Function, Behaviour, and Structure

Y. Umeda, H. Takeda, T. Tomiyama,
H. Yoshikawa
Department of Precision Machinery Engineering, Faculty of Engineering, The University of Tokyo, Japan

ABSTRACT

Although the words *function*, *behaviour*, and *structure* are used in various fields, their definitions are not clear and differ in the fields. In this paper, we define function, behaviour, and state, which is considered as structure, and the relationships among them. We propose the FBS (Function-Behaviour-State) diagram as a framework to model a system with its functional descriptions. Because functions of a system cannot be described objectively, the model should be divided into subjective part and objective part. The consistency of the objective part should be managed by using physical laws. The FBS diagram also represents a functional hierarchy of a system and the way to construct the hierarchy based on relationships among views which are representation schemes for behaviours and states. By using this diagram, advantages and drawbacks of modeling techniques and design methodologies are discussed.

1. INTRODUCTION

The words *function*, *behaviour*, and *structure* are referred to and used in various fields, such as design, production, and artificial intelligence. Designing, for example, is defined as "a mapping of a point in the *function space* onto a point in the *attribute space* [1]." Qualitative physics [2,3], or qualitative reasoning, deals with *behaviour* and *function* of a physical entity using knowledge about behaviours of its components and structure. In the Oxford English Dictionary [4], *function* is "the special kind of activity proper to anything; the mode of action by which it fulfills its purpose" and *behaviour* is "the manner in which a thing acts under specified conditions or circumstances, or in relation to other things." In this way, the definitions of function, behaviour, and structure are too general and depending on the fields.

The goals of our research are to construct a clear, consistent, computable, and widely useful model for function, behaviour, and structure of machines and to examine it in the context of various applications, such as computer aided design, simulation, and diagnosis. It is indispensable to construct such a model for building CAD systems, simulation systems, and diagnosing systems which interact with users and simulate human reasonings.

In chapter 2, we will review conventional approaches to deal with function, behaviour, and structure in such fields as design methodology and artificial intelligence.

Some approaches regard function as transformation from input to output; we consider that this treatment does not suffice to build e.g. an intelligent CAD system. Other approaches treat function without a clear definition. Therefore, there arises a confusion that, for example, the concept of intelligent CAD systems is discussed in completely different and independent ways depending on the definitions of function, behaviour, and structure. In chapter 3, we will define function, behaviour, and structure, and clarify relationships among them. Structure will be considered as state in this paper. We will also point out that there exists a kind of functional hierarchy of an entity. We will then propose the FBS (Function-Behaviour-State) diagram to represent the relationships among function, behaviour, and state and to represent hierarchy that can be commonly observed among mechanical systems. In chapter 4, the FBS diagram approach will be compared with existing modeling techniques and design methodologies and we will demonstrate advantages of the FBS approach. Chapter 5 concludes the paper.

2. CONVENTIONAL APPROACHES

In this chapter, we examine various approaches to function, behaviour, and structure from examples in mechanical design and artificial intelligence. Despite serious efforts observed in these examples, none of them has achieved satisfactory definitions that can be considered universal. Since behaviour and structure are discussed in the context depending on function, we mainly discuss issues related to function.

2.1. Function in Design Methodology

German researchers are active in theoretical works on mechanical design that results in design theories and methodologies. Function has been addressed and defined in the contexts of so-called methodological design and systematic design.

Rodenacker [5] proposed a design methodology which was meant to be a guideline for novice designers. First, a designer determines the entire function of a mechanical entity from the given specification. He should then divide it into sub-functions, sub-functions into sub-sub-functions, and so on, until the level where physical behaviours perform such sub-functions. As a result, the functional structure is clarified. Second, catalogues of mechanical elements are looked up and for each divided sub-function the most appropriate element is chosen. Finally, the designer constructs the machine from those selected elements in the reverse process of dividing the function. This means that the functional structure is copied to the physical structure of the machine in the embodiment design process. Here, function plays a crucial role, because the results of the design entirely depend on the division of the function. In this methodology, Rodenacker defined function as transformation between input and output of material, energy, and information (see Figure 1). Roth [6] compiled a systematic design catalogue which represents correspondence between functions and elements that perform functions. In addition to Rodenacker's definition, function in this approach includes relative motions of parts in mechanical systems as well.

There are several issues in these approaches. First, the word *function* has no clear definition in Roth's approach. It is used in different degrees of abstraction; i.e. from relationships between input and output of material, energy, and information to relationships between surfaces of mechanical parts. Second, Rodenacker's definition of function does not suffice to describe the function which is not transformation between input and output, e.g. the function of a bolt and a nut, which is to fix parts. Third, the mechanism for dividing a function into sub-functions is unclear and can be subjective. There is no objective method nor "algorithm" to do so. Fourth, such subdivision should end up with primitive functions that are used as indices to a design catalogue, but these

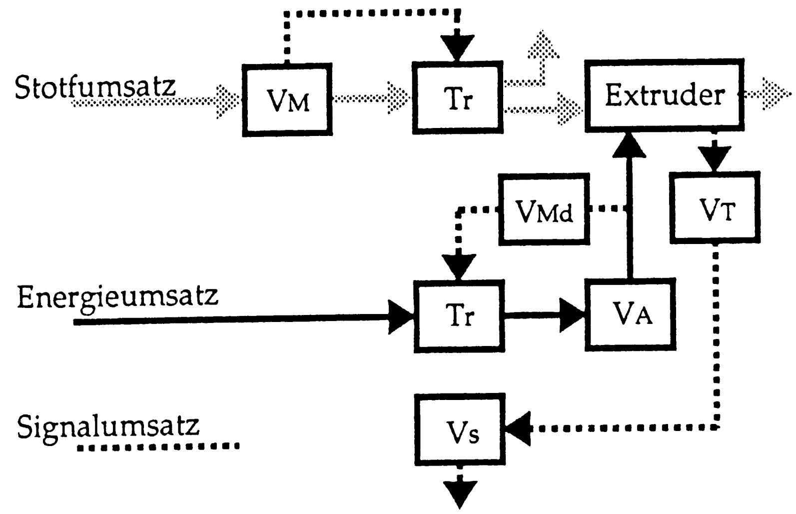


Figure 1. Example of Functional Structure of A Safety Extruder [5]

primitive functions can only be defined in a limited domain (e.g. the world of kinematic pairs). This implies further that the structure of the whole is the *sum* of the sub-structure correspondent to sub-functions, which is not the case in many domains.

2.2. Device-Oriented Qualitative Physics

In artificial intelligence, we can also find some approaches to function, behaviour, and structure. De Kleer [2] proposed *device-oriented* qualitative physics that models a device as a network of components and flow of energy, material, information, etc. De Kleer [7] says that *structure* is "what the device is," *behaviour* is "what the device does," and *function* is "what the device is for." These definitions are rather intuitive and not rigorous. It reasons about behaviour of an entire device by using knowledge about its structure and behaviour of components; this is called *causal analysis*. Furthermore, it reasons about the entire function of the device from the whole behaviour obtained by causal analyses based on transformation rules about fragmental graphs; this process is called *teleological analysis*. In this approach, the difference between function and behaviour is not clear and it cannot deal with hierarchical structure of a device. Similar to Rodenacker's function, the representation of function is abstract transformation flow between input and output. Although he did not restrict the function to the transformation flow, other functions than the transformation flow cannot be dealt with in this approach. This is because function is transformed from behaviour by using rules about fragmental graphs in the teleological analysis and the representation of behaviour is the transformation flow. This representation of function is applicable to, e.g. the electrical domain with which de Kleer deals. However, particularly in the mechanical domain, this is not the case: for example, Faltings [8] pointed out that a mechanical device achieves its function by relatively constrained motions of its parts and that representation of the function must be based on connectivity of the parts rather than the parts by themselves. It is also well known that the no-function-in-structure principle which is introduced in the device-oriented approach is not always strictly applicable in any domains [9]. This is because terminologies for describing behaviour and structure of components are dependent on functionality of the entire device; i.e. terminologies of behaviour and structure are dependent on views which we will introduce in chapter 3. This indicates that in general it is impossible to reason about function and behaviour of the entire device by using only knowledge about behaviour and structure of components which are written with respect to the no-function-in-structure principle. It is necessary for such reasonings to use knowledge about functions. In other words, it is necessary to control the whole reasoning in the viewpoint of function.

Most of physical entities are regarded to have various kinds of hierarchy. For instance, the part-assembly hierarchy is the most easily perceived one. In order to deal with, e.g. mechanical systems, it is necessary to have the concept of hierarchy in the qualitative physics and knowledge compilation techniques are developed for this reason (e.g. Chandrasekaran [10]). Consolidation proposed by Bylander and Chandrasekaran [11] is expanded device-oriented qualitative physics to reason about behaviours hierarchically. They used *causal patterns* to reason about behaviours of a device in the super hierarchical level from behaviours of sub-devices (this is called *consolidation* (see Figure 2)). Drawbacks of this approach are as follows. There might be many kinds of causal patterns which are abstracted from many types of viewpoints and in many different levels of descriptions. Therefore, when the consolidation technique is applied to a large system, it is necessary to choose the most appropriate causal pattern. It is chosen from a functional point of view either by the user or by the system using some knowledge. Since there are no general principles about consolidation independent of viewpoints and functionality, it is not easy to obtain such knowledge. Moreover, since units constructed by consolidation do not always correspond to those made intuitively, meanings and functions of such units cannot easily be understood by human and accordingly such units are not useful for designing other objects. Thus, this consolidation technique is too weak to explain the mechanism for constructing hierarchies of mechanical systems.

2.3. Function Sharing

Ulrich *et al.* [12] proposed the function sharing approach as a design strategy to design cheaply high performance machines. This strategy simplifies the structure of a machine while giving as many functions to a part as possible. Function sharing is achieved by providing a knowledge base that knows about relationships between functions and *physical features*. They use explicit and direct relationships between functions and behaviours which are called physical features, but they failed to explicitly define function.

2.4. Value Engineering

Miles [13] proposed value engineering (VE). VE is a technique to improve values of products or service by changing their material, design, system, etc., aiming at maximising their function while minimising cost. In this approach, a function of a product is represented in the form of *to do something* and its value is represented by price. VE is performed by comparing the value of function with respect to the costs of the product. Since VE is only concerned with evaluation of functions, relationships between behaviour and structure and relationships between function and structure are not clearly mentioned.

2.5. Bond Graph Approach

Karnopp *et al.* [14] proposed an approach where they applied bond graphs to analyse dynamic systems. A bond graph consists of ports, at which power interactions between a component and its environment can occur, and bonds, which interacts power between ports. Figure 3 shows an example of a word bond graph whose ports are words. In this approach, they use a bond graph to represent power flow of a dynamic system and reason about behaviour of the system using the bond graph. This approach treats structure of a system and reasons about its behaviours but does not treat its functions. It has two main drawbacks which device-oriented qualitative physics has. One is that since it treats only power flow of a system, we cannot represent the function of, e.g. a bolt and a nut using the bond graph. The other is that since the represented behaviour of a system should be related to its functionality, the bond graph of the system should be constructed by considering its whole function; i.e. selection of parameter to use in the bond graph and the level of description should be determined manually.

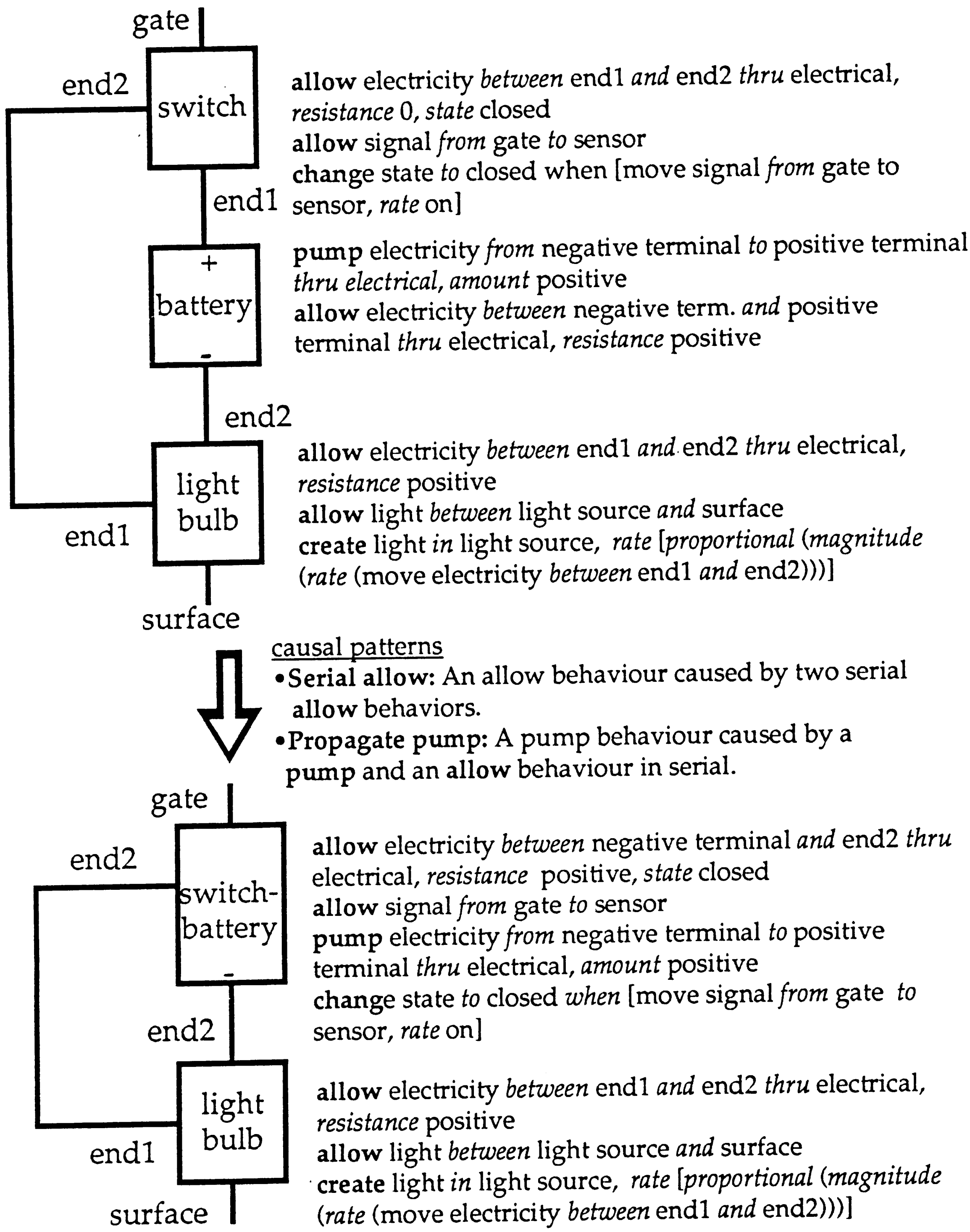


Figure 2. Example of Consolidation [11]

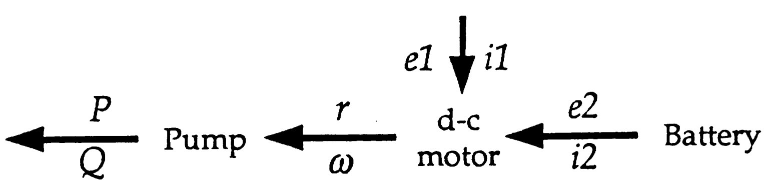


Figure 3. Example of Word Bond Graph [14]

2.6. Summary

Approaches to function, behaviour, and structure illustrated in this chapter have the following three problems:

(1) The concepts of function and behaviour are used without being rigorously defined.

(2) There are three ways to treat function observed in these approaches all of which are more or less non-relevant to each other and thus failed to provide a unified definition. The first definition of function is transformation between input and output as we have seen in Rodenacker's and de Kleer's approaches. The second is that function is performed by relative motions of objects as in Roth's and Faltings' approaches. And the third is that function is represented as *to do something* in Miles' approach.

(3) Methods to treat hierarchical structures of entities are not yet fully developed to include various cases; e.g., the mechanism for constructing such hierarchies is not clear.

3. FUNCTION-BEHAVIOUR-STATE DIAGRAM

As we described in the previous chapter, existing approaches often lack a clear distinction between function and behaviour and dealing with hierarchical structures is problematic. In this chapter, first we define function, behaviour, and state with considering the definitions above. Second, we try to understand *hierarchy* under these definitions. We introduce a new framework, i.e. the FBS (Function-Behaviour-State) diagram to clarify their relationships. And third, we try to clarify the mechanism for constructing hierarchies.

3.1. Definitions of Terms

From now on, we consider only a physical world; i.e., we will deal with physical function, physical behaviour, and physical structure, but not aesthetic function, economic function, etc.

To begin with, let be an *entity* as "an identifier" of the entity in the real world (e.g. its name). And let be an *attribute* of an entity as "a physical, chemical, mechanical, geometrical, or other property which can be observed by scientific means [1]" and a *relation* as "what relates attributes, entities, or relations." Let us define a set of *internal states* S_i of an entity by

$$S_i = < E , A , R >,$$

where E, A, and R are a set of entities, a set of attributes, and a set of relations, respectively. In this paper, $A = < B , C >$ means that A is described by using B and C. When a set of *external states* S_o of an entity is described in the same way as S_i, a set of *states* S of an entity is given by

$$S = < S_i , S_o >.$$

We consider that the distinction between so-called *structure* and so-called *state* is essentially meaningless. Generally speaking, people call a part of an entity which exists for a rather long time and can be considered as a part of essence of the entity *structure* and the remains which change in a rather short time *state*. However, this distinction is relative and rigid distinction between them will remove flexibility from representation of an entity. In this paper, we call the state and the structure altogether *state*. Because the distinction between so-called state and so-called structure is dependent on time, it is quite natural that the distinction does not appear in our *state* which is an instantaneous description of an entity. For example, Figure 4 shows a part of the state representation of a paper weight. In Figure 4, "Paper Weight" and "Paper" are entities and they have the relationship "on" which means that "Paper Weight" is on "Paper." "Paper Weight" has some attributes; i.e. "Weight: $1kg$," "Volume: $100cm^3$," and "Density: $10g/cm^3$," and these attributes are also related with each other.

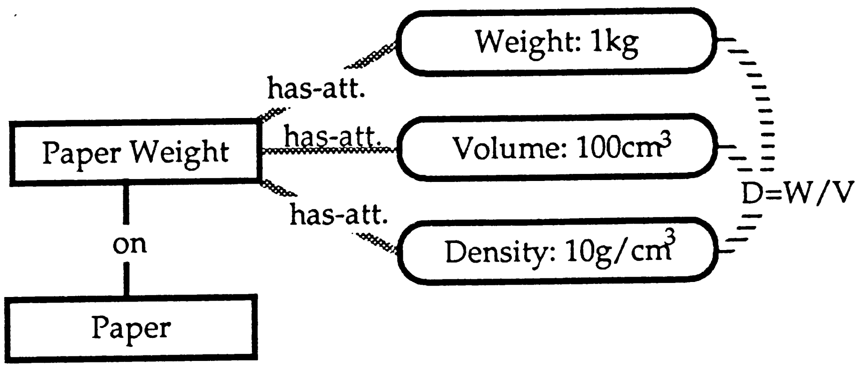


Figure 4. State of Paper Weight

Introducing a discrete unit time, we assume that if a state s_1 is given, the next state s_2 can be determined by some methods. This change from s_1 to s_2 is called as a change of states. Here, we define *behaviour* as "sequential one and more changes of states." We consider a state which does not change for a while as a kind of behaviours. Unfortunately, the number of behaviours is infinite. However, a transition from a state to the next state does not occur at random but is governed by some principles; viz. *physical laws*. We define a *physical law* as "a rule which determines behaviours of an entity under a specific condition of states." Then, we can know all possible behaviours of an entity by using physical laws. For example, it is a behaviour that, if you let a ball go, the ball will fall, which can be explained by the law of universal gravitation. We call this relationship between behaviour and state the *B-S relationship*.

However, representations of the behaviour of the same entity can be different depending on the physical situations of the current interest. For example, a behaviour that electricity passes through a wire can be codified by resistance, voltage, current, and so on, from a viewpoint of electrical engineering. It can also be captured as movements of electrons from a viewpoint of electronics. Let us define *views* to be these specific representation schemes for behaviours and states. A view consists of a vocabulary of states, a vocabulary of behaviours, and a set of physical laws. Only after choosing a view, we can describe states and behaviours. We will later argue that the concept of views is crucial to discuss functions.

We here define a *function* as "a description of behaviour abstracted by human through recognition of the behaviour in order to utilise it." Namely, a function is an image of behaviours abstracted by human and, in general, it is represented in the form of *"to do something."* Let us define the correspondence Γ_{ab}, which represents the process of recognition and abstraction performed by human, as

$$\Gamma_{ab} : B \rightarrow F,$$

where F is a set of functions. We call this correspondence the *F-B relationship*. In many cases, this abstraction is done from the viewpoint of utilisation or value of objects, and as its result the F-B relationship is not a one-to-one correspondence. For example, there are some behaviours which correspond to a function of making a sound; i.e. both a collision of two objects and vibration of an object make a sound. On the contrary, there is no function which does not correspond to any behaviours. This means an unrealisable function, although there might be a behaviour which does not correspond to any function;

a blow of wind in a desert is an example of behaviour without functions for most of us. The vocabulary used for representing functions is often similar to that for behaviours. For example, *to support something for manufacturing it* is a representation of a function, while *A is supporting B* is a representation of a behaviour of *A*. This comes from the fact that functions are observations of behaviours, but the representation of function should include some intention explicitly or implicitly. As we see from this definition, a view must be appropriately selected in order to represent the behaviour which performs the intended function. This suggests that functions and the selection of views are not independent from each other and further that both the decision of the F-B relationships and the selection of views are *subjective*. Figure 5 shows the relationships among function, behaviour, and state described above.

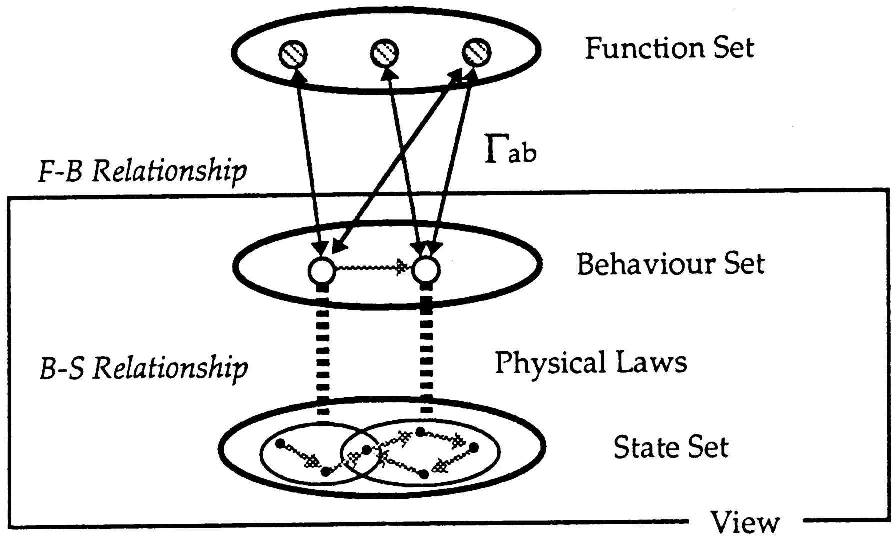


Figure 5. Relationships among Function, Behaviour, and State

As we discussed above, we conclude that functions cannot be described objectively. However, in order to represent mechanical entities on computers, we should propose a general scheme for representing machines. Our definitions above are useful as such a scheme because we can divide the subjective part and the objective part; i.e. the decision of the function of an entity, the F-B relationships, and the selection of views should be made subjectively and consequently the description of its behaviours, its states, and the B-S relationships are decided automatically according to the views Therefore, we can construct a useful scheme by describing information of subjective decisions on such subjective part explicitly. Let us call this scheme for representing entities as the *FBS diagram* (see Figure 6).

3.2. Hierarchy of A System

This section examines hierarchical structures of engineering entities based on the FBS diagram approach. As Rodenacker [5] pointed out, a designer divides a unit into sub-units repeatedly, and then he designs the state of a small sub-unit. This subdivision for building hierarchies can be carried out from different standpoints, e.g. to arrive at a hierarchy based on kinds of motion of an entity or at a part hierarchy that is convenient for manufacturing. Accordingly, we assume that a hierarchy of an entity are neither objective nor physically determinable and are constructed by recognising and abstracting the entity from function standpoints by a human. The information about how a hierarchy is constructed should be described in the function description in the FBS diagram.

When a hierarchy of an entity is constructed, a view should be selected for representing behaviours and states that are corresponding to each portion in the functional hierarchy. Figure 6 depicts such a hierarchy in the FBS diagram. In Figure 6, views are classified into some domains, i.e. mechanical views, electrical views and so on, and each view is different in details of representation in proportion to the level of each functional portion. Consequently, relationships among views play an important role to keep hierarchical representation of an entity consistent, because relationships on the level of the functional hierarchy arrive at the relationships among views. This management mechanism for relationships among views should be added to the FBS diagram. Figure 7(b) shows an example of a portion of the FBS diagram for the buzzer shown in Figure 7(a).

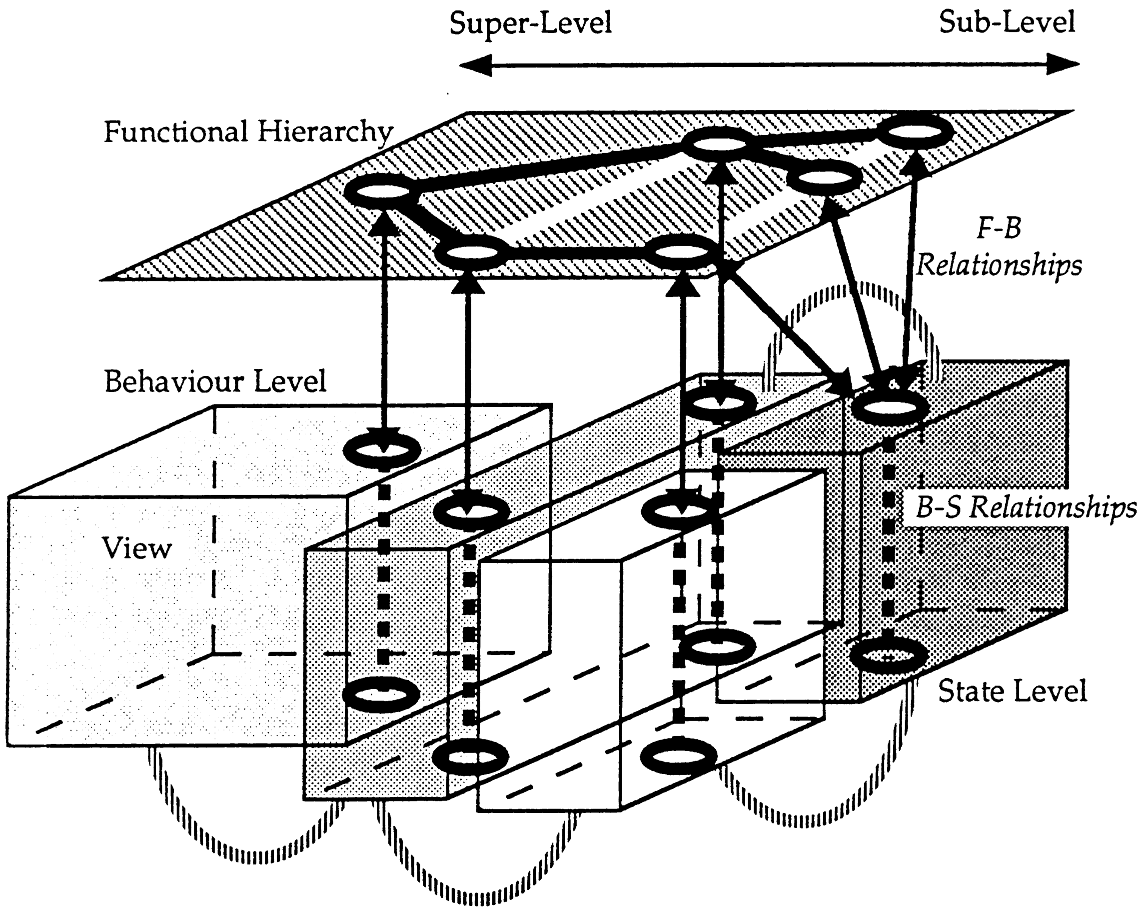


Figure 6. FBS Diagram

The FBS diagram has advantages as follows:

(1) Human can recognise this representation easily. By representing the function of an entity hierarchically, super-portions can be described more generally and sub-portions can be described more particularly.

(2) Subjective parts and objective parts are divided explicitly. The B-S relationships and the relationships among views are objective and are dependent on the selection of views. If we construct a knowledge base which includes various engineering views used in general and relationships among those views, consistency of the B-S relationships and realisability of behaviours and states can be maintained automatically using this knowledge base.

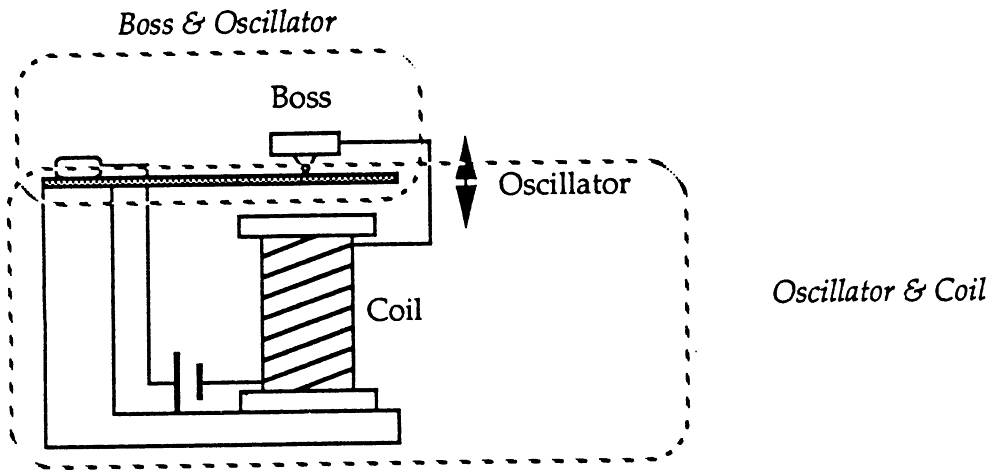


Figure 7(a). A Buzzer

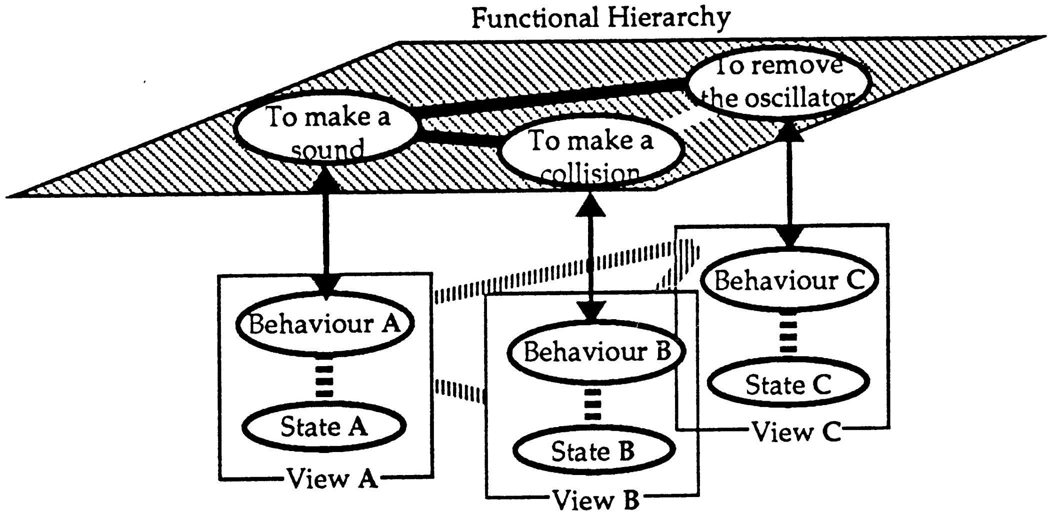
(3) The hierarchy of the FBS diagram is flexible. The FBS diagram can represent a functional hierarchy which does not correspond to representations of behaviours and states, because a functional hierarchy and a network of views, which represents behaviours and states of an entity, are separated. For instance, a behaviour might perform several functions in an entity. The FBS diagram can represent such a case, owing to the flexibleness of the F-B relationships.

3.3. Mechanisms for Constructing Hierarchies

In this section, we demonstrate how a hierarchy of an entity is constructed in the FBS diagram approach. There are typically two ways to do so. We assume that we can determine either functional hierarchies or the relationships among views. Therefore, one mechanism is to construct functional hierarchy first and the other is to select views first. In the case when we build a hierarchy of an entity in practice, both of these two mechanisms are used.

The former is the case when the functional hierarchy of an entity is first determined. For example, when we see a buzzer (see Figure 7(a)), *Boss & Oscillator* and *Oscillator & Coil* can be recognised as sub-portions of the buzzer. We find easily that the function of the buzzer is "to make a sound," the function of *Boss & Oscillator* is "to make a collision in order to make a sound," and the function of *Oscillator & Coil* is "to remove an oscillator from a boss in order to make a sound." We recognise that the function of the buzzer "to make a sound" is achieved by performing the sub-function "to make a collision" and the sub-function "to remove the oscillator" alternatively. In this way, a functional hierarchy is constructed (see Figure 8(a)). Next, a view is selected for each functional portion in order to represent behaviours and states which perform the function and therefore the relationships among views are determined (see Figure 8(b)). However, views cannot uniquely be determined based only on the function; i.e. these are selected by intentions and functional parts and views do not necessarily have one-to-one correspondence. Moreover, there might be no feasible set of behaviours and states for a specific functional hierarchy; it means that this organisation of function cannot be materialised at all. Namely, feasibility of a functional hierarchy is estimated based on physical laws when views are determined.

The latter way is to select views first. If views are changed, representations of an entity are changed. The representation of the buzzer in the *mechanical and electrical* view is shown in Figure 7(a), while another representation of the buzzer in the *electrical*



Behavior A: the oscillator collides with the boss repeatedly
State B: Entity = Buzzer
Attributes = frequency: 400 Hz, loudness: 0 dB
Relations = equal(frequency, frequency of Boss & Oscillator)
View A: mechanics

Behavior B: the iron oscillator are pulled to the coil by the magnetic force
Structure B: Entity = Coil & Oscillator
Attributes = distance between Coil and Oscillator: 1 mm
magnetic force between Coil & Oscillator: 0.1N
k: 1 kgf/mm
Relations = calculation(frequency, distance, force, k)
View B: magnetism and mechanics

Behavior C: the oscillator collides with the boss by elastic force
Attribute C: Entity = Boss & Oscillator
Attributes = distance between Boss and Oscillator: 1 mm
View C: mechanics

Functional hierarchy: to make a sound
= to remove the oscillator from the boss & to make a collision of the oscillator and the boss & alternatively
Relationship among View A, View B, and View C:
the oscillator collides with the boss repeatedly
= magnetic force removes the oscillator from the boss & elastic force makes a collision of the oscillator and the boss & the buzzer repeats them alternatively
identical(Switch in Coil's Circuit, Boss and Oscillator)
identical(Oscillator in the Coil & Oscillator unit, Oscillator in the Boss & Oscillator unit)
has-parts (Buzzer, Boss & Oscillator, Coil & Oscillator)
has-parts(Coil & Oscillator, Coil, Oscillator)
has-parts(Boss & Oscillator, Boss, Oscillator)
configuration of Coil, Oscillator, and Boss

Figure 7(b). Example of FBS Diagram for a Buzzer

view is shown in Figure 8(c). Determining views, since the representations in views are not independent with each other, the relationships among views and the B-S relationships are automatically determined (see Figure 8(d)). Next, based on these relationships, the F-B relationships and the functional hierarchy determined by human recognition under the condition that these relationships are not inconsistent with the relationships among views above (see Figure 8(e)). However, again these relationships concerning the function cannot be uniquely determined but according to intentions. In mechanical design, views tend to be chosen as mechanisms in order to look up catalogues of kinematic pairs.

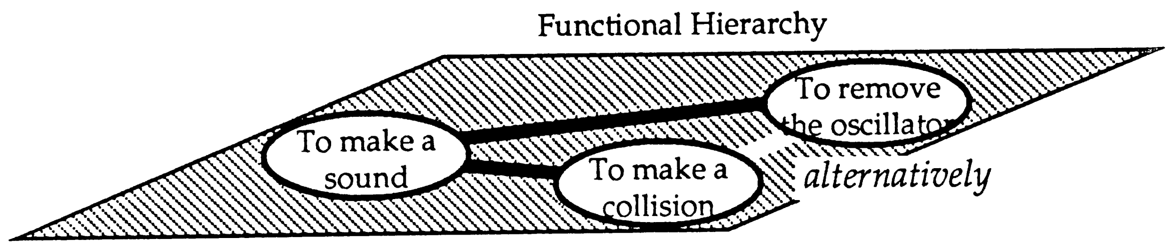


Figure 8(a). Constructing Hierarchy of a Buzzer(1)

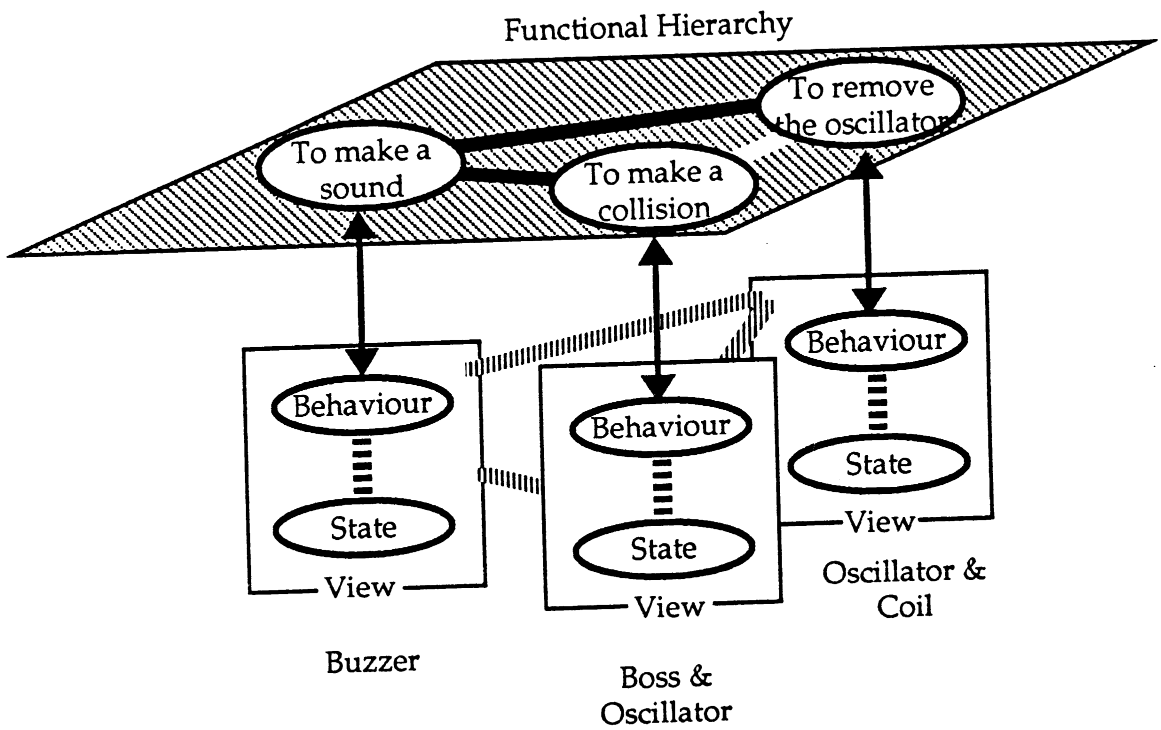


Figure 8(b). Constructing Hierarchy of a Buzzer(2)

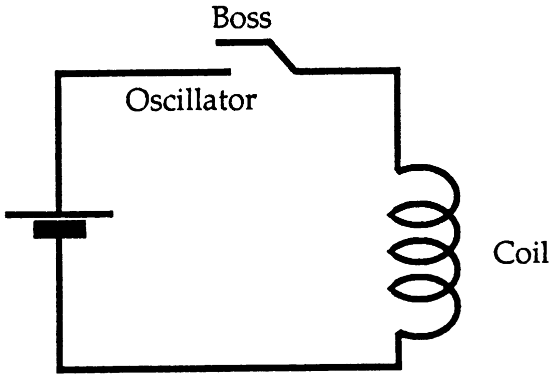


Figure 8(c). Constructing Hierarchy of a Buzzer(3)

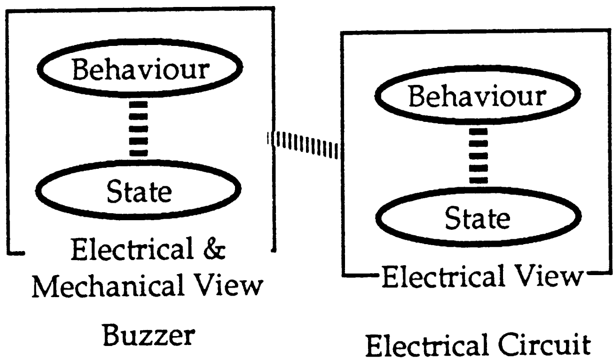


Figure 8(d). Constructing Hierarchy of a Buzzer(4)

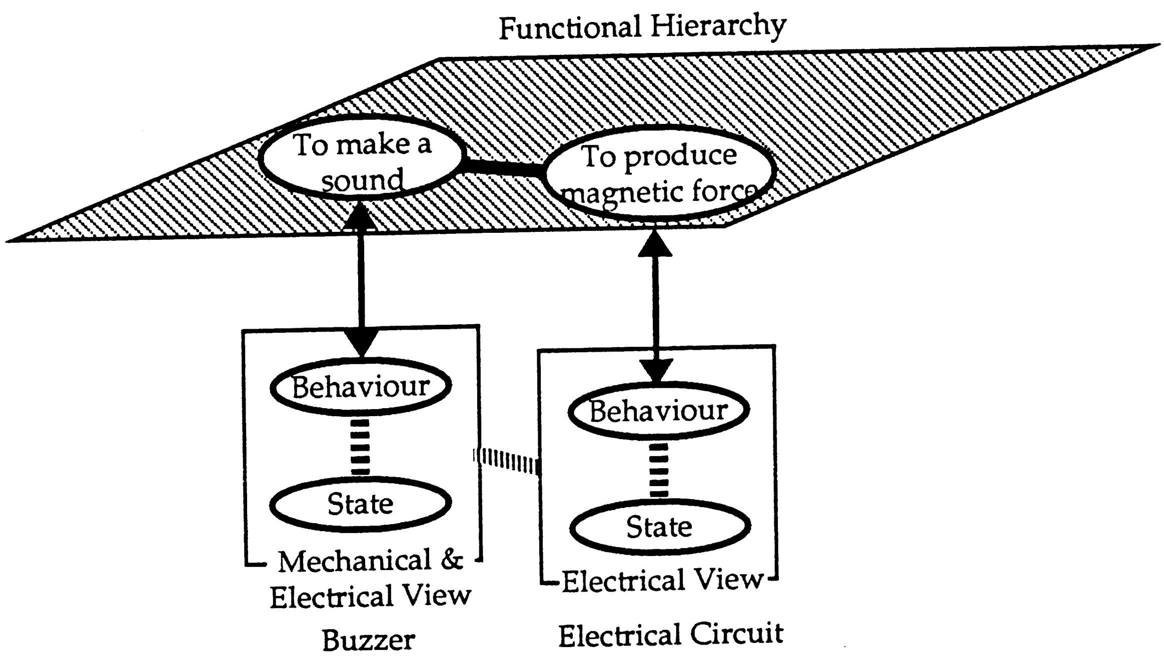


Figure 8(e). Constructing Hierarchy of a Buzzer(5)

4. DISCUSSIONS

In this chapter, we discuss advantages of the FBS diagram approach from the viewpoints of representing the hierarchy of an entity, of modeling strategy, and of design.

4.1. Representation of Hierarchies of Entities

First, we examine our approach from the viewpoint of representing hierarchies of entities. The approaches discussed in chapter 2 have the following problems.

(1) De Kleer's approach cannot deal with hierarchies of entities.

(2) The mechanisms for constructing functional hierarchies are not clear in Rodenacker's and Roth's approaches.

(3) In the Chandrasekaran's consolidation approach, hierarchies of entities is not always equivalent to those made manually.

The FBS approach solves these problems. A hierarchy of an entity is functional and many kinds of views are used to represent behaviours and states of the entity. Therefore, the functional hierarchy should be separated from the representation of the behaviours and states and the relationships among views play an important role in representing the entity. This is our answer to the problem (1). We proposed two mechanisms for constructing such a hierarchy; one is based on division of functions and the other is based on selection of views. These are our answers to the problem (2). Regarding the problem (3), since our functional hierarchy of an entity is made through human recognition, it corresponds well to the hierarchy of an entity made manually. In short, the FBS diagram is appropriate to represent hierarchies of entities.

4.2. The FBS Diagram as A Modeling Strategy

We discuss the FBS approach from the point of view of modeling in this section.

Analytical modeling techniques (e.g. finite element method) take the B-S relationship into consideration from a specific view in the FBS diagram and physical laws are modeled by differential equations and their liner approximations. Therefore, relationships other than the B-S relationship must be introduced in a special way and, moreover, the decision on which physical law is applied on the entity must be also determined. Consequently, these techniques are appropriate only for local and liner modeling aspects.

Qualitative physics models the B-S relationships symbolically and takes the selection on which physical law is applicable into account. Consider the device-oriented qualitative physics on the FBS approach, which tries to reason about behaviours and functions of the entire entity by using the knowledge about behaviour of each component. As we described in section 2.2, there are the following two problems in this approach:

(1) It is impossible to generally reason about functions only from behaviours.

(2) Relevant to (1), it is impossible to achieve the no-function-in-structure principle.

The reason of the problem (1) is the functional hierarchy, the F-B relationships, and differences of views are not considered. Therefore, if we describe structures and behaviours of components generally without any consideration about views, we would get all possible behaviours of a device and therefore cannot reason about the desired functions which occur on a real entity. To avoid this situation, the device-oriented qualitative physics takes two counterplans. One is to filter out unwanted behaviours by heuristics in the teleological analysis [7] and the other is to describe structure of the device and behaviours of components by considering the function of the entire device [9]. The latter counterplan causes the problem (2). In short, the drawback of device-oriented qualitative physics is that since it does not have hierarchies of functions, it deals with functions implicitly. Although qualitative physics has such drawbacks, it is still powerful for modeling entities. Particularly, the *process-oriented* qualitative physics [3] which models an entity focusing on phenomena that occur on the entity is more appropriate than the device-oriented qualitative physics, because it does not assume that a function is transformation between input and output.

Our main idea about modeling is that it is important to model functions which represent human concepts in distinction from behaviour which is ruled by physical laws. You may say that it is not necessary to include functions into models and functions should be kept in human brains. However, designing mainly proceeds in terms of functions and determines states in order to manufacture the designed machine, and the main process of fault diagnosis is to reason about changes of states from losses of functions of an entity. In this way, since men recognise and reason about entities in the viewpoint of function, it is necessary to make a modeling framework which includes functions. Although we introduce the FBS diagram in order to express this idea, to develop a modeling technique for the FBS diagram is our main future work. We consider that the process-oriented qualitative physics will be a powerful tool to develop it.

4.3. Design on The FBS Diagram

Let us discuss design on the FBS diagram. In mechanical design, designers seems to use two types of mechanisms which we mentioned in section 3.2. Namely, in principle, they divide a function into some sub-functions, and decide behaviours and states which can perform a sub-function. This process is the same as Rodenacker's approach [5]. Next, they estimate feasibility and consistency of their behaviours and states by simulation, experiments, or intuitions. Sometimes they divide functional hierarchies by choosing specific views, e.g. the mechanical pair view and the electrical view, in order to use catalogues or to make the estimation easy. And then, according to results of estimation, they change states, behaviours, and even functional hierarchy dynamically. The FBS diagram is useful for representing design objects for the following reasons. First, this diagram can represent those mechanisms for constructing hierarchies. Second, the estimation of feasibility and consistency can be performed by simulation using physical laws described in views. And we can know the reason why such behaviours will occur or why such behaviours will not occur. And third, hierarchies of an entity can be changed dynamically according to designer's subjectivity.

By comparing the Rodenacker's approach [5], he assumed that a functional hierarchy is one-to-one correspondent to representation of states. Namely, there are appropriate parts which can perform each sub-function and the design object can be constructed by combining such appropriate parts. However, this assumption cannot be valid in the mechanical entities in general. For instance, Ulrich's function sharing approach [12] makes states of the entity simpler and as a result the functional hierarchy does not correspond to the states any more. The FBS diagram can represent such a complex hierarchy by using the flexible F-B relationships. Moreover, it is difficult to know how to combine parts in order to keep its feasibility and to perform desirable functions. We can know the feasibility of behaviours and the realisability of the functions by estimating the FBS diagram using the views and their relationships. There is another problem in Rodenacker's approach. In his approach, it is assumed that decomposition of function of a design object will reach primitive function elements; i.e. primitive functions and elements which perform the primitive functions are assumed. On the contrary, such primitive function elements cannot be defined in general. According to our definitions, a function is dependent on behaviours which are changes of states. Namely, a function is not dependent on only inner states but outer states. And because the correspondence between functions and behaviours is not one-to-one correspondent, elements which will preform a specific function differ according to outer states. Therefore, such primitive function elements cannot be collected in general and are only useful for restricted domains. Instead of collecting primitive function elements, it is important and useful to collect relationships between functions and behaviours.

As Gero *et al.* [15] pointed out, experienced designers have a lot of useful *prototypes* of design. By using these prototypes, they can omit estimation, because they believe that these prototypes are feasible and consistent. On the FBS diagram, these prototypes can be represented as a specific set of an entity, a view, and its function. Although relationships among function, behaviour, and structure, and principles for describing prototypes systematically are not clear in his approach, prototypes can be described systematically and consistently by using the FBS diagram which gives an unform framework for prototypes. It is difficult to design new design objects which are not included in prototypes in his approach. One of the reasons is that the relationships among function, behaviour, and structure are rigid. And another reason is that the relationships among prototypes are rigid. Therefore, by changing some these relationships in a prototype and merging some prototypes on the FBS diagram, new design objects can be created.

5. CONCLUSIONS

In this paper, we clarified the difference between function, behaviour, and state and relationships among them. Next, we proposed that hierarchical structures of entities depend on functions and introduced FBS diagram in order to represent the relationships and the hierarchies. The FBS diagram is the framework to represent a system with the description of its functions. Moreover, using the FBS diagram, we clarified advantages and drawbacks of qualitative physics, and analytical modeling techniques. We pointed out the importance to include functions of an entity into models and to divide subjective part and objective part in the models. Future work includes constructing a theory of modeling an entity based on the FBS approach and ensuring usefulness of the FBS diagram for modeling design.

ACKNOWLEDGEMENTS

We'd like to thank Kouichi Ando, Toshiharu Taura, Takashi Kiriyama, and Fumio Yamamoto for ideas, advice, and many important discussions.

REFERENCES

1. T. Tomiyama and H. Yoshikawa, "Extended General Design Theory," in *Design Theory for CAD, Proceedings of the IFIP WG5.2 Working Conference 1985, Tokyo*, H. Yoshikawa and E. A. Warman (eds.), North-Holland, Amsterdam, 1986, pp. 95-130.
2. J. Kleer and J. S. Brown, "A Qualitative Physics Based on Confluences," *Artificial Intelligence*, 24(3), 1984, pp. 7-83.
3. K. Forbus, "Qualitative Process Theory," *Artificial Intelligence*, 24(3), 1984, pp. 85-168.
4. R. W. Burchfield (ed.), *A Supplement to the Oxford English Dictionary*, Oxford at the Clarendon Press, 1972.

5. W. Rodenacker, *Methodisches Konstruieren*, Springer, Berlin, Heidelberg, New York, 1971.

6. K. Roth, *Konstruieren mit Konstruktions Katalogen*, Springer-Verlag, New York, 1982.

7. J. Kleer, "How Circuits Work," *Artificial Intelligence*, **24**(3), 1984, pp. 205-280.

8. B. Faltings, "Qualitative Kinematics in Mechanisms," in *Proceedings of IJCAI-87*, 1987, pp. 436-442.

9. A. Keuneke and D. Allemang, "Exploring the No-Function-In-Structure Princile," *Journal of Experimental & Theoretical Artificial Intelligence*, **1** (1), 1989, pp. 79-89.

10. B. Chandrasekaran and S. Mittal, "Deep Versus Compiled Knowledge Approaches to Diagnostic Problemsolving," in *Developments in Expert Systems*, M. J. Coombs (ed.), Academic Press, 1984, pp. 23-34.

11. T. Bylander and B. Chandrasekaran, "Understanding Behavior Using Consolidation," in *Proceedings of IJCAI-85*, 1985, pp. 450-454.

12. K. T. Ulrich and W. P. Seering, "Function Sharing in Mechanical Design," in *Proceedings of AAAI-88*, 1988, pp. 342-346.

13. L. D. Miles, *Techniques of Value Analysis and Engineering*, McGraw-Hill, New York, 1972.

14. D. Karnopp and R. C. Rosenberg, John Wiley & Sons, Inc., 1975.

15. J. S. Gero and M. A. Rosenman, "A Conceptual Framework for Knowledge-Based Design Research at Sydney University's Design Computing Unit," in *Artificial Intelligence in Design*, J. S. Gero (ed.), Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1989, pp. 363-382.