾, Lévi-Strauss stated that the principle of duality extends into many aspects of human culture, as well.

Duality lies at the very heart of the human systems of classification, which have been developed to great levels of complexity. The dualistic nature of cognition enables humans to perform decomposing and classifying, after which we then recognize things and affairs in the world. For instance, most animals can be distinguished as either edible or inedible, male or female, dark- or light-colored, etc.

There seem to be some analogies in the organization of a language system⁽⁶⁾ and the function of a machine system. For example, the hexagonal head bolt in Figure 5 serves no clear meaning by itself. It may be treated as a sculpture perhaps, with some sense of beauty. The bolt is not meaningful unless it is working with other machine elements, say a part with a threaded hole performing a joining function as shown in Figure 6. In a machine system, therefore, an independent subsystem such as an element is meaningless unless it is integrated within the global system.

A machine system consists of its subsystems. The interrelated functions between each subsystem are

Fig. 4 A symbolic rectangle

Fig. 5 A hexagonal head bolt alone is absent of meaning

Fig. 6 A hexagonal head bolt performing a joining function

requisite for promoting the global functions of the machine system. The notion of duality can be used a powerful tool to describe these subsystem functions. Figure 7 is a Scotch yoke mechanism which contains six elements. Each one is marked with a number. This mechanism can be described in terms of dual properties according to their assembly status, such as shaft (S) and hole (H); relative motion, yes (Y) or no (N); relative motion type, linear (L) or rotational (R); and fit class, tight (T) or loose (L). The interrelated functions are listed in Table 1. The first row shows that element 1 and element 2 are assembled as a hole and a shaft, have no relative motion, and are tightly fitted. As for the fifth row, element 4 and element 5 act as a shaft and a hole, having relative motion of a linear type, and are loosely fitted.

Figure 8 is an arc-and-node diagram, illustrating the relationships between several elements. The numbers stand for each element and arcs indicate their links. The dashed line is the boundary of this six-

Table 1 The interrelated functions of Scotch yoke

element/ element	assembly shaft/ hole	relative motion yes/no	motion type linear/ rotational	fit tight/ loose
1/2	H/S	N		T
2/3	S/H	N		L
1/3	S/H	N		T
3/4	H/S	N		T
4/5	S/H	Y	L	L
5/6	S/H	Y	L	L
1/6	S/H	Y	R	L

Fig. 7 A Scotch yoke mechanism

Fig. 8 An arc-and-node diagram presents the relationships between each element

element system. Two arcs extending past the boundary link this six-element system to other systems.

6. Duality and Design Language

Language related to design work are mostly descriptions of functions or shapes. The part of speech of either functional description or shape description can be attributed to adjectives, verbs, or nouns⁽⁷⁾. Since the language structure is established through the notion of duality, hence, almost all adjectives, verbs, and nouns can find their antonyms and so can descriptive functional design terms.

Designers use linguistic symbols in the descriptions of performance, manufacturability, safety considerations, fit status, etc. for design tasks. Understanding these linguistic symbols is crucial, and duality is a powerful device to distinguish them, as exemplified in the last section. Therefore, a design language can be developed by classifying these descriptive words, thus developing the machine design lexicon.

Through the notion of duality, each word has a meaning relative to other words, no matter which part of speech it is. Human beings organize words using grammar and form sentences. Therefore, people can communicate to each other. Designers use design jargon that is, design language, to express their design concepts everyday. Like languages which change from time to time, they expand their design ideas with productive design language rather than be restricted by fixed terms and forms. Hence, the design language will be robust and creative.

7. Paradigmatic Series and Syntagmatic Chain

"Paradigmatic series" means similarity by virtue of shared properties. "Syntagmatic chain" means similarity as a product of synthesis⁽⁸⁾. The following two simple sentences can explain these two concepts.

I have a new chair.

You buy an old house.

If we examine the above two sentences in column, the term pairs I/you, have/buy, a/an, new/old, chair/house, are in paradigmatic series, because of their shared word classes, parts of speech such as noun, verb, and article. If we examine the two sentences from left to right, they are both connected in a certain relationship, namely as sentences conveying meaning through communication. This relationship is thus syntagmatic. These two sentences can be represented by the phrase marker⁽⁹⁾, a tree diagram, in Figure 9, where "X" means nil.

A phrase structure grammar is generative. Many similar sentences can be specified by the so-called phrase structure rules from which this diagram is

derived: "I eat a big apple", "You bought a beautiful car", etc. It must be noted that not every sentence generated from this structure is necessarily meaningful such as, "I drink a high mountain", for judgements of acceptability are made on the basis of a complex interplay of linguistic and pragmatic considerations.

Since a machine system is a multidisciplinary structure, it is a syntagmatic chain of related subsystems. Comparing machine systems with similar functions, commonalities in structure and in the relationship between subsystems can be found⁽¹⁰⁾. Figure 10 shows five different machine assemblies, all of which have the function of torque transmission, with an identical arc-and-node diagram as shown in Figure 11. Three elements make up a torque transmission assembly. The arc between torque input element and torque transferring element represents that these two

Fig. 9 A phrase marker

Fig. 10 Five torque transmission designs

Fig. 11 Arc-and-node diagram of torque transmission assemblies

elements are related and connected by conjugate shapes, such as pin and hole, or key and keyway. The arc between torque transferring element and torque output element serves the same purpose. As for the arc between torque input element and the torque output element, although there is no torque transferred, their conjugate shapes still fit into each other. So they have the equivalent structure functions.

Another example can be shown in which the reverse thinking is applied. The structure with the functional description "thread fastening" is shown in Figure 12. Four machine system of unique physical shapes, all fastened by screw threads are generated from the given structure drawn in Figure 13. Their relationships in a paradigmatic series can be displayed as in Table 2. By means of thread fastening, elements A and B are joined.

8. Decomposition and Composition

Adopting the concept of a paradigmatic series, a machine system can be decomposed into several subsystems, from which the structure showing their relationships can be built. The concept of the syntagmatic

Fig. 12 The structure with the function describing thread fastening

Fig. 13 Four machine systems fastened by screw threads are generated

chain, on the other hand, composes each subassembly into the whole machine system. The following example, a generative power system, depicts how it is possible for the decomposition-composition concept to be used to generate a new design^{(11),(12)}.

At first, several existing products of a power system are collected: an electric motor, turbo engine, pneumatic pump, and a hydraulic pump. Applying the concept of paradigmatic series, three descriptions of this power system collection are formed. They are power type, medium type, and output motion as listed in Table 3.

Table 3 reveals three pairs of duality. They are electric/fluid for power type, pneumatic/hydraulic for medium type, and rotary/linear for output motion. Using the concept of the syntagmatic chain to rearrange the three pairs of duality, another type of power system can be obtained as shown in Table 4. Note here that the results given in italics have been generated by the model, and have not been obtained before. In this example, if a designer wants to design a power system using this decomposition-composition technique, he may find some new ideas and expand his range of possibilities beyond his original concept. In Table 4, a system using hydraulic pressure, with

Table 2 Paradigmatic series of thread fastening structure

diagram in Fig.13	element A	element B	external thread	internal thread
(a)	plate A	plate B	bolt	nut
(b)	plate A	base B	bolt	tapped base
(c)	gas A	bottle B	threaded bottleneck	threaded lid
(d)	shaft A	bearing B	threaded shaft	nut

Table 3 Descriptions of power systems

power system	power type	medium type	output motion
electric motor	electricity		rotary
turbo engine	pressure	gas	rotary
pneumatic pump	pressure	gas	linear
hydraulic pump	pressure	liquid	linear

Table 4 New arrangement of power systems

		output motion	
		rotary	linear
power type	electricity	electric motor	<i>solenoid valve</i>
	pressure	liquid	<i>hydraulic turbo machine</i>
	gas	turbo engine	pneumatic pump

rotary output, is probably a hydraulic turbo machine and the electric-power-driven linear system could be similar to a solenoid valve. These were not solutions we had previously thought of.

Decomposition can be treated as a process of functional disassembly whereas composition the functional assembly. French⁽¹³⁾ has raised a similar idea as the composition process, combinative procedure, to construct a table of option which lists functional analysis of existing designs and helps creative synthesis too.

9. Another Example

In this section, a shaft and bearing assembly is selected as an example to show how the decomposition-composition technique might proceed. Two popular designs of shaft ends supported by a ball bearing are shown in Figure 14. In (a), a retaining ring is accommodated in the groove and blocks the bearing from sliding out of the shaft. In (b), the bearing is pressed against the shaft shoulder by external force from a nut.

Applying the notion of duality, the relationships between each element are analyzed. First, we separate the function of this assembly into four functional divisions. They are: the shaft, the inner race of the bearing, the left locating position of the bearing and the right locating position of the bearing. Both (a) and (b) in Figure 14 have the same arc-and-node diagram indicating their mutual contact status, as shown in Figure 15. Next, the functions and the relationships between each part are labelled. The inner race of the bearing is tightly fitted on the shaft surface and friction exists between these two elements. The retaining ring is fastened on the shaft groove and behaves non-frictionally. The nut and the shaft are connected by screw threads and are secured by friction. In the axial direction, the bearing is

Fig. 14 Bearing secured on shaft by retaining ring or nut

Fig. 15 Arc-and-node diagram of a shaft and bearing assembly

secured by the shaft shoulder and a retaining ring (in Figure 14 (a)) or a nut (in 14 (b)). However, the shaft shoulder and the shaft are formed as one piece, i.e., are continuous. The shaft shoulder and the retaining ring or nut are separated for assembly reasons, hence they are discontinuous. Two duality sets are obtained by functional decomposition as (1) continuous or discontinuous, (2) frictional or non-frictional. We can now attempt to generate possible assemblies by composing their functions in different ways. The continuous-type or discontinuous-type connection could exist at either the right or left side of the bearing. The assembly type could be frictional or non-frictional as well. Table 5 lists all possibilities of the generated assemblies from the two sides of the bearing. In Table 5, C, D, F, and N stand for continuous, discontinuous, frictional, and non-frictional, respectively. Sixteen assemblies are generated. When the possible assemblies in Table 5 are examined, we find that some of them are impossible. For example, the continuous side must not be frictional, because it is made of one piece. Therefore, simultaneous C and F at one side are marked "X1" in the judgement row. For the reason of assembly and disassembly, a continuous type cannot appear on both sides. The CNCN case is thus judged impossible and marked "X2". Some of the assemblies are structurally identical, different only by virtue of their being left-hand assemblies or right-hand assemblies. In these cases, those assembled from the left side are discarded and marked "X3".

There are still six possible assemblies numbered Y1 to Y6. Practical functions are then substituted into each possible assembly to see if they are still reasonable. Condition Y1 in Table 5 is CNDF which means continuous and non-frictional on the left side of the bearing, and discontinuous and frictional on the right side of the bearing. In physical terms, continuous and frictional on the left side may represent a lathed shoulder. The right side, which is discontinuous, could make use of a retaining ring, nut, or bushing as shown in Figure 16. Note that a similarly shaped element—namely a bushing—is added in this generative procedure, exerting friction when fitted tightly on a pin. In condition Y1, the frictional-type assemblies are a nut

Table 5 All possibilities of generated assemblies

left	C/D	C		C		D		D							
	F/N	F		N		F		N							
right	C/D	C	D	C	D	C	D	C	D						
	F/N	F	N	F	N	F	N	F	N						
judgement		X1		X1	X2	Y1	Y2	X1	X3	Y3	Y4	X1	X3	Y5	Y6

C/D:continuous or discontinuous
F/N:frictional or non-frictional

and bushing. Their matching pairs could be arranged with a tight fit, groove or thread as shown in Table 6. The judgement of their feasibility is as follows. A nut with a tight fit may not be able to turn, and thus as "×" in the judgment column indicates that this possibility is discarded. Nor can a nut be assembled in a groove, and an "×" is indicated as well. The threaded shaft which is the existing matching means, is the best option and is marked "○". A bushing giving a tight fit is workable and marked "○". However, it cannot be assembled on a groove and is thus marked "×". An internal threaded bushing is a nut, and while it is workable, we discard it because this possibility already exists. Likewise, we judge every possible case in Table 5 and list the feasible results in Table 7. The remarks column indicates their corresponding assembly drawings in Figures 14 and 17.

The above generative procedure started from the two existing cases shown in Figure 14 and resulted in the seven other feasible assemblies shown in Figure

Fig. 16 Examples of discontinuous assembly

Fig. 17 Corresponding assembly drawings

17. These different assemblies may lead to different design concepts and manufacturing concerns, and while all may not be feasible for a specific design requirement, they are worth considering. This is only an example showing how different designs can be generated with the decomposition and composition technique.

10. Discussion

(1) Applying the notion of duality, a multilevel tree can be generated. For example, the type of connection can be divided into continuous or discontinuous at the first level. The continuous type can then be divided into two branches such as joining and section. The discontinuous-type connection could use retaining rings, nuts, bushings, etc. The continuous-type connection in a section branch may imply a shoulder by lathing, and the joining branch may imply

Table 6 The possibilities for condition Y1

	left		right		judge- ment	reasons
	C	N	D	F		
shoulder lathing			n	f	×	not working
				g	×	not working
				t	○	existing
				f	○	existing
			b	g	×	not working
				t	○	nut equivalent

r: retaining ring f: tight fit
n: nut g: groove
b: bushing t: thread

Table 7 A list of feasible results

	C	N	D	F	REMARKS
Y1	s	l	n	th	drawing 14(b)
	s	l	b	pn	drawing 17(a)
Y2	C	N	D	N	
	s	l	r	gr	drawing 14(a)
Y3	D	F	D	F	
	n	th	n	th	*
	n	th	b	pn	*
	b	pn	n	th	drawing 17(b)
	b	pn	b	pn	drawing 17(c)
Y4	D	F	D	N	
	n	th	r	gr	*
	b	pn	r	gr	drawing 17(d)
Y5	D	N	D	F	
	r	gr	n	th	drawing 17(e)
	r	gr	b	pn	drawing 17(f)
Y6	D	N	D	N	
	r	gr	r	gr	drawing 17(g)

* Considering assembling from the right side, the nominal size of the left-side thread on the shaft must be larger than the shaft diameter, which serves as a shoulder. Therefore, these possibilities are not feasible.

Fig. 18 The two-level duality tree

a shoulder shape connected by welding. The two-level tree is shown in Figure 18. A lexicon of machine design, as well as a multilevel tree, may be built within this proposed framework.

(2) One of the advantages of using this decomposition and composition procedure is its creativity. The more decomposing steps, the more new designs are generated. However, the procedure taken to its extreme will create designs that are impractical, given pragmatic constraints, in that a meaningful design must be valid in the real world, not just in abstract.

(3) This design method using decomposition and composition is divergent. Its contribution is to enlarge the design space, thus allowing for the creation of new concepts. As for the meaningfulness of the creations, the composing procedure has nothing to do with the eventual judgement of the new designs.

(4) The procedure is more complex when a mechanism has a rather large number of elements. Their relationships are complicated and the multilevel duality tree is large. This process may generate too many assemblies to be judged. Therefore, facing a complicated mechanism, a collection of generation and test rules must be built to suppress the quickly growing number of possibilities.

(5) The decomposition and composition technique based on the notion of duality is not the only method for creative machine design. Some other scholars such as French⁽¹³⁾ have raised combinative ideas which are also very helpful for creative design.

11. Conclusions

From the functional point of view, the machine design structure is very much like the structure of language. Duality seems to be a very powerful tool in classifying machine design function terms as well as

language terms. Through the decomposing procedure, a machine system can be separated into subsystems. By applying the concept of duality, subsystems can then be composed, generating many new systems, some of which might never have been discovered using conventional design thinking.

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