**Proceedings of**
**The 1996 ASME Design Engineering Technical Conference and**
**Computers in Engineering Conference**
**August 18-22, 1996, Irvine, California**

**96-DETC:DTM-1412**

# FUNCTIONAL EVALUATION BASED ON FUNCTION CONTENT

**Yoshiki Shimomura**
Mita Industrial Co,. Ltd.
Tamatsukuri 1-2-28, Chuo-ku, Osaka, 540
Japan
Phone: +81-6-764-3818
Email: simomura@mita.co.jp

**Sadao Tanigawa**
Mita Industrial Co,. Ltd.
Tamatsukuri 1-2-28, Chuo-ku, Osaka, 540
Japan
Phone: +81-6-764-3818
Email: tanigawa@mita.co.jp

**Hideaki Takeda**
Graduate School of Information Science
Nara Institute of Science and Technology
Ikoma 8916-5, Nara, 630-01
Japan
Phone: +81-7437-2-5261
Email: takeda@is.aist-nara.ac.jp

**Yasushi Umeda**
Department of Precision Machinery Engineering
Graduate School of Engineering, The University of Tokyo
Hongo 7-3-1, Bukyo-ku, Tokyo, 113
Japan
Phone: +81-3-3812-2111 (ext. 6481)
Email: umeda@zzz.pe.u-tokyo.ac.jp

**Tetsuo Tomiyama**
Department of Precision Machinery Engineering
Graduate School of Engineering, The University of Tokyo
Hongo 7-3-1, Bukyo-ku, Tokyo, 113
Japan
Phone: +81-3-3812-2111 (ext. 6481)
Email: tomiyama@zzz.pe.u-tokyo.ac.jp

## ABSTRACT

Function is a key concept to integrate design object modeling and design process modeling in design. We here propose the *FEP (Functional Evolution Process) model* in order to integrate design object modeling and design process modeling. In the FEP model, the model of a design object is evolved through three steps, i.e., *function description*, *function actualization* and *function evaluation*. Function description is the step in which a designer modifies required functions of a design object. Function actualization depicts a process to obtain physical descriptions from functional description. Function evaluation is a process to measure realizability of functions of the design object. However, among other steps, how to treat the function evaluation is one of the most important theme, because evaluation executed by designers is based on subjective, ambiguous and tacit standards.

We discuss a methodology for evaluating function and propose the *function content* that quantifies functions and enables evaluation of functions. The function content is a similar concept of Shannon's *information content* and we show an example of functional optimization based on this scheme.

## INTRODUCTION

Treating functions is cruicial not only for representing design object but also for describing design process which is important to aid design by computers. On the other hand, although designers somehow evaluate functions of design objects, criteria of the evaluation differ according to each designer and it is difficult to make them explicit [2][4]. In order to support design and maintenance of machines by a computer, methodology for evaluating functions should be developed. Problems for this computerization include the facts that function is subjective and relations between function and physical parameter are not clear. In this paper, we discuss relation among design and function about this function evaluation and design process representation.

We first introduce the FEP model that is a framework of design object and process modeling and discuss features of the *function evaluation* which is one of the basic steps of the FEP model. Second, we propose *function content* as a meter for evaluating functions. Finally, we represent some

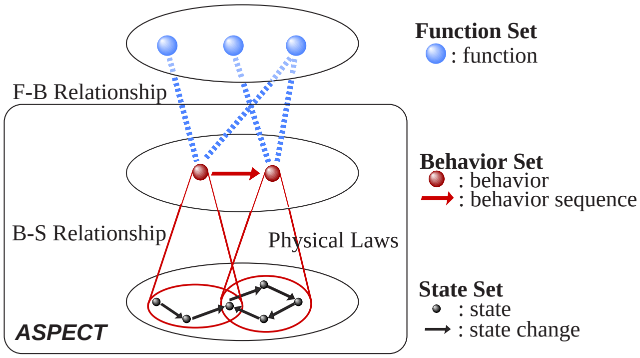



**Figure 1. Relationship among Function, Behavior, and State [13]**

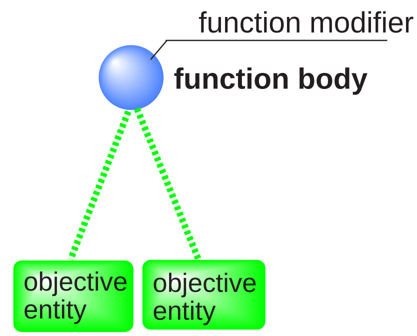



**Figure 2. Structure of Function**

design examples and analyze the results.

## MODEL OF FUNCTION

There are many approaches to represent function (e.g., [8] [6]), however a common problem exists that function and behavior are often confused and mixed each other [12] [3]. For instance, behavior can be defined objectively as transitions of physical states and therefore can be derived from physical states of an entity and physical laws. However, function is related not only to physical behavior but also to human perception of behavior. For example, regarding function of a car, one may say one of its functions is "to move" and others "to carry," even if they observe the same behavior.

We view that function is abstracted and subjective representation of behavior and behavior is physical interpretation of changing of states which can be directly derived from an initial state of objects and physical laws. We here represent functions based on the *FBS* modeling in which a function is represented as an association of the designer's intention and a behavior that can actualize this function (see Figure 1)[14].

In the FBS modeling, we represent a function as combination of a *function body*, *objective entities*, and *function modifiers* (see Figure 2) [10]. A function body is a symbol that carries meaning of the function in the form of verb words like "to move" or "to carry." An objective entity is an entity that a function occurs on. A function modifier is a symbol that details the function body. A typical function modifier is an adverb word like "precisely" or "firmly."

### Relations among functions

Based on the structure of the function, we have defined four kinds of relations among functions that represent a part of results of functional evolution; i.e., *decomposed-into*, *conditioned-by*, *enhanced-by*, and *described-as* relations.

**Decomposed-into relation** This relation indicates that a function body is decomposed into sub-function bodies (see Figure 3). This relation is an abstract-concrete on a whole-part relation.

**Conditioned-by relation** When a behavior $A$ cannot actualize a function $A$, a designer adds additional behavior that realize the function $A$ with the behavior $A$. This relation denotes this operation. In Figure 4, the behavior $B$ is the additional behavior and this relation denotes that a new function body $B$ is needed to actualize a function body $A$. In other words, the behavior $B$ is necessary condition for the behavior $A$. This relation should be supported by causal relation in the behavior level.

**Enhanced-by relation** This relation denotes that a new function body $B$ is needed for satisfying a modifier $A1$ of function body $A$ (see Figure 5). In this case, though the function body $B$ is not a necessary condition for the function body $A$, the modifier $A1$ is achieved better by adding the the function body $B$.

**Described-as relation** This relation denotes that a modifier is detailed into one or more concrete modifiers (see Figure 6).

## FUNCTIONAL EVOLUTION PROCESS (FEP) MODEL

In a design process, functional description of a design object is gradually refined and detailed as the design proceeds. In order to support design by a computer, it is indispensable not only to represent functional description of design objects but also to represent and to support such a design process in which functional description is refined and detailed. We have model this desing process by representing evolution of the FBS model of a design object. We call

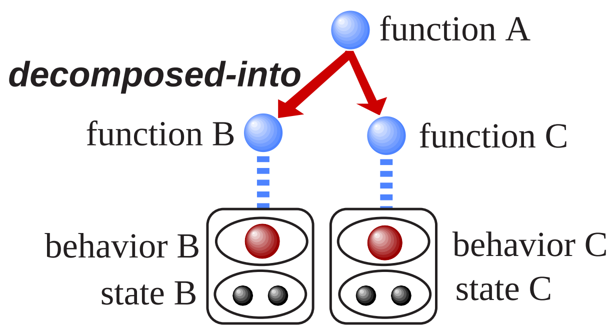



**Figure 3. Evolution by Decomposed-into Relation**

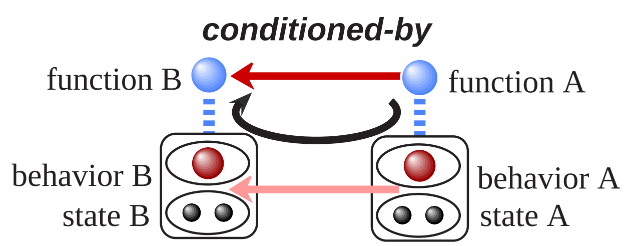



**Figure 4. Evolution by Conditioned-by Relation**

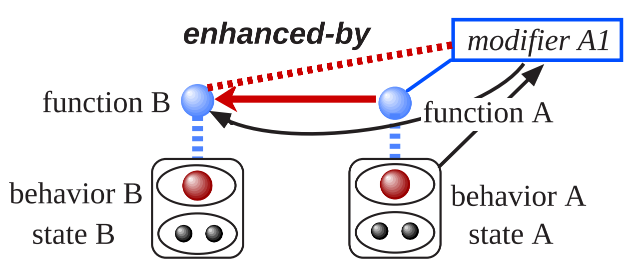



**Figure 5. Evolution by Enhanced-by Relation**

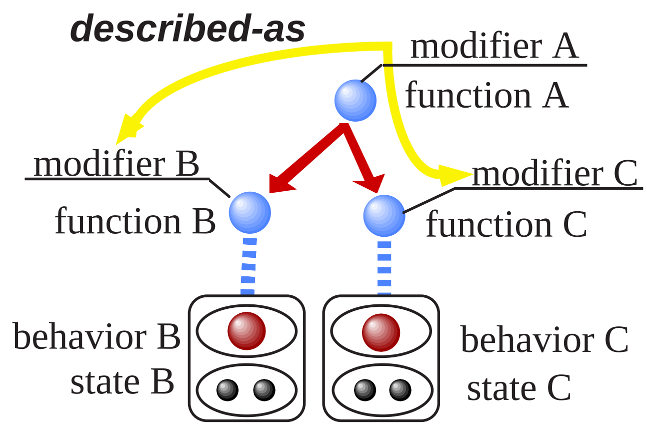



**Figure 6. Evolution by Described-as Relation**

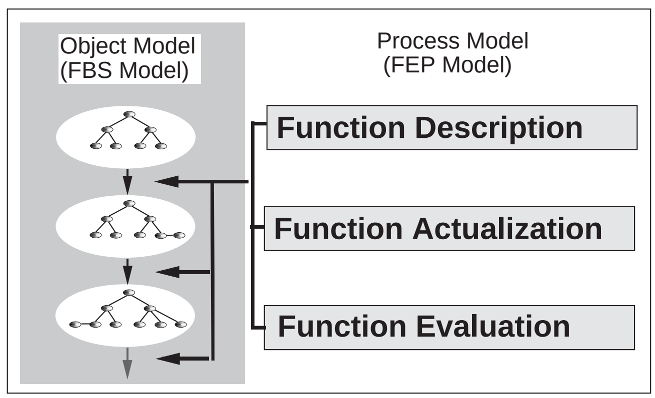



**Figure 7. Steps of the FEP Model**

this model *functional evolution process (FEP)* model [10]. A cycle of the functional evolution process consists of three steps, namely, *function description*, *function actualization*, and *function evaluation* (see Figure 7), and a model of a design object is revised by the designer after each cycle of the process. Namely, in the FEP model, the FBS model of a design object is evolved through these three steps.

*Function description* is the step in which a designer modifies required functions of the design object by operating function bodies, objective entities, and function modifiers. We represent this step of FEP with functional operations by a designer which include adding new functions, function modifiers, or functional relations and removing them.

*Function actualization* corresponds to the step to obtain behavioral description from the functional description by using the knowledge about function. We have proposed a *function prototype* as the knowledge for function actualization [14].

*Function evaluation* is the step to evaluate how intended functions are satisfied by the proposed behavioral description. A designer measures realizability of functions of the design object in this step.

### Modeling an Actual Design of a Photocopier

We analyzed an actual design process of a photocopier using the FBS and FEP schemes in the following steps:

1. First, we collected the documents and the technical drawings about a photocopier and interviewed with the designers to complement these documents.
2. Then we extracted FBS elements, namely, functions, function modifiers, behaviors, and states.
3. After extraction of the FBS elements, we constructed descriptions of the FBS model at each step of the design process (see Figure 8) and represented the FEP model of this design process by tracing the evolution of the FBS models (see Figure 9).

Finally, we investigated how each function or functional modifier was developed with functional relations in this design process and obtained following results:

**Decomposed-into relation** It has been claimed that decomposition of functions is the most basic procedure to deal with functions in design [6]. In this design, we found 53 decomposed functions in this category.

**Conditioned-by relation** Since most of behaviors were implicit or non-verbal in this design, it was difficult to find such causal relations among functions. However by interviewing the designers, we found 10 functions in this category.

**Enhanced-by relation** In our model, converting modifiers into functions is achieved by adding *enhanced-by* relations. An enhanced function is found by evaluating the modifiers. The initial function model of this design had relatively a few functions and many modifiers. It implies that interpretation of those modifiers plays important role in this design. In this design, we found 29 functions in this category.

**Described-as relation** A typical procedure observed in this design process is adding modifiers with *described-as* relations. This way to add modifiers gives more detail descriptions to other modifiers. In this design, we found 30 modifiers in this category.

As we mentioned, there were relatively a few functions and many modifiers in the initial function model of this design. It means that operating modifiers is important process to evolve function models.

## MODEL OF FUNCTION EVALUATION

Here, we assume that functions are classified into two types, namely, verbal type that is embodied as physical behavior and adverbial type that is embodied as physical parameter. First type of function corresponds to function body and second type of function corresponds to function modifier [10].

A function body is evaluated in a binary manner, that is, whether or not the behavior to which the function corresponds occurs in a design object [14]. On the other hand, a designer judges how much a function is achieved in the design object and often compares two design candidates with respect to the degree of satisfaction of the specifications. This kind of evaluation is executed with the parametric conditions described in the function modifier.

However, since this kind of evaluation is executed subjectively, it is not easy to describe the relationship between the parametric conditions and the degree of functional satisfaction. To deal with this subjective relationship, we propose *function content*, which is quantified by using probability distribution of subjectivity of a physical parameter that characterizes a function modifier.

### Modeling Method

We use *SD* method (Semantic Differential method) [5] for making correspondence between function modifiers and physical parameters. The SD method is a method for representing human subjectivity quantitatively by making correspondence between evaluation and physical values that can be evaluate objectively. The SD method employs a psychological test and *principal component analysis*[1]. Here, we define the probability of subjectivity of a modifier for a certain parametric value as the rate of persons who recognize that the modifier is achieved mostly at this parametric value in a certain group of testees.

As a result of the psychological test developed by the SD method, we can obtain the probability distribution of subjectivity about evaluation against physical parameters (see Figure 11). By quantifying function modifiers in this way, we can represent the balancings or negotiations between different modifiers. In the following sections, we define the *function content* that represents degree of satisfaction of a function by using the probability of subjectivity.

### Function Content

As we discussed, function evaluation is to measure functional satisfaction. However, each process of function evaluation can yield different result and the distribution of results of function evaluation processes indicates the degree how the function has acceptable definition. We introduce concept *function content* as the degree of fitness of definition of function.

From our experience to observe functionality in design, we assume these three criteria which function content should satisfy.

1. Because higher probability of subjectivity means that the function is supported by more persons, high probability should provide high value of function content (*assumption 1*).

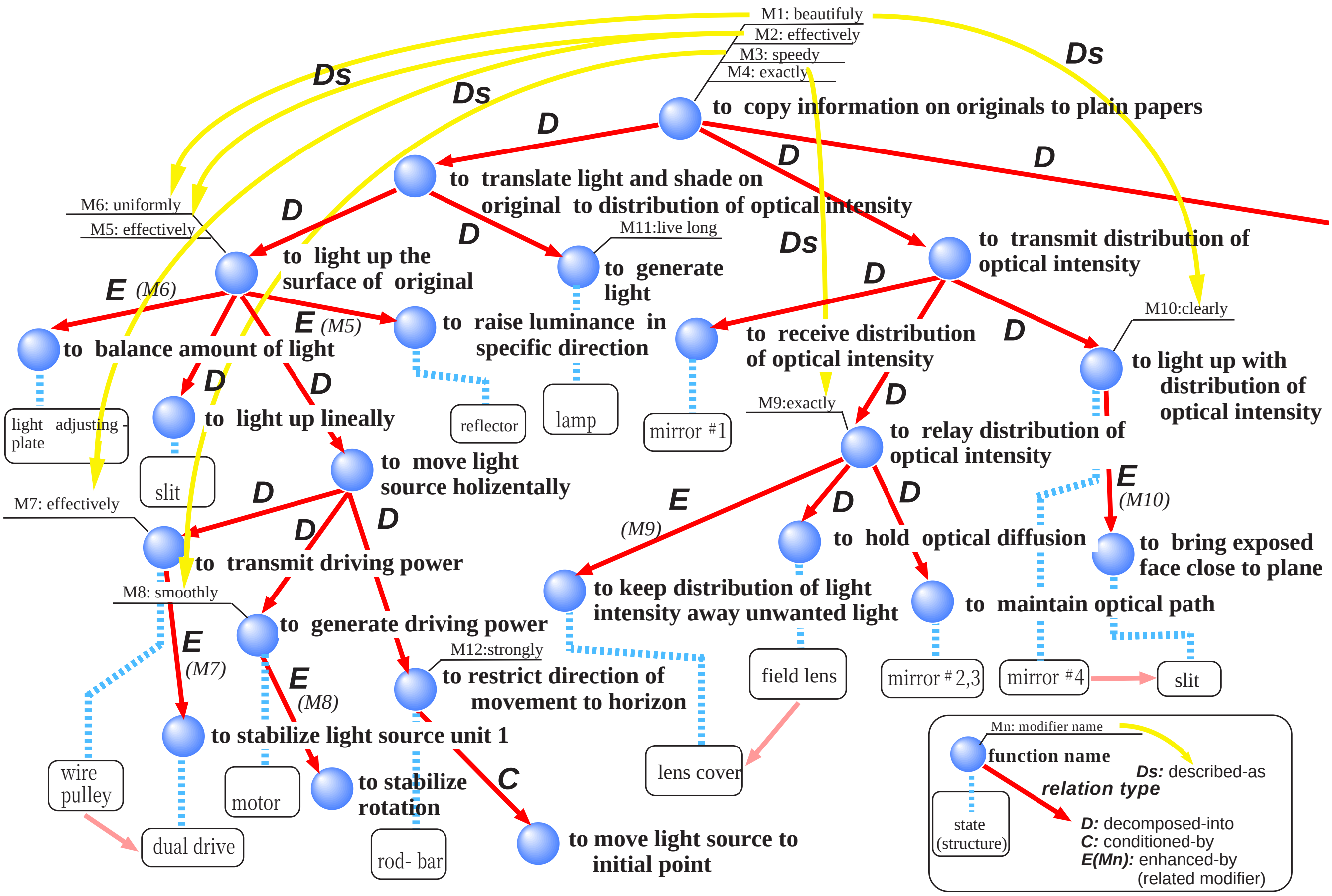



**Figure 8. An FBS Model of the Photocopier**

2. If the distribution of the probability of subjectivity has a peak, it means that there is a common sense about the function and importance of the function is high. We model this as the *mean function content*. In other words, if the shape of the distribution is more sharp, the mean function content should be higher (*assumption 2*).
3. We should be able to explain the difference of results of function evaluation by difference of groups (*assumption 3*).

Shannon models a *information source* as probabilistic in nature. He defines a quantity called *entropy*, which is a measure of the unpredictability of information from the information source [9] [7]. Function evaluation can also be viewed probabilistic. Since function evaluation is a measure of satisfaction of function which depends humans judgement of value, it is intrinsically unpredictable. The difference is that function that evaluated with less unpredictability has more value to use, while information with more unpredictability has more value to use. Here we define *function content* similar to definition of information content but change the definition of probability to complement the difference among these two concepts.

Shannon defined the *information content* as the change of *entropy* by receiving the information . Entropy $H(S)$ of an information source $S$ is given as the following equation.

$$H(S) = -\sum_{i=1}^{M} p_i \log_2 p_i \quad (1)$$

where

$p_i$: occurring probability of $a_i$

$a_1, \ldots, a_M$: output unit of information source Entropy $H(S)$ is also called the *mean information content* $\overline{I}$, which means the average of information content when one

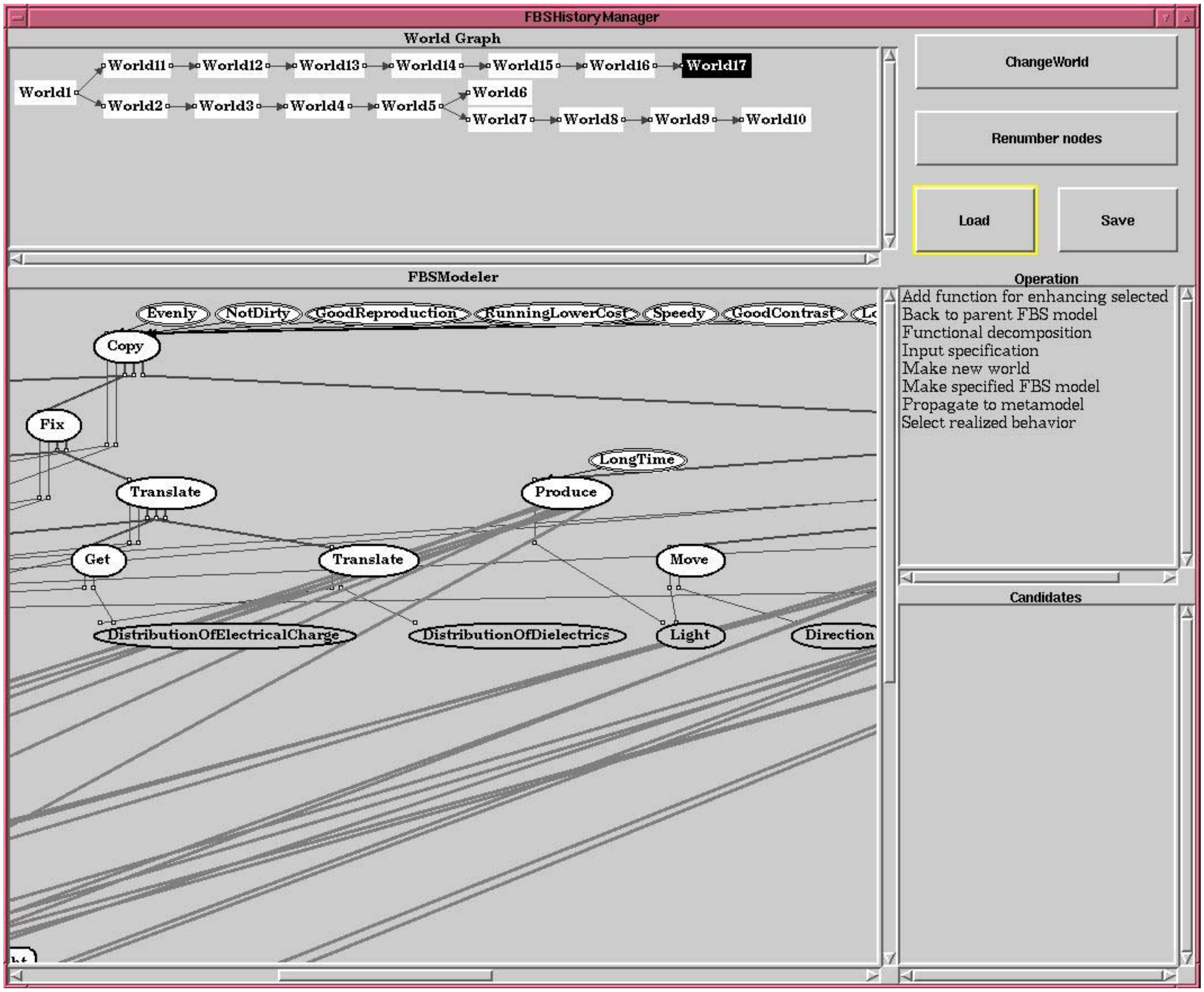



**Figure 9. Functional Evolution in Design of a Photocopier Design**

knows an output from the information source $S$. On the other hand, the information content of an output $I(p)$ is given by the following equation.

$$I(p) = -\log_2 p \qquad (2)$$

Here, we define $F(p)$ and $\overline{F}$ by using the idea of the information content as follows.

$$F(p) = -\log_2(1-p) \qquad (3)$$

$$\overline{F} = -\sum_{i=1}^{M} p_i \log_2(1-p_i) \qquad (4)$$

Where
$p_i$: probability of subjectivity of $v_i$
$v_1, \ldots, v_M$: value of physical parameters

Firstly, while the information content $I(p)$ means the scale of unknownness, the function content (we call this $F(p)$) means the scale of satisfaction of the function according to the *assumption 1*. Secondly, while the mean information content $\overline{I}$ is minimum when one of $p_1, \ldots, p_M$ is 1 and others are 0 and it is maximum when $p_1, \ldots, p_M = 1/M$

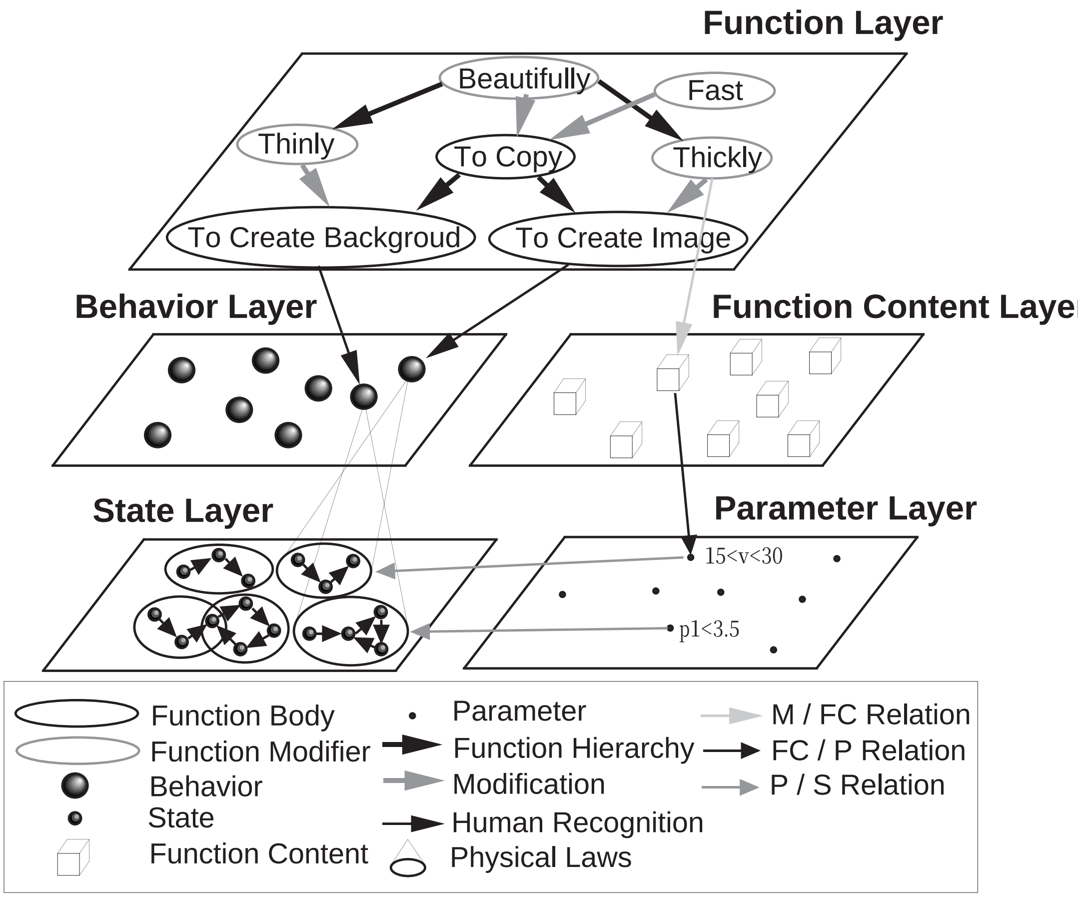



**Figure 10. Relation among Function, Behavior, State and Parameter**

(occurring probabilities of all output units are equal), the mean function content $\overline{F}$ takes opposit value of $\overline{I}$ based on the *assumption 2*, namely, $\overline{F}$ is maximum when one of $p_1, \ldots, p_M$ is 1 and others are 0, and it is minimum when $p_1, \ldots, p_M = 1/M$. Furthermore, the *assumption 3* is explained by the fact that change of probability distribution is caused by change of the groups of testees (see Figure 11).

## EXPERIMENTS OF FUNCTION EVALUATION

In order to verify usefulness of our method for the function evaluation, we executed an experiment of the function evaluation. We take image quality of photocopiers as an example.

We verify the following points with this experiment.

- **Point 1: Characteristics of the function content**
  The mean function content should be high for a function modifier which the testees consider important. On the contrary, the mean function content should be low for a function modifier that has low importance.
- **Point 2: Difference of groups**
  The probability distribution should reflect differences of groups of testees.
- **Possibility of functional optimization**
  If we succeed in quantifying function modifiers by using the function content, we can optimize the evaluation of the function modifier by finding out the value of physical parameter that makes the function content maximum.

### Method of the Experiment

We here explain the SD method which we used for obtaining the function content.

The probability of subjectivity is needed for obtaining the function content. We extract the probability of subjectivity by using SD method [5]. The SD method is a psychological evaluation method which is effective for quantifying human ambiguous impression.

This method is executed in the following steps:

1. Present some different samples to testees (see Figure 12).
2. Extract the impression about each sample from the testees.

The testees represent their impression by using the form shown in Figure 13, which consists of some sets of adjectives (here, they are the function modifiers).

The conditions of the experiment are as follows.

1. We set two groups according to occupations of testees; namely, one group consists of engineers and the other consists of desk workers. We present two same sets of samples to two groups.
2. In order to evaluate the letter image, we chose a function modifier "beautifully." However, since this vocabulary was too abstract, we could not determine the quantity of impression directly. Therefore, we decomposed the function modifier "beautifully" into lower three function modifiers "clearly," "thickly" and "with bright background," which contribute to "beautifully" higher, by using principal component analysis [1] (see Figure 14).
3. We obtained physical parameters, which control these three function modifiers effectively and can be controlled directly by actuators in the machine, by using principal component analysis again.
4. In order to obtain the mathematical function of probability distribution of subjectivity, we converted discrete probability of subjectivity derived by the SD method into continuous function.

## RESULTS OF THE EXPERIMENT

### Quantifying Function Modifier

Figure 15 depicts function contents of two function modifiers "clearly" and "with bright background" achieved from two types of occupations, namely, engineers and desk workers. Here, the parameter "surface potential" makes both of the mean function content of three function modifiers maximum. Figure 15 signifies that the mean function content of the function modifier "clearly" is higher than the mean function content of the function modifier "with bright background," and this trend is notable in the engineers. This difference tells that the testees considered the function modifier "clearly" more important, which is considered as one of the machine's basic performances, than

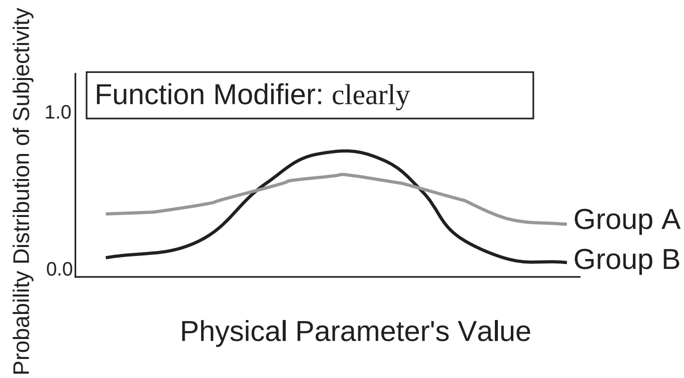



**Figure 11. Probability Distribution of Subjectivity**

**Figure 12. Example of Samples**

the function modifier "with bright background," which is dominated by kinds of paper material. This result satisfied the *Point 1*.

Figure 15 also indicates that the mean function content about the function modifier "clearly" in engineers is higher than in desk workers. This result denotes that the engineers have stronger common criteria for the machine's performance than the desk workers. This result satisfies the *Point 2*.

### Functional Optimization

We can obtain the values of physical parameters which maximize the function content of the function modifier "beautifully" if we can decide weights of sub-modifiers depicted in Figure 14.

Here, we decided weights of the sub-modifiers as shown in Figure 16 by using the rates of the mean function contents that represent their importance. By using these weights, we obtained the value that maximizes the function content of the modifier "beautifully" (see Figure 17). Table 1 depicts the results of comparison between the image created by using this value and the image created by using original design value (see Figure 18). In Table 1, the output image created

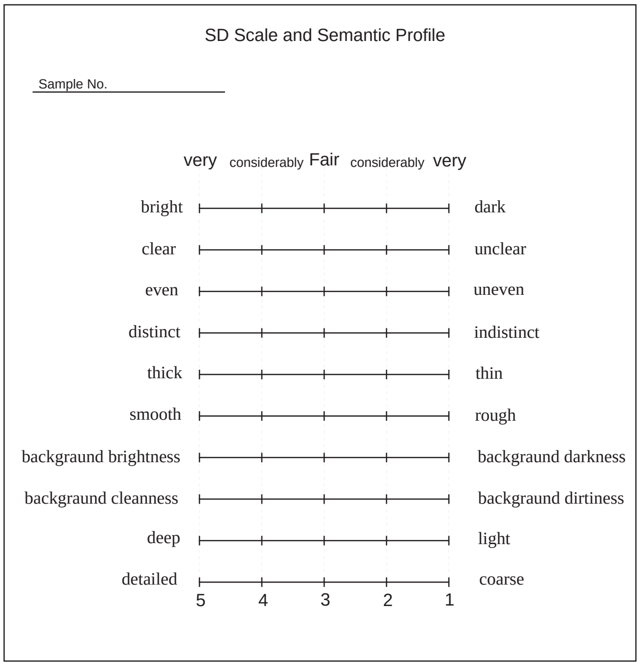



**Figure 13. Example of the Test Chart**

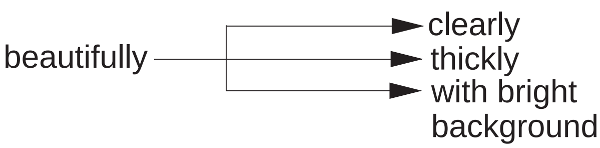



**Figure 14. Decomposition of Function Modifier**

by the function content was supported by larger number of testees than the original one. This result verifies the *Point 3.*

Furthermore, this difference can be explained as follows:

- The value of the original design is determined as a result of negotiation among many other function modifiers, such as, "evenly," "smoothly," and so on. Therefore we cannot say that this derived value is optimal for actual commercial machine. Nevertheless, this result of optimization fits subjective evaluation of functions of testees.
- It is difficult for a designer to examine all combinations of parameter values with considering many function modifiers because of hugeness of search space and ambiguity of function evaluation. Therefore, the designer could not find out the optimum value. The functional optimization based on the function content proposed here will be a strong method for solving this problem.

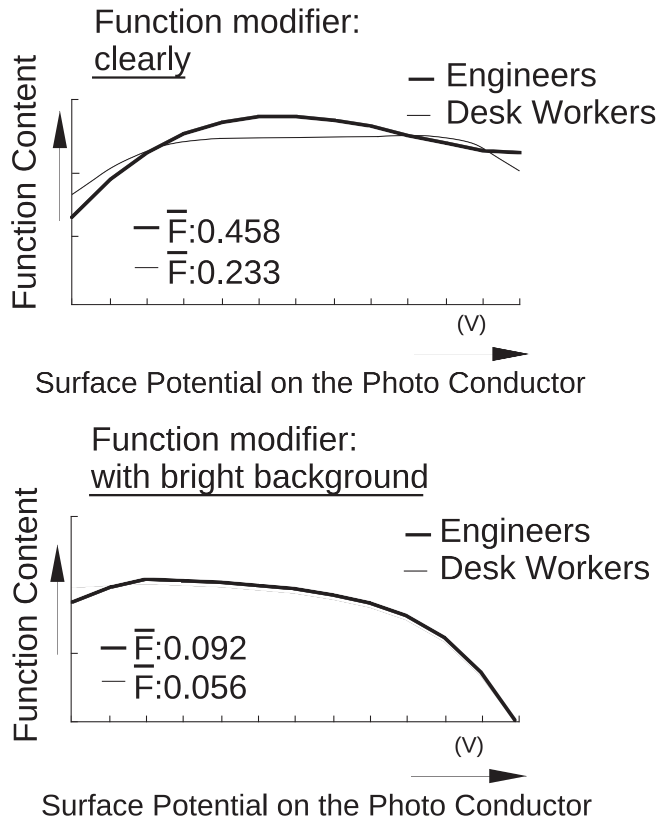
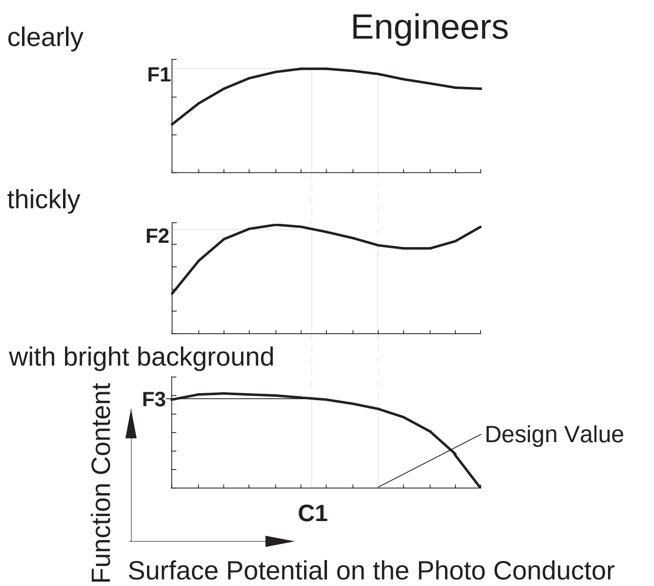



**Figure 15. Comparison between the Results of Function Evaluation**

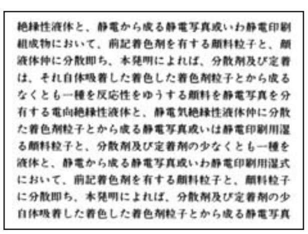

**Figure 16. Functional Decomposition with Weights**

In short, the experiment clarified that the function content satisfied *points 1-3.* Therefore, we conclude that we succeed in quantifying function modifiers for evaluating them by using the function content. Moreover, usefulness of our approach is clarified by the experiment of the optimization.



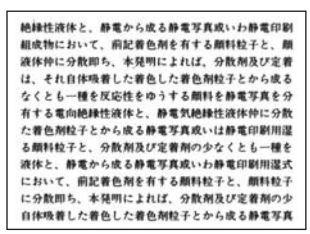

F =(0.639F1+0.236F2+0.125F3) takes maximum value at C1.

**Figure 17. Decision of Values of Physical Parameters by Using the Function Content**



絶縁性液体と、静電から成る静電写真或いわ静電印刷
組成物において、前記着色剤を有する顔料粒子と、顔
液体仲に分散即ち、本発明によれば、分散剤及び定着
は、それ自体吸着した着色した着色剤粒子とから成る
なくとも一種を反応性をゆうする顔料を静電写真を分
有する電向絶縁性液体と、静電気絶縁性液体仲に分散
た着色剤粒子とから成る静電写真或いは静電印刷用湿
る顔料粒子と、分散剤及び定着剤の少なくとも一種を
液体と、静電から成る静電写真或いわ静電印刷用湿式
において、前記着色剤を有する顔料粒子と、顔料粒子
に分散即ち、本発明によれば、分散剤及び定着剤の少
自体吸着した着色した着色剤粒子とから成る静電写真

Output Image by the Optimized Value



絶縁性液体と、静電から成る静電写真或いわ静電印刷
組成物において、前記着色剤を有する顔料粒子と、顔
液体仲に分散即ち、本発明によれば、分散剤及び定着
は、それ自体吸着した着色した着色剤粒子とから成る
なくとも一種を反応性をゆうする顔料を静電写真を分
有する電向絶縁性液体と、静電気絶縁性液体仲に分散
た着色剤粒子とから成る静電写真或いは静電印刷用湿
る顔料粒子と、分散剤及び定着剤の少なくとも一種を
液体と、静電から成る静電写真或いわ静電印刷用湿式
において、前記着色剤を有する顔料粒子と、顔料粒子
に分散即ち、本発明によれば、分散剤及び定着剤の少
自体吸着した着色した着色剤粒子とから成る静電写真

Output Image by the Design Value

**Figure 18. Comparison between Output Images**

**Table 1. Evaluation about the Output Images**

| | |
|---|---|
| Support the result by the function content | 17/25 |
| Support the result by the original value | 8/25 |

## CONCLUSION

In this paper, we proposed the FEP (Functional-Evolution-Process) model in which a design object is gradually evolved according to results of functional evaluation. Furthermore we discussed human function evaluation as an important step of design and proposed a method for quantifying functions, which are subjective concepts, by relating them to physical parameters. For this purpose, we introduced a value called function content. We evaluated an actual design based on the function content and verified correctness and usefulness of the function content as the method for function evaluation. As an application of this methodology, we show an example of functional optimization based on the function content.

Future works includes:

- Making the differences between the function evaluations of the actual design and the function evaluation based on this framework more clear by analyzing the results of decision making in actual design based on this method.
- Developing a *self-maintenance machine* [11] which can make repair planning more flexible by using this method for its fault diagnosis and repair planning.

## REFERENCES

[1] A. P. Dempster. *Elements of Continuous Multivariate Analysis*. Addison Wesley, Reading, MA, 1969.

[2] D. Herling, D. G. Ullman, and B. D'Ambrosio. Engineering decision support system (EDSS). In *Proceedings of Design Theory and Methodology – DTM'95–*, pages 619–626. ASME, 1995.

[3] Y. Iwasaki, R. Fikes, M. Vescovi, and B. Chandrasekaran. How things are intended to work: Capturing functional knowledge in device design. In *Proceedings of IJCAI-93*, pages 1516–1522, 1993.

[4] M. Orelup and J. R. Dixon. Trade-offs in robust design: Comparing optimization, taguchi's approach and guided iteration in three examples. In *Proceedings of Design Theory and Methodology – DTM'95–*, pages 423–435. ASME, 1995.

[5] C. E. Osgood, G. J. .Suci, and P. H. Tannenbaum. *The measurement of meaning*. The University of Chicago Press, 1957.

[6] G. Pahl and W. Beitz. *Engineering Design*. The Design Council, London, 1984.

[7] A. Ralston and E. D. Reilly, editors. *Encyclopedia of computer science*. Van Nostrand Reinhold, 1992.

[8] K. Roth. *Konstruieren mit Konstruktions Katalogen*. Springer-Verlag, Berlin, 1982.

[9] C. E. Shannon. A mathematical theory of communication. *Bell Syst. Tech. J.*, 27:379–623, 1948.

[10] Y. Shimomura, H. Takeda, Y. Umeda, and T. Tomiyama. Representation of design object based on the functional evolution process model. In *Proceedings of Design Theory and Methodology – DTM'95–*, pages 351–360. ASME, 1995.

[11] Y. Shimomura, S. Tanigawa, Y. Umeda, and T. Tomiyama. Development of self-maintenance photocopiers. *AI Magazine*, 16(4):41–53, 1995.

[12] K. T. Ulrich and W. P. Seering. Function sharing in mechanical design. In *Proceedings of AAAI-88*, pages 342–346, 1988.

[13] Y. Umeda, H. Takeda, T. Tomiyama, and H. Yoshikawa. Function, Behaviour, and Structure. In *AIENG'90 Applications of AI in Engineering*, pages 177–193. Computational Mechanics Publications and Springer-Verlag, 1990.

[14] Y. Umeda and T. Tomiyama. A CAD for functional design. In A. N. Kumar, editor, *AAAI-93 Workshop Working Notes of Reasoning About Function*, pages 172 – 179. AAAI, 1993.