Paper:

Design Methodology for Human Symbiotic Machines Based on the Description of User's Mental Model

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This research establishes a methodology for designing human symbiotic machines. In our proposal, the mental model of a user is described by a user model diagram as an extended version of the well-known System Modeling Language (SysML). The user model diagram originated in the state machine diagram and the activity diagram of SysML. Concretely, the behavior of a machine observed by a user (user model), is drawn as a parallel to the actual behavior of a machine (system model). The user model diagram can visualize the physical processes required to use the machine and can reveal any inconsistencies between user and system models. We have selected a non-industrial stacker crane, which stores and retrieves containers through human manual operation, as an application target of the proposed design methodology. To make the stacker crane interface more user-friendly, several design plans are proposed and discussed together with descriptions of user model diagrams. To evaluate the relationship between diagrams and actual performance, prototypes of interfaces are developed, and usability tests are conducted. Results of usability tests indicate that the user model diagram is a good design tool for estimating the basic usability of a human symbiotic machine.

Keywords: system modeling language (SysML), human-machine symbiosis, mental model, manual operational instrument

1. Introduction

Machines that assist people in non-industrial areas such as public facilities and at home are required to cooperate with human beings in the areas. A system for supporting human actions in which the system and the persons supported affect each other is called a human symbiotic machine. A popular example is an automobile with drive support that assists in automated driving. With human symbiotic machines, safety and operating efficiency are expected to be improved by combining the advantages of human beings who make flexible decisions and machines that are superior in numerical/quantitative control [1].

In general, the consistency between system and user models is said to be important. A system model is a conceptual model that presents the behavior of a machine system, while, in contrast, the user model is a conceptual model that presents the behavior of a machine that the user imagines in his/her mind by using or observing the machine system [2, 3]. (Reference [3] discusses the relationship between two models and an image; the design model that a designer would have, the system image that an actually created system has, and the model that a user has.) In this paper, the system model is defined as the system image that a designer or design evaluator considers the system to have. In contrast, the design model is defined as the model that the designer intends to apply to the system. In an ideal situation, system and design models are identical.

The occurrence of a difference between system and user models is called an "automation surprise" [4], which confuses users and could result at worst in a serious accident [5]. In this paper, the user model for a human symbiotic machine is described using diagrams and a method to design a user-friendly machine will be proposed as a summary.

Related studies have covered the expression of interaction between a user and a system by extending Unified Modeling Language (UML), a widely-used tool supporting systematic software implementation [6–8].

Kim et al. proposed constructing a hierarchical structure of a Graphical User Interface (GUI), consistent with user awareness from the user's input trends [9]. Technical modeling and design of the system structure and behavior, including embedded systems and other hardware, have also been proposed in ways such as in [10, 11] where UML was used, in [12] where a flowchart was used, and in [13] where MATLAB SimMechanics was used. There has not, however, to our knowledge been a proposal on a method of systematic description for a user's mental model (user model) nor on machine system design based on such a mental model.

In this study, extended SysML (user model diagram) is proposed for describing a user model by extending System Modeling Language (SysML) [14, 15, a] that models machine system specifications and behavior. Basic grammar and description (diagram elements, etc.) of extended SysML are to agree as well as possible with SysML. In other words, extension is made in the description of the user model. With SysML-compatible grammar, extended SysML is acceptable to designers experienced in design using SysML.

In this paper, a non-industrial stacker crane – a tool to help users store daily items as shown in **Fig. 1** – is selected as an example for applying proposed extended SysML (user model diagram) [16]. For storing items, the stacker crane lifts a container and hangs it on a hanger fixed on a wall. For the stacker crane to be symbiotic to users and introduced easily into their life space, it is basically operated manually without expensive actuators, although actuators may be added afterward to drive the crane electrically. A wall storage method that can tolerate positioning error and a mechanism that smoothly propagates a user's effort for driving the machine were proposed in a preceding study [16]. This system, either manual or automated, was shown in evaluation experiments to have sufficiently-high performance in physical motion. By combining mechanisms for two degrees of freedom (DOF), the system allows a user to make multiple operations without switching multiple handles, for example. This system configuration could also reduce the number of mechanical parts. The user needs, however, to press a switch each time the operation direction is changed, so there is room for improving operability for general users who know little about machine configurations.

In this study, a user model diagram of extended SysML is used to model a design idea for improving the operability of the non-industrial stacker crane based on both system and user models. Then we make a prototype from the improvement idea, and evaluate its usability. The relationship is clarified between the expected usability and the system/user model described as the user model diagram. It is also made clear how the user model diagram is used to design a human symbiotic machine and predict its performance.

To show the application of user model diagrams to cases other than the machine systems we developed, a thought experiment is conducted to describe the model of existing automobile drive support.

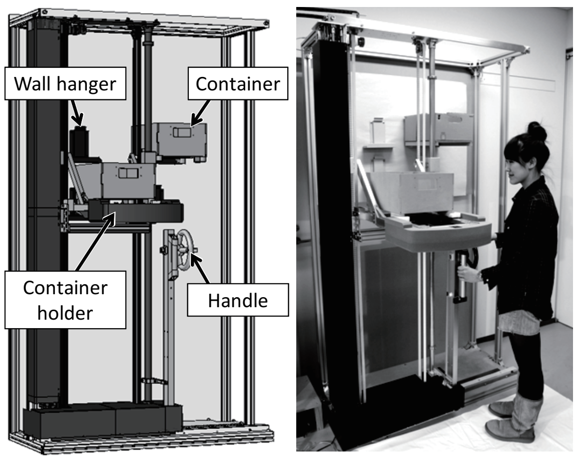

Fig. 1. Non-industrial stacker crane.

This paper is organized as follows. Section 2 describes a user model by extending SysML. Section 3 introduces the non-industrial stacker crane for which an operating system is designed using extended SysML (user model diagram), and lists problems with the basic operating system. Section 4 discusses the specific design of the operating system and shows how modification changes the user model diagram. Section 5 describes usability testing of the crane's operating system and discusses the relationship between changes in operability and changes in the user model diagram. Section 6 introduces a thought experiment in which modeling using extended SysML (user model diagram) is applied to automobile drive support technology. Section 7 gives conclusions.

2. Description of Mental Model by Extending SysML

2.1. SysML Overview

SysML is a graphical modeling language of diagram expression rules for defining, analyzing, designing, and evaluating complicated systems that combine hardware and software. SysML consists of nine kinds of diagrams – requirement, block definition, internal block, parametric, activity, package, use case, sequence, and state machine – with different purposes such as defining required specifications, describing structures, and detailing internal process flows. Diagrams where users are explicitly expressed are the use case diagram, which shows the behavior of a system from a user's viewpoint, and the sequence diagram, which shows time-sequential description of interactions between the user and individual parts of the system. A use case diagram, however, only outlines actions that a user takes in relation to the system. The user in a sequence diagram is described as a step in a series of sequential operations, but the diagram does not describe the user's awareness of the system during operations or interaction between the user and system.

2.2. User Model Description Through Extending SysML

This section presents a way of describing a user model by extending SysML. User model diagrams require the following two basic functions:

(1) Consistency between system and user models in each type of processing and operational input processes must be clarified.

(2) The number of operations and decisions made by the user until a task is completed must be visualized.

To meet these requirements, we designed a description of user model diagrams based on the state machine diagram and the activity diagram in SysML. **Fig. 2** shows an example of the description of a user model diagram, which shows a process for an airplane accident that occurred due to a discrepancy between an automatic control unit and a user's awareness of the unit [17]. In this accident, the airplane was ascending in vertical speed mode, but could not attain the necessary climb rate because of bad weather and plane overloading. Vertical speed mode was then automatically switched to altitude hold mode in accord with software specifications.

In the user model diagram, the system's actual behavior (system model) and system's behavior from the user's viewpoint (user model) are drawn side by side. Basically in regular operation, the process flow is written straightly from up to down. If a current step is cancelled and the process returns to the previous step, the flow is written recursively. An error due to incorrect processing is emphasized as an incorrect state by being written at the side of the regular process flow. Information that the system sends and the user receives, i.e., information output and input, is expressed as communication between the two models.[1]

The similarity of the two diagrams drawn in this description rule indicates consistency between the two mental models and the number of the blocks indicates the amount of user operations and the number of decisions to make in conditional branches. In general, the smaller the number of blocks, the more the amount of operation and the number of decisions is reduced. In addition, since sideways show possible errors, a minimal number of sideways indicates a smoothly operating system.

Let us examine the operating system of this airplane using the user model diagram. Since the pilot (user) did not have sufficient information about the mode switching automatically made by the system, inconsistency arose between system and user models because of unintended mode switching, as shown in **Fig. 2(a)**, resulting in the accident. To improve the operating system, a display showing system status to the user as shown in **Fig. 2(b)** is introduced to make system and user models as similar as possible. This unit makes the operating system more user-friendly.

1. Here, the diagram does not show whether the user receives information appropriately but shows only that it's necessary for the user to receive information in order to go through conditional branches in the diagram. Receiving information appropriately depends on the detailed specifications of the machine (e.g., appearance of user interface), so the focus is placed on finding an inconsistency in conditional branches between system and user models.

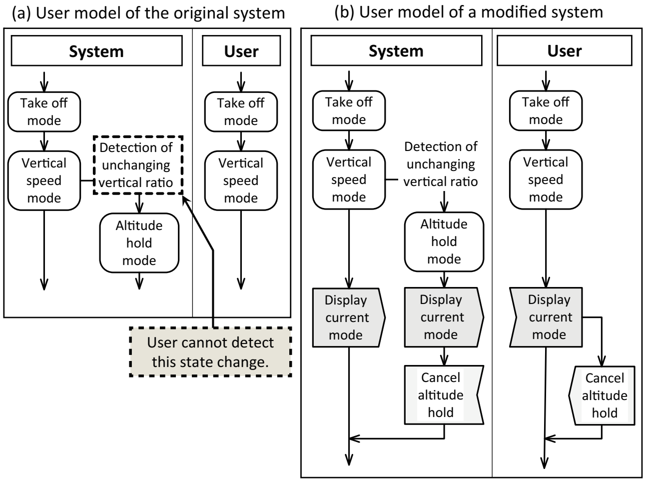

Fig. 2. Example of proposed "user model diagram" in extended SysML.

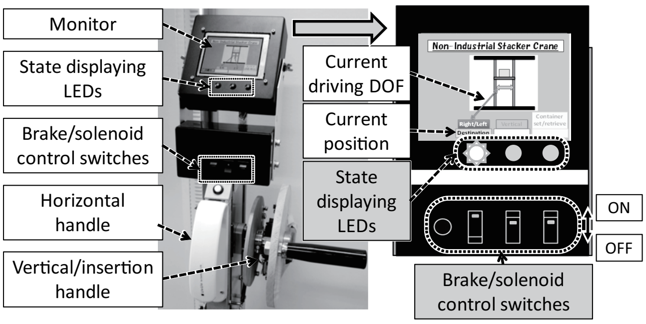

Fig. 3. Overview of handle and monitor.

3. Application of Design with Extended SysML: the Non-Industrial Stacker Crane

3.1. Stacker Crane Overview

The non-industrial stacker crane in this paper consists of wall hangers that work as shelfless storage units and a manually-driven container manipulator that can be extended to an electrically driven system. The manually-driven crane uses integrated power transmission by combining the two DOF of the driving system, i.e., the first DOF is moving a container up or down and the second DOF is positioning (inserting) the container where it is supposed to be set on.

Figure 3 outlines the handle and the monitor used by the user to control the system. The monitor displays the current direction of motion and the current position of the container unit. When the unit reaches a position where the container can be set on or removed from a wall hanger, the monitor shows a notification indicating that position adjustment has finished. The user then takes a directional control based on displayed information. A horizontal handle is used to move the unit to the left or right. For mo-

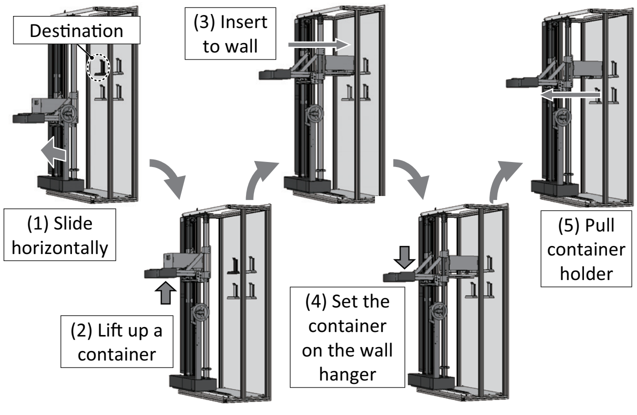

Fig. 4. Operating sequence of container storing motion.

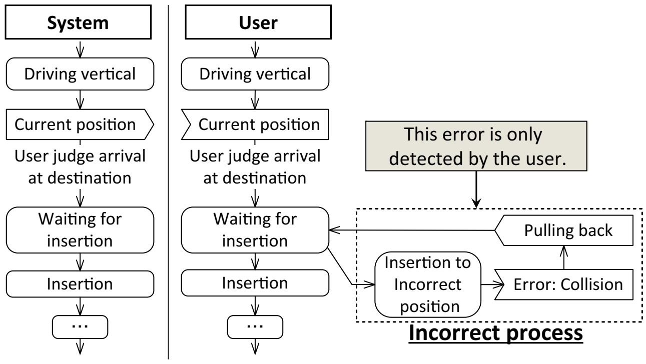

Fig. 5. User model diagram of unintentional collision between container and holder.

tion up or down and insertion, the vertical/insertion handle is rotated to drive the integrated two DOF mechanism. Namely the system, which has three DOF for operations, uses two handles for operations although the direction of operation must be switched.

Figure 4 shows the process for putting a container on a wall hanger. Doing so requires the following operations: (1) The crane body is slid to the left or right and positioned at the line of a container. (2) The up-down brake is released to raise the container to the position where the container is to be put on the wall hanger. (3) The insertion brake is released to insert the container. (4) The up-down brake is released to move the container holder down and place the container on the wall hanger. (5) The insertion brake is released to move the container holder back.

To remove a container from a wall hanger, the crane body is moved to where this can be done in step (2) and the container holder is moved to where it removes the container from the wall hanger in step (4). Due to the wall hanger structure, the heights at which the container is put on and removed from the wall hanger are different.

3.2. Problem 1: Error that the System Cannot Recognize

In a previous system, called the basic system [16], errors may arise that the system cannot detect but the user can.

The basic system monitor notifies users both when a container can be set on and when a container can be removed from a wall hanger. Due to the wall hanger structure, the heights at which the container is put on and removed from the wall hanger are different. A user misunderstanding information displayed on the monitor could move a container to an incorrect height, e.g., the set height for putting the container on the hanger or moved to an incorrect height to remove the container. This process is presented as a user model diagram in **Fig. 5**. Since the system cannot recognize whether the user is positioning the container correctly, it allows the user to continue operation without the mistake being correct. In contrast, the user tries to put the container on the wall hanger not realizing the error and finally finds the error when the container collides with the hanger or another container. The user model and the system model therefore are different from each other with respect to errors that users may recognize.

3.3. Problem 2: Complicated Motion Direction Switching

Due to the mechanical design of this system, the following three sequential steps are required for placing a container:

Step 1: Insertion of the container holder.

Step 2: Moving the container holder down.

Step 3: Pulling the container holder back.

In this process the user must make frequent switching operations in a short time in order to make fine position adjustments and change the direction of motion during operation. Users (beginners) unfamiliar with the system could therefore become confused and even experienced users familiar with the system could feel stressed.

3.4. Problem 3: Gap Between Beginner's Awareness and System Behavior

In the basic system, direction of motion is controlled by the monitor switch. This system requires that even beginners understand and assume internal specifications of the machine. They need to know, for example, that switching must be made for the intended direction of motion and that a specific brake is released to drive the unit in the selected direction.

4. Design Modification of Stacker Crane Operating System Using Extended SysML

Ideas for modification of the operating system are shown below to solve the above problems.

4.1. Idea 1: Reduction of Operation Errors by Introducing Container Detection Sensors

In order to prevent an error that causes the container holder to stop at an incorrect height and insertion operation to start at that height, an optical sensor (photoreflector) is mounted on the container holder to detect the presence/absence of a container. With this sensor, the system recognizes whether the user is trying to place or remove the container. Since only information necessary for the user's current operation is displayed on the monitor, the "incorrect process" in **Fig. 5** does not occur.

4.2. Idea 2: Reduction in the Number of Operations Using Automatic Change in Direction of Operation

To reduce frequent switching operations for position adjustment and motion direction change in placing or removing a container, two system functions for automatically switching are examined:

- Automatic motion direction switching function:

  In switching between insertion and vertical motions of the two DOF drive mechanism to place or remove a container, the automatic motion direction switching function automatically switches the direction of motion each time the unit reaches a target position in each direction and each time a series of operations is completed.

- Automatic insertion function:

  When the unit is stopped at the position where the container is set or removed, the system determines that the user intends to stop the unit at the current position and begins to insert the container holder.

How the user model diagram is changed by these automatic functions is shown in **Fig. 6**. Since the number of physical process blocks decreases as shown in the figure, it is expected that these functions will reduce the number of switching operations and the user's burden in memorizing the order of operations.

After the insertion of the container holder there is only one procedure for motion direction switching steps and the user has no choice. However, if a user keeps stopping the unit for a certain period of time at an incorrect position considering whether to start insertion, the system automatically switches the mode to insertion mode before the user decides to do so. This new error is one that only the user can recognize (shown by the right sideway in **Fig. 6**). If insertion begins at an unintended position, it can be cancelled by a button on the monitor. This error may occur often, however, when switching is made from one direction to the other in horizontal and vertical position adjustment and it therefore becomes one of the central issues (i.e., discussion points) in usability experiments.

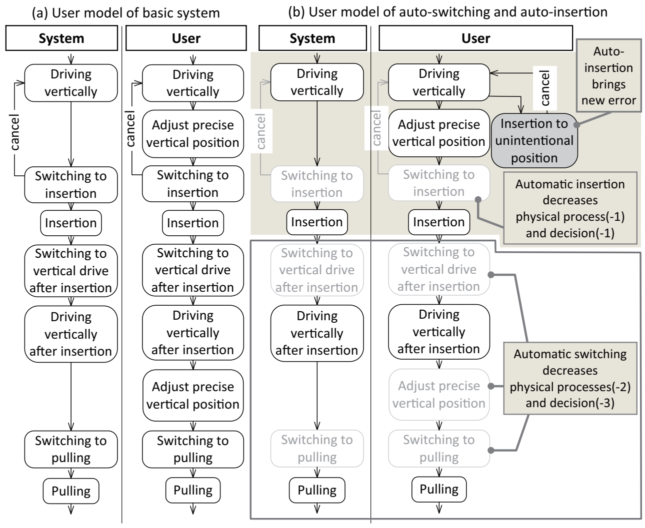

Fig. 6. Comparison of user model diagrams between basic and advanced systems.

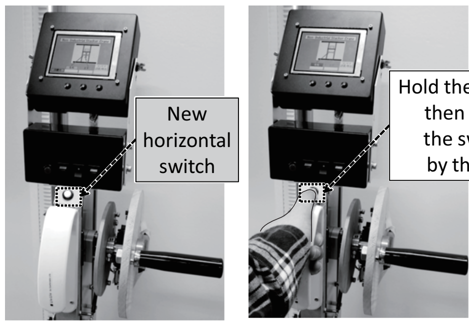

Fig. 7. Overview of horizontal handle sensor.

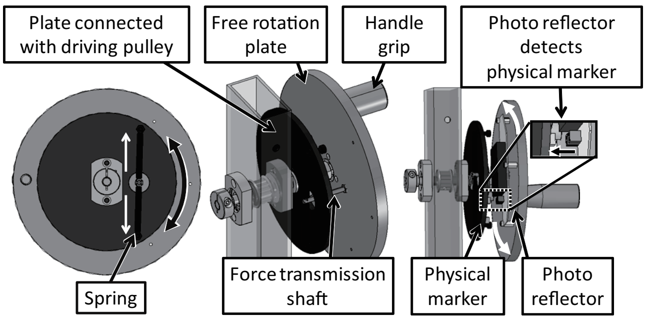

Fig. 8. Overview of vertical/insertion handle sensor.

4.3. Idea 3: Sensor on Handle for Detection of User Operation Intention

For switching the direction of operations, a sensor for detecting the direction of motion and mounted on each of the horizontal and vertical/insertion handles is used instead of a switch on the monitor. **Fig. 7** shows the sensor on the horizontal handle. A switch is attached to the handle and pressed by the user's thumb holding the handle to make a horizontal motion. **Fig. 8** shows the sensor on the vertical/insertion handle. The handle grip is connected to a free rotation plate and user pressure on the handle is transmitted by a force transmission shaft that contacts

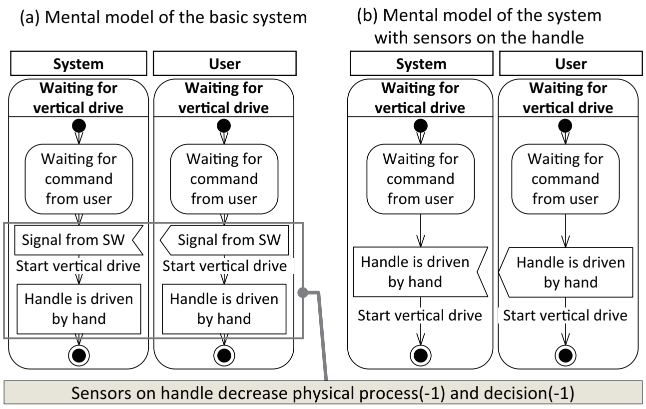

Fig. 9. Comparison of user model diagrams between basic and improved systems with handle sensors.

Table 1. Variations in modified stacker crane.

Type	Basic Structure	Container detection sensor	Automatic Switching	Automatic Insertion	Sensors on handle
1	Yes	No	No	No	No
2	Yes	Yes	No	No	No
3	Yes	Yes	Yes	No	No
3a	Yes	Yes	Yes	Yes	No
4	Yes	Yes	Yes	No	Yes

with the edge of a hole on a plate connected to the drive mechanism. The plate stays in its neutral position held by a spring if the user applies no force. The photoreflector measures the relative position between the free rotation plate and the drive pulley by detecting their markers, and it is recognized that the user applies pressure to the handle when the force transmission shaft contacts with the drive pulley.

Figure 9 shows a change in the user model diagram due to the introduction of handle sensors that directly recognize the user's application of force. In the new diagram, the number of physical switching operations made when the system is driven from a standby state is reduced. Namely, the diagram shows that the new system realizes a simple operation in which a user holding the handle and applying force releases the brake in the corresponding direction.

5. Usability Evaluation Experiments

In this section, the usability of the modified design of the stacker crane operating system is evaluated and the influence of the change in the user model diagram on the operability of actual machines is examined.

5.1. Experiment Setup

Participants were 11 men and women in their 20s to 50s, who had not used the system before the experiment. We used five types of stacker cranes for comparison as shown in **Table 1**.

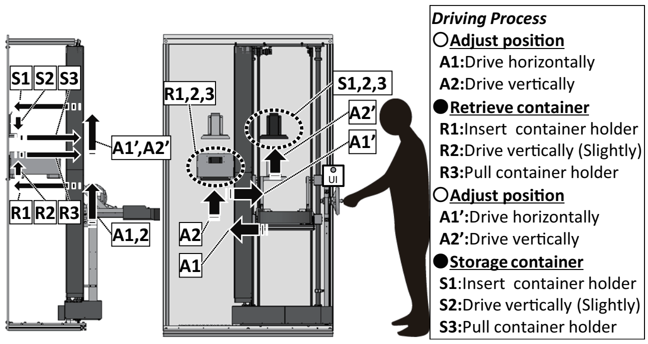

Fig. 10. Experimental configuration.

Participants took a container from a wall hanger at a lower left position and set it on the hanger as shown at upper right and following the procedure in **Fig. 10**. They repeated this process three times for each type of stacker crane and did these 15 operations twice. The test was conducted from the simplest type, i.e., Type 1, to the most highly functional one, Type 4. Before testing, participants were given sufficient training in operation. In order to examine machine-specific performance rather than the participant's skill dependent results, the three operations of each type of stacker crane in the second half of the experiment were employed for analysis because participants would be more used to operations in the second half.

A questionnaire was given to participants after experiments. The aim of the questionnaire was to subjectively evaluate the mental and physical burdens the participants faced in stacker crane operations.

The following four questions were asked and scored using 11 points from 0 to 10:

(α) How much did you actually think to move the container?

(β) Did you find that there were too many operations for moving the container?

(γ) Did you feel stress in moving the container?

(δ) Did you feel a sense of urgency in moving containers?

These questions were made with reference to NASA-TLX [18], a subjective evaluation of usability.

Table 2 shows the block number of the physical process, that of the decision process, and the number of errors in the user model diagram discussed in Section 4 for each type of stacker crane.

In horizontal and vertical positioning operations with the container detection sensor, the monitor displays less information and the user has fewer decisions. The error in which the container holder is inserted at an inappropriate position was thus prevented.

In comparison to the basic type (Type 1), the stacker crane with automatic insertion (Type 3a) required fewer operations because the system rather than the user switched the mode to insertion mode. With Type 3a, however, an error in which container insertion began at an un-

Table 2. Variations in user model diagram.

○ **Adjust position (A1-A2, A1'-A2')**

<table>
<tr><th rowspan="2">Type</th><th colspan="2">Container detection sensor</th><th colspan="2">Automatic Switching</th><th colspan="2">Automatic Insertion</th><th colspan="2">Sensors on handle</th><th colspan="2">Error</th></tr>
<tr><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>Appear</th><th>Disappear</th></tr>
<tr><td>1</td><td colspan="2">NC</td><td colspan="2" rowspan="2">NC</td><td colspan="2" rowspan="3">NC</td><td colspan="2" rowspan="4">NC</td><td rowspan="3">NC</td><td>NC</td></tr>
<tr><td>2</td><td rowspan="4">NC</td><td rowspan="4">-1</td><td rowspan="3">Error 2</td></tr>
<tr><td>3</td><td rowspan="3">NC</td><td rowspan="3">NC</td></tr>
<tr><td>3a</td><td>-1</td><td>-1</td><td>Error 1</td></tr>
<tr><td>4</td><td colspan="2">NC</td><td>-2</td><td>-2</td><td>NC</td><td>Error 2&3</td></tr>
</table>

● **Storage/retrieve container (R1-R3, S1-S3)**

<table>
<tr><th rowspan="2">Type</th><th colspan="2">Container detection sensor</th><th colspan="2">Automatic Switching</th><th colspan="2">Automatic Insertion</th><th colspan="2">Sensors on handle</th><th colspan="2">Error</th></tr>
<tr><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>PP</th><th>DEC</th><th>Appear</th><th>Disappear</th></tr>
<tr><td>1</td><td colspan="2">NC</td><td colspan="2" rowspan="2">NC</td><td colspan="2" rowspan="3">NC</td><td colspan="2" rowspan="4">NC</td><td rowspan="5">NC</td><td rowspan="2">NC</td></tr>
<tr><td>2</td><td rowspan="4">NC</td><td rowspan="4">NC</td></tr>
<tr><td>3</td><td rowspan="3">-2</td><td rowspan="3">-3</td><td rowspan="3">Error 3</td></tr>
<tr><td>3a</td><td>NC</td><td>NC</td></tr>
<tr><td>4</td><td colspan="2">NC</td><td>NC</td><td>NC</td></tr>
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PP: Physical Process
DEC: Decision Process
NC: No Change
Error 1: Insertion to unintentional position
Error 2: Insertion to incorrect position
Error 3: Switch operation mistakes

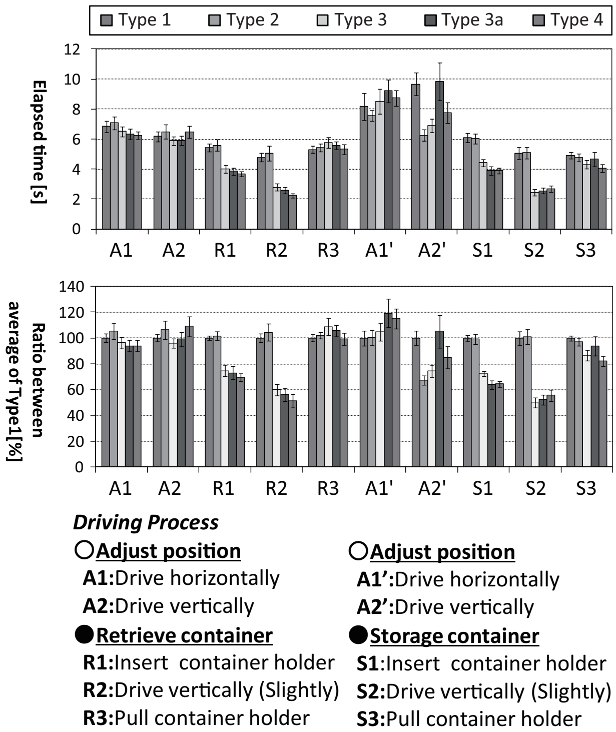

Fig. 11. Experimental results: elapsed time.

intended position could occur. Type 4, with its handle input detection sensor, required fewer switching operations.

In placing or removing a container using the automatic direction switching function, it is expected that stacker crane Types 3, 3a, and 4, with its automatic motion direction switching function, would, first, reduce the user's physical burden in switching the direction of motion and, second, reduce the mental burden in finely positioning and determining whether positioning is done as intended. These types of stacker crane are also expected to prevent users from making incorrect switching.

5.2. Experimental Results and Analysis

Figure 11 shows the average time for each operation by the 11 participants and ratios to that of operation using Type 1. The ratio is calculated to eliminate personal differences in operating speed and to clarify differences in each participant's operating speed among stacker crane types. A normal distribution cannot be assumed for the operation time variation of each stacker crane type, so we employ the U test, which tests differences in central values of ratios to average times of operation using Type 1.

In operation A2', the vertical motion Type 1 crane takes longer than other cranes except for Type 3a, which has an automatic insertion function. The U test indicated that this difference in central values is statistically significant for a significance level of 5% ($p = 1.1 \times 10^{-5} \leq 0.05$). This is an improvement in operability that could be expected from the user model diagram where the number of judgment items decreases by one. In the operation of the Type 1 crane, the monitor shows different information for placing and removing a container, and the user must recognize the difference in information displayed on the monitor. The user may make a mistake in recognition and repeat the same operation or may need more time to read information carefully, reducing operating speed, and this may be the reason for the longer operation time with the Type 1 stacker crane.

In operations R1 to R3 and S1 to S3, in which the container holder is positioned and a container is placed or removed, stacker cranes with the automatic motion direction switching function – Types 3, 3a, and 4 – reduced time for operations R1, R2, S1, and S2 requiring motion direction switching. This difference in central values was found to be statistically significant in the U test ($p = 2.3 \times 10^{-66} \leq 0.05$), as can be expected from **Table 2**, where the number of physical processes for Types 3, 3a, and 4 is fewer by 2 than that for Type 2 and the number of decision processes for Types 3, 3a, and 4 is fewer by 3 than that for Type 2. Namely, for Types 3, 3a, and 4, the system automatically switches the direction of motion without waiting for the user's decision and hence operations and decisions that must be made by the user are reduced.

In contrast, in operations A1' and A2' where the container removed from the wall hanger is transferred to the next hanger, Type 3a having the automatic insertion function takes longer than Types 2 and 3 having no such a function, even though the difference is not statistically significant ($p = 0.054 \geq 0.05$). Although the reduction in operations by the automatic insertion function could have been expected from **Table 2**, it could also have been cancelled out by a new system error involving unintended insertion.

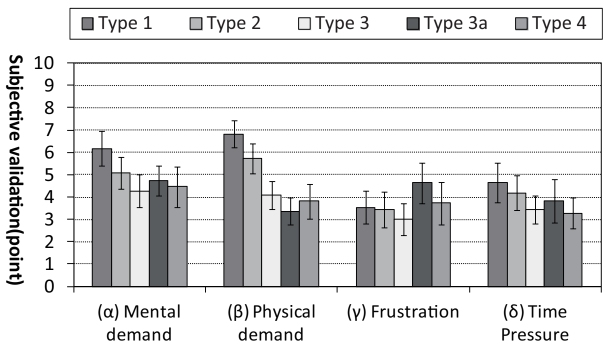

Fig. 12. Experimental results: questionnaires.

Figure 12 shows average answers in the questionnaire about each type of stacker crane. Scores are low when participants used the system in a positive manner. Compared to Type 1, Types 2, 3, 3a, and 4 having container detection sensors had lower scores, i.e., were ranked higher, for question items (α) mental demand and (β) physical demand. This may be because the number of decision processes for these types in the user model diagram is smaller by 1 than that for Type 1.

Overall evaluations indicate that Types 3, 3a, and 4 having the automatic motion direction switching function were evaluated positively in comparison to Type 2 having no such function. This trend is statistically significant for (β) physical demand, which could be because the number of the physical processes in the user model diagram is smaller by 2 for Types 3, 3a, and 4 than for Type 2. Namely, the system does motion direction switching before the user makes a decision and thus reduces the user's physical burden.

Type 3a having the automatic insertion function was ranked higher for (β) physical demand, but lower for (γ) frustration. This indicates that users felt noticeable stress about a new error caused by the automatic insertion function.

Type 4 having the handle input detection sensor received almost the same evaluation results as Type 3 not having the sensor. This is not consistent with **Table 2** where the number of the physical processes and of decision processes for position adjustment are smaller by 2 and 1, respectively, for Type 4 than for Type 3.

Unlike the insertion process where a single handle is used to switch the direction of motion frequently, the vertical and horizontal position adjustment process requires the user to change the handle to operate. Types 3 and 4 could be ranked almost the same due to this fact. Since the number of the user's physical and decision processes varies depending on the type of operation, a change in operation performance could be predicted in detail if processes were weighted in the description of the user model diagram.

5.3. Summary

To summarize, the modification plan for stacker cranes was systematically made using the proposed user model diagrams, and improvement and possible errors in the system due to modification could be almost predicted from the number of physical and decision process blocks and from the number of errors in the diagram. The system whose user model diagram of the extended SysML had a simple operation flow was accepted positively by users and showed superior operation performance. Operation performance expected from the user model diagram and that of an actual machine could be made closer by describing the magnitude of the operational burden in the diagram.

It is considered from experimental results that the description of a user model diagram as extended SysML would be effective in the usability design of human symbiotic machines. The user model diagram needs to be described only when the behavior of a machine system from the user's viewpoint is clear to some extent. In the later phase of the basic design process of a machine system, decisions on the design of the system can therefore be made to a certain extent before the production of a prototype if a user model diagram is given. The user model diagram could therefore reduce the trial and error burden in the prototype production process.

6. Application of Extended SysML to Automobile Drive-Support Technologies

This section describes two practical automobile drive-support technologies with user model diagrams based on extended SysML and discusses their usability:

(i) Intelligent Parking Assist System (IPA) [19, 20].

(ii) Adaptive Cruise Control (ACC) [21].

6.1. Description of IPA User Model Diagram

The principle of the Intelligent Parking Assist System (IPA) is that the system controls the steering wheel and the user controls accelerator and brakes. According to the classification by Inagaki [5], the IPA is a drive-support technology with automation level 4. If the system also controlled the accelerator, the automation level would be increased to 7. **Fig. 13** shows user model diagrams of these two cases.

In the automation level 7 system with automatic control of acceleration and braking, the physical process in the upper part of **Fig. 13** is removed and the driver's operations for acceleration and braking are reduced. In this case, the user would only need to watch the system park the car automatically. If the system fails to detect an obstacle, the user is not supposed to make an emergency stop since the lower right block in **Fig. 13** is deleted from the automation level 4 diagram. The drive-support function actually used for automobiles is semiautomatic and classified as the level 4. The user model diagram indicates that in order to be made fully automatic, the system must have a function to recognize the environment without error. Otherwise, the system cannot respond to emergencies

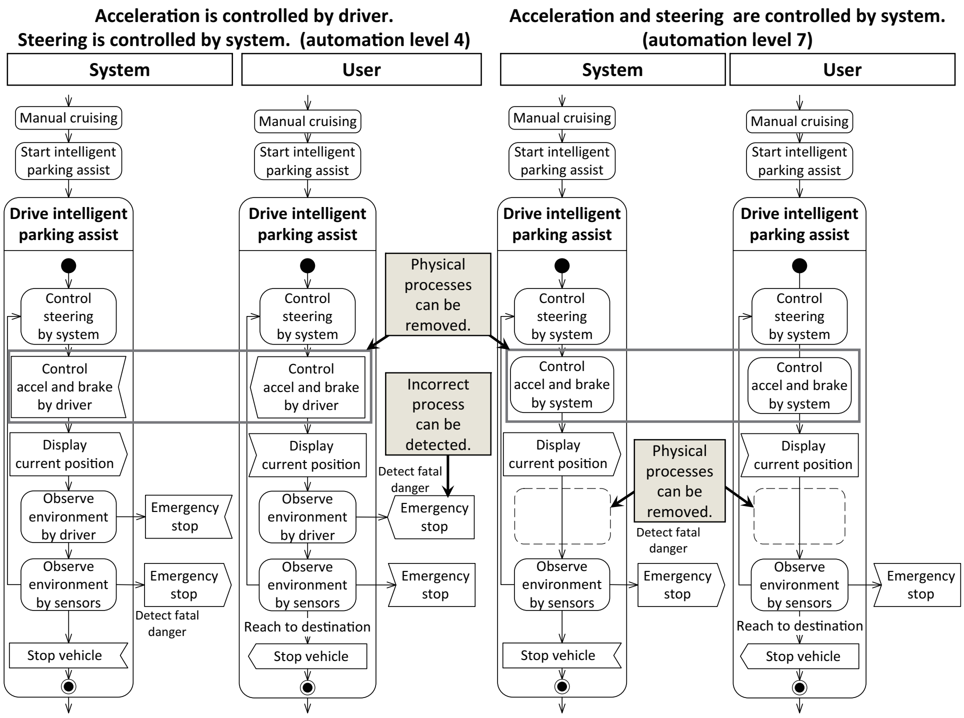

Fig. 13. Comparison of user model diagrams between different automation levels in intelligent parking assist system.

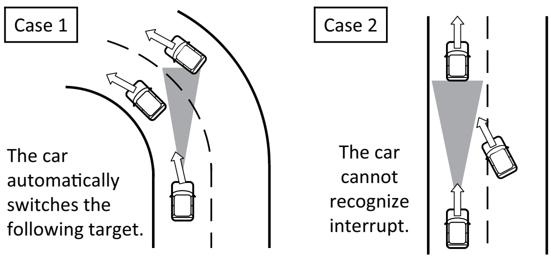

Fig. 14. "Automation surprises" in adaptive cruise control.

and the user's observation of the environment to assist the system cannot always be expected to operate in a completely automated system.

6.2. Description of ACC User Model Diagram

With Adaptive Cruise Control (ACC), an automobile travels at the speed designated by the driver if there is no vehicle in front of it. Otherwise, the ACC drives the automobile automatically following the vehicle while keeping a certain distance from the vehicle in front. As shown in **Fig. 14**, in current ACC, an "automation surprise" could occur if the automobile came into a curve while multiple leading vehicles are existing or another automobile cut in between two cars. When the system follows a car different from the one that the driver intends to follow, for example, the automobile could change lanes unintentionally. When an automobile cut in from an area not covered by the system sensor, the system might not decelerate the automobile despite the driver's intention to do so. This situation is described in the user model diagram in **Fig. 15(a)**, where the user cannot find the error before recognizing environmental change due to the speed change made by the system.

In order to reduce the influence of such phenomena as the "automation surprise," an intelligent display system that displays the vehicle currently tracked on the front windshield could be introduced. With this system, the user model diagram would come to resemble that shown in **Fig. 15(b)** and the driver would notice the error in tracking the incorrect vehicle before approaching the vehicle too closely. BMW currently uses a head-up display to show the setting of the ACC [b]. It does not, however, show the current status of ACC controller vehicle recognition. It is therefore expected that our proposal would help realize a machine more symbiotic to human users.

To add a display, the displayed information must be appropriate in terms of human factors [22] and the interface must be designed carefully. Here, a user model diagram based on extended SysML would be a useful design tool for estimating the effect of the new interface in user awareness.

7. Conclusions

In this study, we have proposed a design method supporting to realize a machine that works collaboratively with humans. A user model diagram has been introduced as an extension of SysML by combining a user model that shows the behavior of a machine system from a user's viewpoint and a system model that shows the designed behaviors of the machine system. The user model diagram enables the amount of user operations and any gap

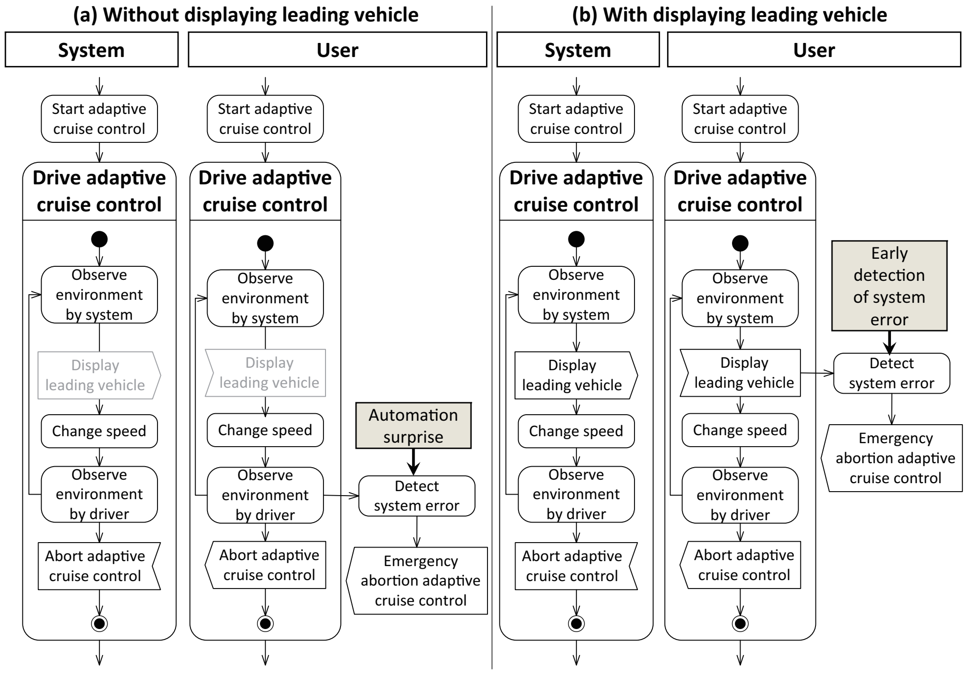

Fig. 15. Comparison of user model diagrams for presence and absence of intelligent display in adaptive cruise control.

between actual machine behaviors and user's awareness to be identified. We have designed and implemented a non-industrial manually operated stacker crane based on the user model diagram and have conducted usability evaluation experiments. As a result, the difference in usability among different types of stacker crane was observed, as expected, from the number of physical process blocks and decision process blocks and the number of errors in user model diagrams. This design method was also applied to automobile drive-support technologies and the effect of a change in the automation level and the estimated effect of an additional intelligent display system have been discussed.

Future work is to realize a design method that reflects the magnitude of the operational burden of user operations and decisions in the user model diagram and to apply the proposed user model diagram to human symbiotic machines other than non-industrial stacker cranes or automobiles and to evaluate its effect in the design of machines.

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