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A Model for Representing Artifacts Based on the Modality of Operations and States

Toward design focusing on user interaction

Hidetsugu SUTO*, Hiroshi KAWAKAMI** and Osamu KATAI**

In this paper, we will propose a representational model of "interactive" artifacts which reflects interactions between human and artifacts base on the discussion of alethic, deontic and temporal aspects of the interaction. From these three types of modality, we will define three layers to represent the interactions. The base layer represents causal relations which are governed by physical laws or effects. The main layer represents state transitions by unrestricted operations. Some operations are restricted by teleological necessities which are derived from designers' intention. The top layer represent this type of restrictions by using what we call "task unit graph". The tight interactions among the three layers explain interactions among designers, operator and environment via an artifact.

Key Words: interactive artifact, hierarchical artifact model, modal logic, Petri net, Physical Causal Network (PCN)

1. Introduction

There has been a recent trend away from developer-centered concepts to user-centered design, and this new approach to design is attracting increasing interest [1]. Interactive artifacts are such a human-centered design concept, where the interaction between artifacts and operators (i.e., feedback) is important. Development of supporting systems for the conceptual design process of interactive artifacts requires understanding and representation of physical systems, as well as a means of representing the relationship between operators and the systems. This necessitates objective models of physical systems that included operations.

The present authors have proposed a model of hierarchical knowledge space for design. The scheme consists of four spaces (goal set space, functional knowledge space, structural knowledge space, and real set space) and a medium, reflecting the three rationalities (value, purpose and causal rationality) in understanding sociology [3),4)].

However, few models that describe artifacts from the viewpoint of "goal → function → structure" include "operation" as an important point. Thus, it is difficult to describe and understand artifacts from a human-centered perspective using such models. Operations play an important role in the understanding of artifacts, particularly for objects used as part of daily life. For example, when analyzing a hand grip, it would be difficult to determine the real purpose of the object without accounting for the operation, such as repeated gripping for hand muscle training. Therefore, this paper discusses a new model for physical systems, focusing on representation of the relationship between human (designers and operators) and artifacts.

One of the standpoints of designers is that they tend to embed all their intentions in the design structure and forbid non-intended operations. However, this strategies require high quality design perspective. If it is not enough, operators should get into a deadlock situation, and it is designed as "black box" manner with the result that an escape is very difficult.

On the other hands, there is a standpoint that making use of operations actively. Norman proposed the concept of affordance as a means of allowing designers to impart their intentions on operators in a more appropriate manner [5)]. Norman's concept can be regarded as a method by which designers' intentions are realized in the nature of an artifact. However, it is difficult to determine general laws between the nature of an artifact and affordance, and it is not easy to construct appropriate design support systems using computers. Furthermore, as the operations may be complex and the operations manuals may be difficult to understand, operators generally will not read well the manuals. This gives rise to the assertion that operation

* Department of Industrial Design, Akita Municipal Junior College of Arts and Crafts (He is currently with Department of Computer Science and System Engineering, Muroran Institute of Technology, 27-1, Mizumoto-cho, Muroran-shi, Hokkaido 050-8585, JAPAN)
** Graduate School of Informatics, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, JAPAN

manuals should consist of simple operation sequences, allowing the artifact to be understood intuitively, or the manual should be written before the structures are designed [5].

In this paper, the authors adopt the latter standpoint, that is, in preference to a system that forbid operator "liberty", active interaction between the operator and artifact is asserted. An appropriate representational model for this assertion then needs to be developed.

2. Background theory

This paper proposes a hierarchical model for artifacts based on aspects of necessity and possibility, as outlined in Table 1. As proper feedback corresponding to operations is essential for interactive artifacts, representing operations and state transitions is important. Therefore, the liberty and possibility of operations are represented in the main layer of the proposed model. Liberties and possibilities in the main layer are restricted to the layers reflecting necessities, which are placed upper and lower of the main layer. The upper layer contains teleological necessities such as the operation sequence, which reflect the designers intentions, while the lower layer represents causal necessities such as physical laws and effects.

The background theories on which the hierarchical model is constructed are discussed below.

2.1 Alethic modality

Interesting ideas about the relationship between operators and artifacts were discussed by von Wright, an analytic philosopher [6]. Traditionally, it is well known that a scientific explanation is either causal or teleological. In connection with this contrast, von Wright presented the scheme of physical phenomena that causal closed systems are created by teleological actions. This concept states that behavior explained by teleology has the "property of action." That is, not only surfaces, i.e., motion and stop, but also internal properties, i.e., background intention, will and intentional omission, are accompanied by such behavior.

After a teleological operation has been performed, the world changes according to the causal laws in a closed system. The law on which causal explain depend reflects causal necessity. Necessity is classified in several ways [7),8]. When according to causality and teleology, necessity can be thought of as being in direct opposition to the free state. Furthermore, causal necessity and teleological necessity are therefore not logical or conceptual, but assumptive, supported by facts or experiences. That is, causal necessity is a rationality that connotes natural phenomena, and teleological necessity depends on intentions or purposes.

Here, the concepts of necessity and free here can be respectively related to necessity and possibility in alethic modality, as shown in left column of Table 1. Therefore, the operands ($\Diamond$ and $\Box$) and universal axioms of modal logic can be imported into the proposed model. In alethic modal logic, the fact that r is true in any possible world is represented by $\Box r$, and it means that proposition r is "necessarily" true. On the other hand, the fact that r is true in at least one possible world is represented by $\Diamond r$, and means proposition r is "possible."

2.2 Deontic modality

Designers entrust their intentions to artifacts through the implementation of physical structures, and in the operation sequence of tasks. An operation sequence, which is derived explicitly from the designers' intentions, reflects the obligations of operators, whereas the structure, in which the designers' intentions are embedded implicitly, reflects the permissions for the operators. Therefore, designers' intentions can be interpreted as the deontic modalities of "obligation" and "permission" for operators.

Based on this viewpoint, deontic modality can be related to alethic modality as shown in Table 1. Teleological necessity corresponds to an obligation, which is described in the operations manual. Even if operators do not obey the operations manual, they are necessarily restricted to possible operations through the constraints of physical laws or effects. This necessity correspond to "causal necessity," and the remaining liberty of operators correspond to "free" in alethic modality.

Under deontic modality, $\Box p$ is interpreted as "p is obliged to be true", $\Diamond p$ is "p is permitted to be true," and $\Box{\sim}p$ (${\sim}\Diamond p$) is "p is forbidden to be true."

2.3 Temporal modality

An operation yields state transitions. State transitions and operation sequences necessarily involve a temporal order. Although causalities are sometimes analyzed using temporal order relationships, such analyses are subject problems such as feedback loops in physical causal relations [9] and the constraint that reaction cannot be asserted before an action. Usually, a time scale is applied to explain whether a causal relation involves time order [9] [(1)].

Consider the situation where an item is being placed on

(1) Causality can also be classified by "can be observed or not" or "cognitive or physical," etc.

Table 1 Background theory and content of three layers

	Alethic modality (Teleological vs. Causal)	Deontic modality	Temporal modality	Subjects
Top layer	Necessity (Teleological)	Obligation	Conscious	Operation sequence
Main layer	Possibility (Free)	Permission	Conscious	Each operation
Base layer	Necessity (Causal)	n.a.	Unconscious	Closed system

a desk. In this case, action and reaction occur simultaneously from a macroscopic perspective, yet from a microscopic perspective, changing the consistency of molecules leads to a balanced state. In this way, the size of grains is fixed depending on which phenomenon is described, and it may be necessary to consider the time order [12].

Accordingly, it is possible to introduce the concept of a "snapshot of causal relations." Within a snapshot, time order does not need to be considered. A causal explanation of functions involved in a physical system is then represented by a collection of snapshots, and there is "an operation" or "a change in structural conditions caused by self-causal relations" between each snapshot.

As a result of the introduction of snapshots, there is an essential difference in tense between "operation sequence" or "possible operation and states" and "causal explanation." In this case, temporal modality correspond to alethic modality and deontic modality as shown in Table 1.

3. A model for representing artifacts based on modality

Possibility of operations, and causal and teleological necessities, which constrain the possibility can be analyzed naturally from the three viewpoints, i.e., alethic, deontic and temporal modality. This scheme clarifies the relationships between designers' intentions and operations, and makes it possible to analyze systems considering the relationship with operators. In this sense, modeling form these three viewpoints is suitable for representing interactive artifacts. The proposed model is described in detail below.

3.1 Alethic/deontic/temporal model

Figure 1 outlines the alethic/deontic/temporal (ADT) model proposed in this paper. The model consist of 3 layers, corresponding to the layers in Table 1.

The main layer, representing possible states and operations as important aspects of interactive artifacts, is implemented as a Petri net. Operations, which are performed freely, can be naturally regarded as a concurrent system, which can be well represented by a Petri net.

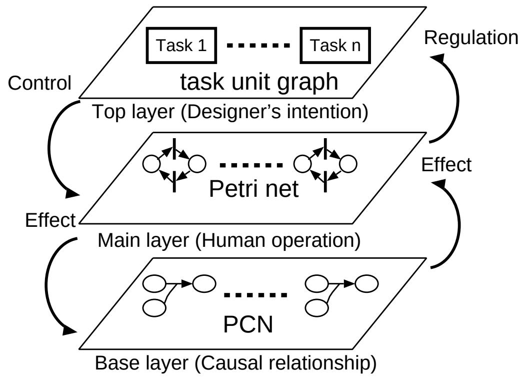

Fig. 1 Overview of the proposed model

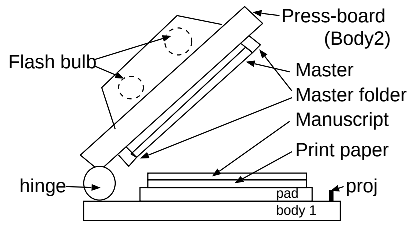

Fig. 2 Schematic of a mimeograph

The top layer, corresponding to tasks encoded in an operations manual, are represented using logical formulae of deontic modality and temporal modality. This layer reflects the teleological necessities of a physical system.

A causal closed system [6] consists of physical phenomena governed by causal necessity is represented by the base layer. These physical phenomena are divided into causal relationships as snapshots, which are represented using a PCN in this layer. The structure of the PCN corresponds to the Petri net content "place" of the main layer, and this structure is suitable for representing interaction between the main layer and the base layer.

In the following, the contents of each layer and the relationships between them are discussed using a mimeograph (Fig. 2) as an example.

3.2 Main layer

An artifact works objectively without designers' intentions if it's design process is finished and released. The comprehension of possible operations and states of products is therefore important not only from the standpoint

Table 2 Modal operand

$\mathcal{T}A$	A is true at the next moment
$\mathcal{G}A$	A is true at all future times
$\mathcal{F}A$	A will be true at some future time
$A\mathcal{U}B$	A will be true at all times from next moment until the first instance that B is true

that raising completeness of black box nature of artifacts, but also in terms of the flexible utilization of artifacts and providing diversified operations.

In the main layer, possible states and operations are represented using a standard 1-bounded Petri net [?]. Generally, transitions represent events, and places represent local states in Petri nets. In this layer, places represent the local states of an artifact, transitions represent possible operations, and a marking represents the whole state of an artifact. Here, any transition can be triggered if it is permitted to do so. It corresponds to making choice of an operation form permitted operations.

The main layer in Fig. 3 shows an excerpt of the operations and states for a mimeograph. For example, in the case where a token exists at"up(body1)", the transition "down(body1)" can be triggered. It corresponds that body1 can be pressed down if it is lifted. When the transition "down(body1)" fires, that is, body1 is pressed down, the token moves to "down(body1) ".

3. 3 Top layer

Designers entrust their intention to operators via operations manuals. In other words, operations manuals reflect designers' intentions that are entrusted to operators. Here, attention is paid to the fact that only teleological phenomena can explain the necessity of the temporal order of operations. That is, operations manuals can be regarded as a "limiter of operational possibility" depend on teleological necessity. In this respect, temporal order also plays an important role.

Operation sequences planned by the designer to achieve the intended goal are encoded in the top layer. In this layer, the temporal order of events is important and reflects the teleological information. That is, an arbitrary sequence of operations may loose physical reality.

For example, Table 3 shows an operation sequence for the mimeograph. It is necessary to perform operation 1 before operation 2 because the press-board hides the fix-lever unless it is raised. However, the necessity of this operation sequence cannot be understood until the teleological explanations are provided.

This type of information is encoded by modal logic formulae, including temporal logic [13] and deontic logic [14]. Temporal logic introduces objective tense concepts such as "next time, statement A will be true", while deontic logic introduces subjective modal concepts such as "next time, statement A must be true". In order to regulate future events, modal operands of temporal logic are introduced as show in Table 4.

Designers' intentions, which are embedded in the operation sequence shown in Table 3, are encoded as the following temporal expressions, where $X \prec Y \prec {\sim}X$ if "$\prec$" refers to a relationship of time order.

(i) Operation Y should be performed immediately after operation X in order to change the state to "y." $\cdots[\mathcal{T}y]$

(ii) State x caused by operation X should be maintained. $\cdots[\mathcal{G}x]$

(iii) As a special case of ii), if operation ${\sim}X$ is the reverse of operation X, state x, which is caused by operation X, should be maintained (${\sim}X$ is forbidden) until state y caused by operation y occurs. $\cdots[x\mathcal{U}y]$

The first expression (i) forbids unprepared operations between two continuous prepared operations. Generally, immediate fixing is requested after modification of the position in the example of the mimeograph. This is represented by substituting operation 3 in Table 3 for X, and operation 4 in Table 3 for Y.

The second expression (ii) forbids unnecessary operations. For example, once the master has been set in the holder, it should not remove during subsequent operations. This is represented by substituting the state after operation 5 in Table 3 for x.

The last expression (iii) indicates that substitutions such as $\{$ $x, y, {\sim}x$ / state after operation 1, state after operation 7, state after operation 8 $\}$ and $\{$ $x, y, {\sim}x$ / state after operation 2, state after operation 3, state after operation 4 $\}$ represent the designers' intentions. For example, the latter means that if the fixing lever is unlocked, it should not be locked until adjustment of the paper position has been completed.

As a special case of (iii), state x can be an initial state. In this case, state x is not described in the operations manual directly. However, if the "state before operation (${\sim}X$)" is determined on the main layer, a request such as "do not place paper on the pad until the pad position has been adjusted" can be represented by regarding it as state x and substituting $\{$ $x, y, {\sim}x$ / before operation 6, after operation 3, after operation 6$\}$.

Each operand can be translated into an extend Petri netas a task unit graph [23], which represents deontic modality and temporal modality, and which is extended from

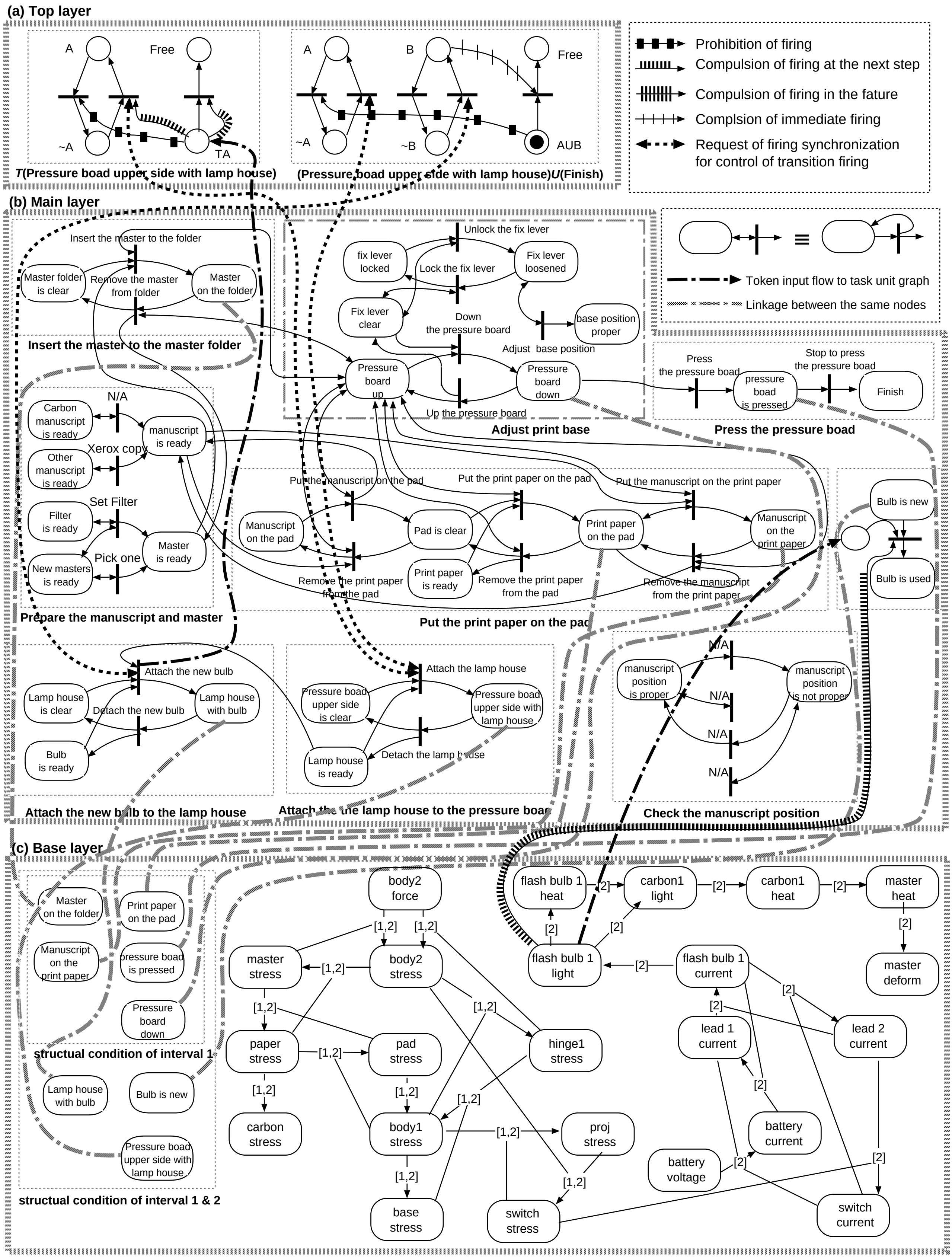

Fig. 3 *Hierarchical representation model for a mimeograph*

Table 3 Operation sequence

0.	Prepare the manuscript
1.	Raise the press-board
2.	Unlock the fix-lever
3.	Adjust the base position
4.	Lock the fix-lever
5.	Attach a master to the holder
6.	Place paper on the pad
7.	Place the manuscript on the paper
8.	Pull down the press-board
9.	Confirm the paper position
10.	Attach bulbs to the lamp housing
11.	Attach the lamp housing to the press-board
12.	Lower the press-board
13.	Confirm bulb flash
14.	End

Table 4 Modal operands for "future"

$\mathcal{T}A$	A is true at the next moment of time
$\mathcal{G}A$	A is held true forever
$\mathcal{F}A$	A will be true at some time in the future
$A\mathcal{U}B$	A will be true at all times from the next moment until the moment that B becomes true

standard 1-bounded Petri net by introducing special arcs as shown in Fig. 3. The task unit graphs, which is subject-independent, can be constructed using these special arcs [15].

The left part of the top layer shown in Fig. 3 reflects the task $\mathcal{T}A$, while the right part represents the task $A\mathcal{U}B$.

In this case, "A" means the state after attaching the lamp housing to the press-board. When the transition "put(f_bulb, l_house)" triggered, a token moves from "$\sim$connect(l_house, l_bulb)" to "connect(l_house, l_bulb),", and a token is placed in the "$\mathcal{T}A$" in the task unit graph indicating that "in the next step, lamp housing is connected(body1) should be true."

For $A\mathcal{U}B$, substituting "before state of operation 11" for A, and "after state of operation 10" for B represents the the task request "lamp housing should not be attached to body1 (operation 11) until lamp is attached to lamp housing (operation 10)."

3.4 Base layer

In this layer, artifacts are represented from the viewpoint of causal relationships using the PCN. The PCN represents the causal relationships that drive phenomena based on background principles, that is, physical laws or effects required to realize functions, but not teleological information.

The PCN is constructed using fragmentary causal relationships (PC code). The PC code consists of nodes and arcs. Each node represents a pairing of an element and a label of physical quantity, and each arc represents a causal relationship between nodes. Each physical causal relationship has structural conditions.

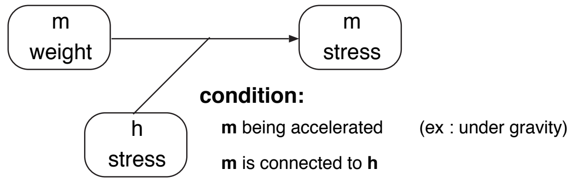

Fig. 4 Example of a PCN

Consider the situation where an entity m hung by hook h, the usual explanation is "m imparts stress on h." Therefore, the occurrence of the stress of m must precede the stress on h for this to be the case. On the other hand, as shown in Fig. 4, one of the primitive constituents of PCN claims that the occurrence of stress in m ("cause") requires a stress to arise in h ("result"). The format is derived from the consideration of fragmentariness, generality and independence of the PC code. Although this definition may be curious from your sense, in fact, the stresses in m and h can be considered to occur at the same time, unless the situation is analyzed at the molecular level where situations are governed by "balance" rather than "causality." The PCN explains complete system by chaining together this kind of primitive elements.

The lower part of Fig. 3 shows an integrated PCN at different moments. The causal relationship represented by the arcs labeled "[1]" establish in interval 1 which shown in the left lower part of Fig. 3. Similarly, the arcs labeled "[2]" establish in interval 1 & 2.

3.5 Interaction between top layer and main layer

A physical system permits you several operations, but an operations manual restricts the operations. In the proposed model, local states of the system are transmitted from the main layer to the top layer, and information of the restrictions is transmitted from the top layer to the main layer. For example, in Fig.3, a token is placed on $\mathcal{T}A$ in the top layer if the transition $put(f\_bulb, l\_house)$ (i.e., operation 10) fires, as shown by the thick dotted arrow. Then, the state "after operation 11" is substituted for A, and the request for $\sim A \rightarrow A$ in the top layer is synchronized with the request for operation 11 in the main layer. In the case of task $A\mathcal{U}B$ in the top layer, if a token is placed in B in the top layer by performing operation 10 and firing of $A \rightarrow \sim A$ is allowed, operation 11 in the main layer is also allowed to fire as a result of synchronization.

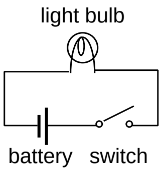

Fig. 5 Example of interaction between causality and operation

3. 6 Interaction between main layer and base layer

The structural conditions of each causal relationship in the base layer are represented using places of the Petri net in the main layer. When a place has a token, the condition represented by that place is true. Thus, if transitions of local states, which are derived from operations, are noticed from the main layer to the base layer, the information will be a trigger for the generation of a snapshots. On the other hand, transitions of local states, which are derived from causal relationships in the base layer, are noticed to the main layer and the causal relationships are terminated.

Figure 5 shows a simple example. Consider the situations "switch is on/off" and "light is flashing or not." The state of the switch is changed by a free operation, and a such is described in the main layer as a transition. On the other hand, the state of the light is necessarily changed by the state of the switch. In this case, the state of the light is represented in the main layer as a place in the Petri net, but it is controlled by causal law, that is, a closed circuit causes current to flow and the light bulb flash, as described in the base layer.

4. Applications and related studies

4. 1 A simple example

Figure 3 shows a part of an ADT model representing the mimeograph in Fig. 2. The top layer includes two tasks derived from the operation sequence shown in Table 3; "if a flash bulb is attached to the lamp housing, the lamp housing should be attached to body1 continuously," and "the lamp housing should not be attached to body1 until a flash bulb has been attached to the lamp housing."

Without these tasks, operators can attach lamp housing to body1 before attaching a flash bulb to the lamp housing. If the operator does so, the transition "put(l_house, body1)" fires, and the token is removed from "∼connect(body1, l_house)," which is a prerequisite for firing of the transition "put(f_bulb, l_house)." As a result, the operator cannot attach a flash bulb to the lamp housing, with the result that even if body1 pressed, there is no flash. If according to a request from the top layer, a flash bulb is attached to the lamp housing before the lamp housing is attached to body1, the bulb will flash and result in a successful copy.

4. 2 Applications

Interactive artifacts are designed based on the designer's understanding of the lifestyle of users or workers. Thus, it is expected that in addition to the direct benefits of the development of such artifacts, such as improved usability or lower cost of user support, the cost for research and development arising from the need to investigate user demands will be reduced.

This model reflects "free" in terms of alethic logic in the main layer, and represents "causal necessity" in the base layer. The possible operations and states are represented by associating the relevant physical phenomena, and the state of the top layer controls the movements of tokens in the main layer. Therefore, measures against failure of interactions between operators and artifacts can be implemented by investigating deadlocks or reachablities in the Petri net. Thus, the model is expected to be a useful measure with regard to product liability, which states that if the users of a product suffer damage, the manufacturer should be held responsible.

On the other hand, when unexpected operation make it smartly, designers can refer it to modify operation manual.

Furthermore, the proposed model can be applied to analyze the artifacts which have several functions. Arbitrary PCNs can be merged with general algorisms because of their simple format [17]. By merging the base layers of the physical devices in a system, the operators' behaviors can be investigate. It is usable for constructing operation manuals of the system.

4. 3 Relevant studies

4. 3. 1 Relevance to design process model

Human-centered design has recently attracted attention as a design method for interactive artifacts. In a human-centered design process, products are developed by analyzing the user and evaluating prototype models in order to understand the users' life or business style. A human-centered design process does not always result in the production of objects per se, and is just as relevant to products, as outlined in the JIS Z-8530 standard. Thus, ADT models can be expected to be useful for human-centered design processes.

In artifact engineering, design is treated as major stream. A criterion for the synthesis process is pointed for, and an abduction as a logic operation is set center of discussion [18], and from this standpoint, concept structure for describing physical world is supplied [18]. The goals of both artifact engineering and the present research are to construct a representational model for artifacts using symbols. However, artifact engineering focuses on describing the synthesis process for designers, whereas the present model focuses on describing interactions with operators.

4.3.2 Understanding and representing physical systems

Petri net is employed several studies on human behavior [19].As a model of operation using Petri net, MVC model [20] has been proposed. This model represent physical function using information that specializes in individual device, on the other hand, present model represent physical phenomena using causal relations without teleological meaning. A model for KIEF [11] is also known as representational model for artifacts using Petri net. In this model, physical phenomena are represented by using conditional equation, e. g. "$f = ma$." Therefore, this model can illustrate continuous state transitions, whereas it is not suitable for merging physical phenomenon. Moreover, this model dose not include operation sequences.

When discussing the generality or reusability of concepts that regulate the representational model of a physical system, ontological engineering should be considered. As a result of adapting ontological engineering for design, both progress in the sharing or generalization of knowledge in synthesis, and the elucidation of design rationales by tacitly specifying information can be expected [12]. The structure and content of the three layers of the ADT model were determined based on three points of view; alethic, deontic and temporal modalities, therefore the model consist of the concepts of three different modalities, operations, local states, causal relations, physical quantities and structural elements. Thus, an ontological scheme based on modalities can be constructed by defining each concept strictly.

Qualitative reasoning also focuses on causal relationships in order to understand phenomena. For example, in Reiger's model [21], both operations and necessary events are described in the same network, distinguished through the use of different symbols. In the ADT model, the main and base layers are clearly separated, and a relevance is defined between them. Accordingly, a concise method of merging the PCN of the base layer and Petri net of the main layer can be introduced. In this way, an estimation system for events when several systems operate simultaneously can be introduced. In this case, however, common items though systems should be increased by any effort, e. g. introducing system resources (operator hands, graze and so forth) to token of Petri net.

5. Conclusion

A model for representing artifacts based on the modality of operations and states was introduced. This model represents possible operations and states in a main layer, placing importance on "events" derived from "objects." Relationships between "designer intentions," "physical phenomena or effects" and "operations" are then expressed by interaction between the main layer (" liberty or responsibility") and 2 other layers reflecting "teleological necessities" "causal necessities." Thus, the proposed model is suitable for representing interactive artifacts that must be designed with full consideration of the characteristics of the users.

Operators' comments should be respected in the design process in order to achieve fine interaction between operators and the product, thus human centered design process is important. Participatory design [22] is one such human-centered design process, and the authors are currently examining a new style of participatory design using the proposed model. Participatory design is a concept of design process in which the users participate in order to improve the usability of products. Generally, in participatory design processes, operators' requests are reported directly, using the proposed model, however, it will be possible to summarize the requests indirectly. That is, designers can recognize the operations selected by users by observing the transitions of markings in the Petri net. This is expected to support design using affordance, although by an indirect approach.

In application to participatory or collaboratory design processes, it becomes necessary for unspecified designers to refer to the information on each layer in order to modify the design. In this situation, in order to maintain consistency among designers, strict definitions are required for each layer of the ADT model. The authors have already proposed a conceptual class for describing the ADT model based on ontological engineering concepts. Construction of a participatory design support system using these classes is an intended target of future work.

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Hidetsugu Suto (Member)

2002- Instructor at the Dept. of Industrial Design, Akita Municipal Junior College of Arts and Crafts. 2006- Associate Professor at the Dept. of Computer Science and System Engineering, Muroran Institute of Technology.

Hiroshi Kawakami (Member)

1989- Instructor at the Dept. of Information Technology, Faculty of Engineering, Okayama University. 1998- Associate professor at the Dept. of System Science, Graduate School of Informatics, Kyoto University.

Osamu Katai (Member)

1974- Instructor at the Dept. of Precision Engineering, Kyoto University. 1983- Associate Professor, 1994- Professor at the Faculty of Engineering, Kyoto University. 1998- Professor at the Dept. of System Science, Graduate School of Informatics, Kyoto University.

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