Framework for Functional Verification in Product Design Considering Ways and Situations of Use

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Recent industrial globalization have increased importance of functional verification in product design for various ways/situations of use. In particular, for shortening development period, it is desired to perform functional verification and necessary modification of the design plan in the conceptual design phase. This paper describes a framework for such individual functional verification that can be applied to the conceptual design phase. A study with simple examples focusing on definition of function indicated that ways/situations of use affect functions indirectly through behavior of the product. This result implies the functional verification can be performed by modeling functions, behavior and physical phenomena caused by a way/situation of use respectively, by integrating those models and then by analyzing behavior that occurs on the integrated model. This paper presents a method based on graph modeling approach. Those three elements are modeled by function decomposition tree, Petri net and cause-and-effect graph, respectively. The designer relates the function and behavior models by interpreting transitions as sub-functions. The phenomena model is transformed into a Petri net and then integrated with the behavior model by specific places and transitions. This integration can make some behavior infeasible and shows the corresponding function cannot be satisfied. This method was applied to an example and its potential was proven.

1. Introduction

Product design is a creative operation of generating an entity in the real space for satisfying required functions defined in the conceptual space. Relationships between the required functions and the entity are not constant but dependent on how the entity exists in the real space. Therefore, unexpected troubles, such as failing to satisfy the anticipated functions and causing undesirable events, can occur depending on the way or situation of use. Due to recent globalization in product development, manufacturing and business, products are utilized in various areas of the world. This resulted in increase of the number of troubles caused by using products in unexpected situations or ways. In order to avoid such troubles, it is necessary to carry out the following three processes — (i) assuming various ways and situations thoroughly, (ii) verifying whether the design plan can fulfill required functions when the product is utilized in the ways/situations, and then (iii) modifying the design plan in advance if some functional troubles may occur. Processes (i) and (iii) are dependent mainly on creativity and knowledge of designers, and therefore they are hard to be automated. On the other hand, it is expected that process (ii) is automated by computers. Although it might be possible for experienced designers to perform this verification process without special computational support, automation of this process would still bring benefits not only to unexperienced designers but experienced designers, since they may be required to develop a new type of product for which they have no experience. It is, therefore, valuable enough to provide a methodology for the automation of this process.

Verification of a design plan is usually performed by using a prototype or design data in the embodiment design phase or the detailed design phase of the product design process. This is because it is hard to carry out the verification without concrete information on the product. However, to meet recent requirements for shortening development period due to shortening product life cycle, it is desirable to perform the verification in the earlier stage of the design process—the conceptual design phase. There have been numerous works for analyzing products or systems without concrete/detailed information about them by computers, such as qualitative reasoning[1,2], Modelica[3,4] and 1D-CAE[5,6]. These works focus only on behavior of the products or systems and do not consider any external factors like ways and situations of use. Therefore, it is necessary to provide a new framework for the automated functional verification.

In order to realize this automation, it is necessary

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to find out about relations between ways/situations of use and functions of products and then develop a methodology for systematically analyzing influence of the ways/situation on the functions. Function is defined as the concept generated in the designer’s or user’s consciousness by interpreting behavior of the product in the real space[7]. This definition implies that ways/situations of use and functions are related to each other not directly but indirectly through behavior of the product. Therefore, it is expected that influence of the ways/situation on the functions can be analyzed by modeling functions, behavior and the ways/situations, integrating those models, and then analyzing relations between the ways/situations and the functions based on the integrated model. Functions, behavior, and modeling of them have been discussed by many research groups[7–12]. Modeling of phenomena depending on ways/situations of use and the influence of them on the entity have been also discussed in the field of maintenance technology[13,14]. However, there are few works concerning to modeling of them for the integrated analysis and evaluation.

This paper proposes a framework for functional verification considering ways/situations of use and provides a set of methods for realizing it. The next section describes the framework derived from the definitions of functions and behavior and from relations between them and also between behavior and phenomena caused by ways/situations of use. To realize the framework, it is required to model functions, behavior and the phenomena, respectively, and then integrate the models. Section 3 describes modeling and integration methods for the realization of the framework. Section 4 presents conclusions.

2. Framework for Detecting Functional Troubles Depending on Situations/Ways of Use

Product design can be regarded as an operation of generating an entity which satisfies specified requirements. However, if the product is used in an unexpected way or situation, some of the requirements cannot be satisfied. For example, a washing machine satisfies the required function “wash clothes” by satisfying the sub-functions “soak clothes”, “generate water-flow” and so on. It was reported that, in a region, a washing machine was used for washing vegetables and a functional trouble had frequently happened. This trouble occurred because vegetable parings stuck to some parts of the machine, rotational motion for producing the water-flow was prevented from being generated, the sub-function “generate water-flow” was not satisfied, and then the required function was not achieved. For another example, electronic products driven by dry cell batteries obtains electric energy for satisfying their required functions from the batteries, and the sub-function for fixing and electrically connecting a battery to the body is satisfied usually by the mechanism using springs. Utilizing such products in a vibration situation caused a trouble of electrical conduction because the connecting point varied due to the inertia of the battery, the terminal of the battery was shaved, the shavings at the terminal was oxidized, and then the conductivity was lost. These examples show that product design without consideration of unique ways and situations of use may cause unexpected functional troubles. In order to avoid such troubles, it is necessary, in addition to assume various ways and situations thoroughly, to systematically detect the troubles caused by the ways/situations.

The entity of a product has its own behavior which achieves its functions (Fig. 1). For instance, in the example of a washing machine stated above, the sub-function “generate water-flow” is achieved by a chain of each behavior like “rotation of the motor”, “revolution of the belt”, “rotation of the pulsator”, and so on. The other sub-functions are also achieved by the same way, and then the required function “wash clothes” is achieved. As can be seen in this example, a required function is composed of sub-functions and each of them is achieved by a set of behavior of the entity. On the other hand, as shown in the above examples, a set of physical phenomena depending on ways/situations of use may make some of the behavior inactive. This results in failing to satisfy some sub-functions and finally the required function (Fig. 2) or generating unexpected behavior which has undesirable functional meaning.

For avoiding such troubles, it is necessary to carry out the following five processes:

1) assuming various ways and situations of use thoroughly
2) describing the physical phenomena caused by the ways/situations
3) analyzing their influence on behavior
4) analyzing functional effect of the behavior
5) modifying the design result

Processes (1) and (5) depend strongly on creativity and knowledge of the designer. On the other hand,
the rest of the processes can be systematically performed by modeling functions, behavior and physical phenomena, respectively, and then integrating the models.

Modeling of functions and behavior has been widely discussed in the field of conceptual design support[8–12]. A representative method of function modeling is the function decomposition tree, where each function is decomposed into its sub-functions and their structure is described by a tree. Based on one of the most representative definition, a function is an abstract concept generated through subjective interpretation of behavior in the real world by designers/users[7]. Considering this definition, decomposing a function into simpler sub-functions decreases the degree of abstraction and repeating the decomposition would ultimately derive behavior itself. Modeling of physical phenomena and relations among them which depend on ways/situations of use of products have been discussed in the research field of maintenance methodology. There was proposed a graph-based method was proposed[13,14].

As stated above, modeling of functions, behavior and physical phenomena has been discussed, respectively. However, there has been little discussion on integration and integrated analysis of them and modeling methods which are appropriate for this point of view. The next section provides methods for modeling them and describes integration of the models.

### 3. Modeling of Functions, Behavior and Physical Phenomena, and Integration of Them

#### 3.1 Modeling of Functions, Behavior and Physical Phenomena

Although there have been proposed some definitions and description methods of functions and their structures, they are not generic and therefore are utilized depending on the purpose. In this paper, the method used in value engineering[10] is adopted and a function is described with a verb or verb phrase and an object. A function structure is described by a tree. For example, a mechanical pencil (Fig. 3) has the sub-function “draw lead” and its structure is described as shown in Fig. 4.

Behavior is defined as a change of the entity’s state into its another state, and this is regarded as a discrete event. Therefore, a product can be regarded as a discrete event system, and the behavior is modeled by a Petri net as done in the field of computer science.

A Petri net, which is a kind of a directed graph, is composed of two kinds of nodes which are places and transitions, edges which connect two nodes, and tokens whose distribution shows a state of the entity. In this paper, a state of a part of the entity is expressed by a place, and each behavior of the entity is expressed by a movement of a token from one place to another place via a transition. Fig. 5 shows an example of behavior of a mechanical pencil for drawing the lead. In each place (p1,p2,...,p17), a state of a part of the entity is described with words as shown in Table 1.
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Fig. 5 Petri net model of behavior of mechanical pencil

Table 1 Definition of places in Fig. 5

| ID No. | State |
|-------|-------|
| p1    | The clamping chuck has force in the forward direction. |
| p2    | The clamping chuck has force in the backward direction. |
| p3    | The clamping chuck does not have displacement. |
| p4    | The clamping chuck has displacement in the forward direction. |
| p5    | The clamping chuck has displacement in the backward direction. |
| p6    | The clamping chuck has a contact with the chuck ring. |
| p7    | The clamping chuck does not have a contact with the chuck ring. |
| p8    | The clamping chuck has a contact with the lead. |
| p9    | The clamping chuck does not have a contact with the lead. |
| p10   | The clamping chuck has force to the lead. |
| p11   | The clamping chuck does not have force to the lead. |
| p12   | The clamping chuck and the lead have friction. |
| p13   | The clamping chuck and the lead do not have friction. |
| p14   | The lead has force in the forward direction. |
| p15   | The lead has force in the backward direction. |
| p16   | The lead has displacement in the forward direction. |
| p17   | The lead has displacement in the backward direction. |

modeling method using a directed graph[13,14], and is also adopted in this research. In this method, information on each phenomenon is assigned to an edge. It was proposed to standardize description of the information by the form “A (do not) have B” for reduce dependency of the description operation on the designer. Figs. 6, 7 show models of the set of phenomena causing the troubles in which the lead moves in the backward direction due to shavings of the lead and in which the lead cannot be drawn due to a broken lead, respectively.

3.2 Integration of the Models

As stated in the previous section, a function is an abstract concept generated through subjective interpretation of behavior by designers/users. Considering this definition, integration of the function model and behavior model is performed through designer’s recognition process, and a sequence of transitions in the Petri net model of behavior is regarded as a function. For example, the sequences of the transitions “t3-t16”, “t7-t9-t11-t13”, “t1-t4” and “t6-t8-t10-t12” are regarded as the sub-functions “send out lead”, “quit hold of lead”, “return clamping chuck” and “clamp lead”, respectively, through the designer’s recognition process.

The directed graph model of physical phenomena and relations among them can be integrated with the behavior model via conversion of the directed graph into a Petri net. This conversion can be performed by converting the edges and nodes in the graph into places and transitions in the Petri net, respectively, as shown in Fig. 8. Fig. 9 and Table 2 show the conversion results of the graph in Fig. 6, and Fig. 10 and Table 3 show that of the graph in Fig. 7.

After this conversion, the integration is performed based on relations among places and transitions of the both Petri nets. There are two kinds of the relations. One is the relation where both places are identical to each other, and the other is that where a place and a transition contradict each other. If a place of the
behavior model and a place of the phenomena model are identical, the integration can be carried out just by merging both models via the places. For example, the places “p1” in Fig. 5 and “p19” in Fig. 9 are identical. “p8” and “p18”, “p12” and “p23”, “p14” and “p20”, “p15” and “p25”, and “p17” and “p26” are also identical, respectively. Therefore, the Petri nets in Figs. 5, 9 can be merged via those places and the integrated model is generated as shown in Fig. 11.

If a transition of the behavior model and a place of the phenomena model contradict each other\(^1\), which means that the condition described by the place prevents the transition from firing, the both Petri nets can be merged by the operation shown in Fig. 12. By connecting the place and the transition by the red element in this figure, it is possible to make the place in the phenomena model prevent the transition in the behavior model from firing. Fig. 13 shows the integrated model obtained by merging the models shown in Figs. 5, 10 by this type of integration method. (In this case, the integration was performed by not only this method but the method for identical places (described with blue lines).)

\(^1\)At the current stage, finding such a pair of place and transition which contradict each other depends on the user of this methodology and is performed by checking manually whether the place of the phenomena and some places connected from the transition of the behavior model contradict. We will consider automation of this process in a future work.

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Fig. 9 Petri net model derived from the graph in Fig. 6

Fig. 10 Petri net model derived from the graph in Fig. 7

Table 2 Definition of places in Fig. 9

| ID No. | State                                                                 |
|-------|----------------------------------------------------------------------|
| p18   | The clamping chuck has a contact with the lead.                     |
| p19   | The clamping chuck has force in the forward direction.              |
| p20   | The lead has force in the forward direction.                        |
| p21   | The lead has reduced volume.                                        |
| p22   | The lead has shavings.                                              |
| p23   | The clamping chuck and the lead have friction.                      |
| p24   | The clamping chuck and the lead have reduced friction.              |
| p25   | The lead has force in the backward direction.                       |
| p26   | The lead has displacement in the backward direction.                |

Table 3 Definition of places in Fig. 10

| ID No. | State                                                                 |
|-------|----------------------------------------------------------------------|
| p27   | The clamping chuck has force in the forward direction.              |
| p28   | The lead has force in the forward direction.                        |
| p29   | The lead retainer has a broken lead.                                |
| p30   | The lead has a contact with the broken lead.                        |
| p31   | The lead retainer and the broken lead have friction.                |
| p32   | The lead has force in the backward direction.                       |
| p33   | The lead does not have displacement.                                |

Fig. 11 Integrated model of behavior and phenomena generated Figs. 5 and 9.

Fig. 12 Merging two Petri nets containing place and transition which contradict each other

Fig. 13 Integrated model of behavior and phenomena generated from Figs. 5 and 10
3.3 Analysis of Influence of Physical Phenomena on Functions

The set of modeling and integration methods make it possible to analyze the influence of the physical phenomena caused by a way/situation of use on functions and detect functional troubles. Simulations based on the integrated models in Figs. 11, 13 show that the transition “t16” from “p12” to “p16” may fail to fire due to firing of the transition “t12” in Fig. 11 or the transition of the red element in Fig. 13. This means that the sub-function “send out lead” and finally the function “draw lead” may not be satisfied.

4. Conclusions

Recent industrial globalization has increased the number of functional troubles by using products in unexpected ways or situations. In order to avoid such troubles, it is necessary to assume various ways/situations thoroughly, analyze troubles caused by the ways/situations, and then modify the design result to prevent the troubles in advance. The first and third processes are dependent mainly on creativity and knowledge of human beings and therefore hard to be automated. On the other hand, it is expected that the second process is automated by computers. It is desirable that any designer can perform this analysis process perfectly by using some tools for automated analysis, though it is hard to completely assume various ways and situations of use. For the automation of the analysis process, this paper has described a methodology for systematically detecting such troubles caused by a specified way/situation of use. First of all, relations among functions and ways/situations of use were analyzed and a framework for the detection based on functions, behavior, physical phenomena caused by the ways/situations was proposed. Achieving this framework requires modeling of those elements and integration of the models. For this issue, a set of methods have been proposed. Those elements were modeled by graphs and natural language descriptions—functions by function decomposition trees, behavior by Petri nets and physical phenomena by directed graphs. Although integration of the function and behavior models completely depends on recognition process of designers, the principle of relations between the two models was clarified. Integration of the behavior and phenomena models was also discussed and a method composed of converting the latter model into a Petri net and connecting them via identical places or places and transitions which contradict each other was proposed. This methodology was applied to a mechanical pencil and its potential was proven.

There are still issues which should be discussed further for applying this methodology to real product design. One of the most important issues is automatic generation of the physical phenomena model, since it must be generated for each way/situation of use. A standard approach for the automatic generation is to construct a database of physical phenomena and exploit the data. Behavior modeling using Petri nets would be a laborious work and special knowledge would be required for obtaining a proper model to detect troubles. Constructing a database of standard Petri net behavior models of common methods for satisfying functions would be helpful for solving this problem. Additionally, ability of Petri net for behavior modeling and techniques for obtaining proper models should be discussed in detail. In order to perform the integration of the behavior and phenomena models, it is necessary to find in advance identical places or places and transitions which contradict each other. This requires proper standardization of the national language description of states and phenomena. These issues will be discussed in future works.

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