Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2008
August 3-6, 2008, Brooklyn, New York, USA

DETC2008-49728

APPLYING USER INTERFACE-OPERABLE 3D DIGITAL PROTOTYPES TO HUMAN-CENTERED DESIGN OF INFORMATION APPLIANCES

Satoshi Kanai*
Division of Systems Science and Informatics

Taiga Higuchi
Division of Systems Science and Informatics

Graduate School of Information Science and Technology,
Hokkaido University, Kita-ku, Sapporo 060-0814, JAPAN

Yukiaki Kikuta
System Development Division
C's Lab Co., Ltd., Chu-o-ku, Sapporo 060-0002, JAPAN

ABSTRACT

One of the critical issues of realizing human centered design (HCD) for information appliances is how to efficiently find the weakness of usability of the user interfaces (UI). At present, user test is the most reliable method of evaluating usability of UI. But executing user-test costs much due to fabrication of physical prototypes, securing of test subjects and facilities and the manual-based analysis of the test results. To solve the problems, we propose a computer-supported environment for testing and usability assessment for human centered-design of information appliances in the paper. In the environment, UI-operable 3D digital prototypes can be designed and used for user tests instead of physical prototypes, and the test results can be automatically analyzed to clarify the weak points of the UI design. UI-operable 3D digital prototypes can be modeled by integrating the state-transition-based UI behavior model with 3D CAD models of the housings. A function of graphically displaying user's operational history helps the designers identify which portions in the UI specification induce wrong operations of users. A function of indicating digital questionnaire based on cognitive walkthrough method also enables them to reveal causes of the wrong operations and to clarify point of redesign. Comparison of the test results using different types of digital prototypes showed that the proposed UI-operable 3D digital prototype could fully replace the physical prototype in early design stage.

1. INTRODUCTION

1.1. Background and Purposes

With so many people using high-performance information appliances such as mobile phones, digital cameras and digital audio players, the manufactures have been recognizing the importance of human centered design (HCD) to enhance product qualities and market competitiveness. Consciousness of "usability" of user interfaces (UIs) is strongly needed to realize the HCD for the information appliances. In the international standard [1], the "usability" is defined as "an extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use".

There are several methods of evaluating usability [1]. Among the methods, "user-test" is recognized as the most objective and effective one where end users are directly involved in the evaluation. In the user-test, designers make end users operate a physical prototype of the appliance, observe the user's operational situation, and investigate closely ergonomic issues of the UI design.

One of the critical issues of the HCD is how to efficiently find the weakness of usability of UIs and how to rapidly correct them in the design process. In that sense, user-test must be executed in the early design stage. However, executing user-test costs much due to fabricating UI-operable physical prototypes of the appliance, securing subjects for the test, and preparing an environment of the test studio. The results of the test have to be manually logged and analyzed by usability specialists. The analysis takes a couple of weeks in general. Moreover, the UI-operable physical prototype becomes available only in late stage of the design. If problems of the UI design appear at this time of the day, it is often too late for change in the UI design within their development schedule. For the sake of the limitations of cost and time, manufacturers

* Professor and author of correspondence, Phone: +81 (11) 706-6448, Fax:+81 (11) 706-6448, Email: kanai@ssi.ist.hokudai.ac.jp

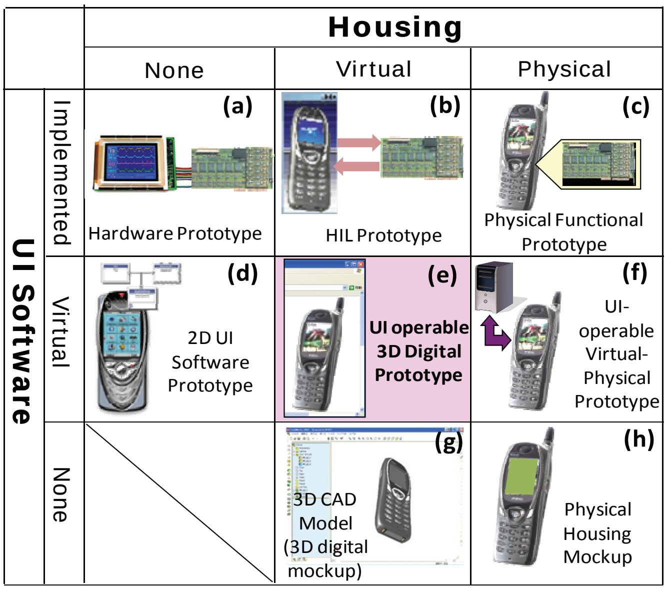


Figure 1. Prototypes for developing information appliances.

of the information appliances often unwillingly give up executing user-tests.

Therefore, the manufactures strongly need advanced techniques where UI-operable prototypes can be fabricated in less-expensive way at the earlier stages, and where the user test and usability evaluation can be performed in more efficient way. For responding these needs, the purposes of our study are;

1) to develop a computer-supported environment for testing and usability assessment of information appliances where UI-operable 3D digital prototypes can be used for user tests instead of physical prototypes and where the test results can be automatically analyzed in order to clarify the weak points of the UI design,
2) to verify whether the UI-operable 3D digital prototypes can replace the physical prototypes by closer comparison of user performance indices obtained from the tests using 2D, 3D and physical prototypes, and
3) to indicate that the proposed environment can help UI designers detect and clarify the points to be redesigned in the UI specification and that the environment can make test-evaluate-redesign cycle of the UI faster.

1.2. Related Works

Shown in Figure 1, different kinds of prototypes are currently used for the user test of information appliances. These prototypes differ according to the type of the housing and the UI software. The related works of ours can be classified into the categories shown in Figure 1(d)(e)(f).

As for 2D UI software prototype shown in Figure 1(d), there are some commercial prototyping tools available [2,3] which have UI simulation functions. The prototyping tools for conceptual design phase were also proposed in [4,5]. Moreover, there are several tools which have usability assessments functions [6,7] as well. However, these tools were aimed to prototype UIs of PCs or mobile phones, and their UI simulations are only limited to 2-dimensional one. In case of the user test for the portable information appliances whose UI elements (buttons, dials, LCDs etc.) are placed in 3-dimension such as digital cameras, UI operating situation in the 2D prototype is far from the one of real appliance, and the interaction feeling is not satisfactory for the subjects of the user test.

On the other hand, UI operable 3D digital prototypes have been studied which corresponds to Figure 1(e). It consists of a virtual housing model (3D CAD model) and UI simulation function which works on 3D housing model. In spite of lacking physical housings, UI simulation functions working on the 3D housing enhance the reality of interaction in the user test. However, most of these 3D digital prototypes have to be built and run using commercial Web3D formats[8,9]. Usually these formats only provide the script-based simulation function of the UI, and do not provide functions of modeling the state-based UI behaviors, supporting user test execution, and evaluating the usability from the operation logs.

To make these UI operable 3D digital prototypes more suitable for the user test, Kuutti et al [10] added logging functions of user events to a VRML viewer, and applied this tool to the user test of mobile phones. Their experimental results indicated that 3D digital prototype enhanced reality of interactions compared with the 2D UI software prototype. However, evaluation of the usability after the test was not automated in their system. Bruno [11] also developed a VR system where the user took a head mounted display to manipulate the UI of 3D electric cooker model. Their results suggested that there was a strong correlation of the user performance measures between the 3D digital prototype and the real product. However, their system needs the expensive devices of VR, and the UI was modeled in 2-dimension. The functions of modeling the UI behavior and evaluating the usability were also not discussed in their paper.

On the contrary, UI operable virtual-physical prototype which corresponds to Figure 1(f) has a physical housing prototype and a UI simulation function. The UI simulation function usually runs in the external host computer. The subjects can directly grasp a physical housing and can manipulate the UI elements on it. The prototype enables to obtain most reliable test results on the user performance. However, these prototypes need the extra cost of fabricating the physical prototype of the housing and hardware connection between the housing and the host computer. Mixed reality techniques such as image-projection of the UI screen have been used to eliminate the hardware connections between the displays and host computers [12,13,14,15]. However, very expensive or specific devices such as head-mounted display, magnetic position and orientation sensors etc are needed to realize the prototypes. Moreover, in these studies, how to model the UI behavior and evaluating the usability were not discussed, and correlation of user performance measures between their 3D digital prototype and a real product were not fully investigated.

In order to keep the fabrication cost of UI-operable prototype relatively low and to assure the reliability of the user test results, at this point, the UI operable 3D digital prototypes which have dedicated functions of user test and usability assessment are the best solution in early design stage of the portable information appliances.

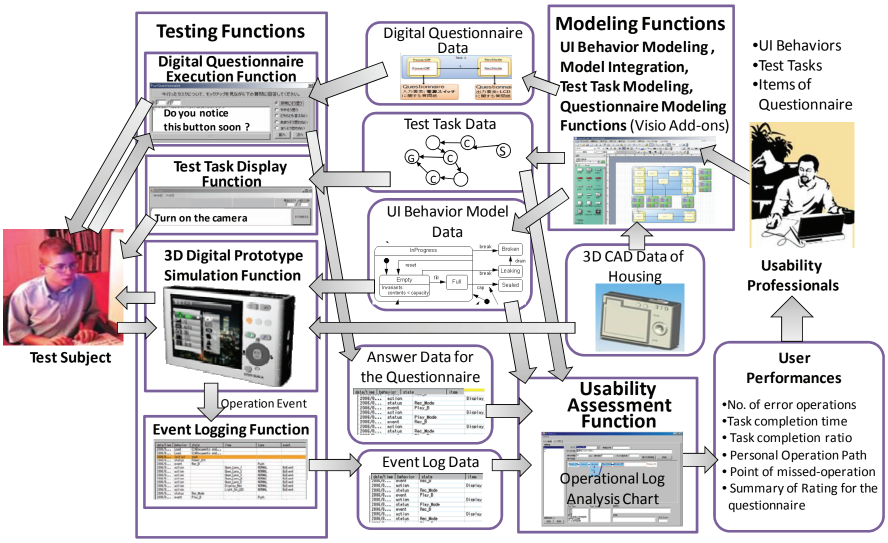


Figure 2. The overview of the environment for testing and usability assessment.

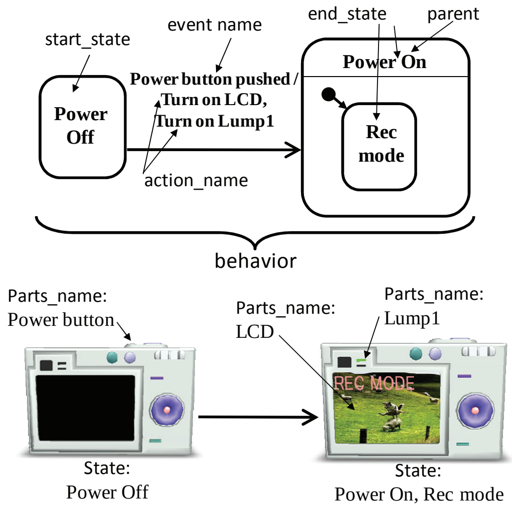


Figure 3. UI behavior model.

2 OVERVIEW OF THE ENVIRONMENT

Figure 2 shows the functional overview of our developed computer-supported environment for testing and usability assessment. The functions are roughly divided into the modeling functions, the testing functions and the usability assessment function. The outlined description of each function is the followings:

(1) Modeling functions

The functions consist of the UI behavior modeling function, the model integration function, the test task modeling function and the questionnaire modeling function. These four functions are all implemented as the add-ons of the MS-Visio. The UI behavior modeling function is to interactively build the Statechart based model of UI behavior of the appliance. The model integration function is to make logical links between the UI behavior model and the 3D CAD model of the appliance's housing in order to build the UI-operable digital prototype. The test task modeling function is to define tasks indicated to subjects of the user-test. And the questionnaire modeling function is to define questions indicated to subjects for identifying what needs improvement in the UI design.

(2) Testing functions

The functions consist of the 3D digital prototype simulation function, the event logging function, the test task display function and the digital questionnaire execution function. The functions works during executing user test using 3D digital prototype, and are implemented as the add-ons of Virtools player. The 3D digital prototype simulation function is to execute UI simulation in response to incoming events such as mouse click issued from a subject on the UI operable 3D digital prototype. The event logging function is to collect a sequence of events from the subject during the operation together with states passed and time stamps. The test task display function is to indicate a goal of each task to the subject, and the digital questionnaire execution function is to accept the rating for the questionnaire from the subject.

(3) Usability assessment functions

The usability assessment functions are to analyze the event log data by comparing it with the test task data and UI behavior model, and outputs measures of user performances. The number of the error operations, personal task completion ratio, and task completion time can be automatically calculated. The operational log analysis chart is drawn to clarify the UI operation path and the points where many subjects take wrong operation. The functions also summarize the results of rating for the questionnaire which is useful for the usability professional to identify what needs improvement in UI design.

3 MODELING FUNCTIONS

3.1 Modeling of UI Behavior

The UI operable 3D digital prototype consists of two models: 3D CAD model of the housing and UI behavior model. The UI behavior model is the specification of event-driven behaviors of the UI system. The model represents how state on the output devices (CRT, LCD, lumps etc.) of the appliance changes as a result of the event coming from input devices (buttons, dials, etc.) of the UI. The behavior is modeled by the Statechart [16] which is an extension of finite state machines.

Figure 3 shows the behavior model based on the Statechart. The model consists of "state", "event", "behavior" and "action". A state represents an unique status of the UI. An event represents a user's action inputted into the UI such as "a power button is pushed", and brings on a transition from one state to the other state. An action expresses dynamic change occurred on the appliance. A change of the LCD property such as "turn on a LCD from dark to blue" is an example of the action. A behavior expresses a transition between two states, and is defined as a combination of two states before and after the transition, an event causing the transition and a sequence of actions of the appliance caused by the transition.

The UI behavior is initially defined based on the specification documents by interaction designers. Therefore, we developed

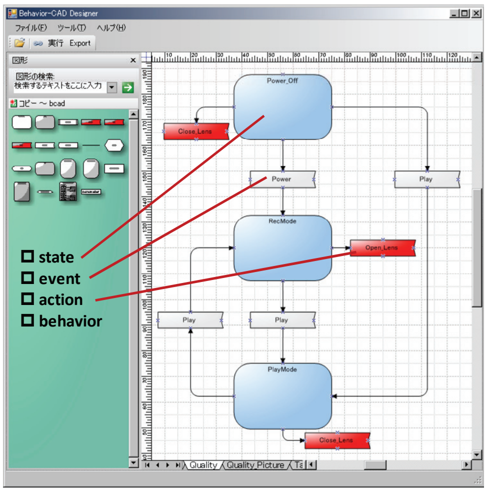


Figure 4. UI behavior modeling function.

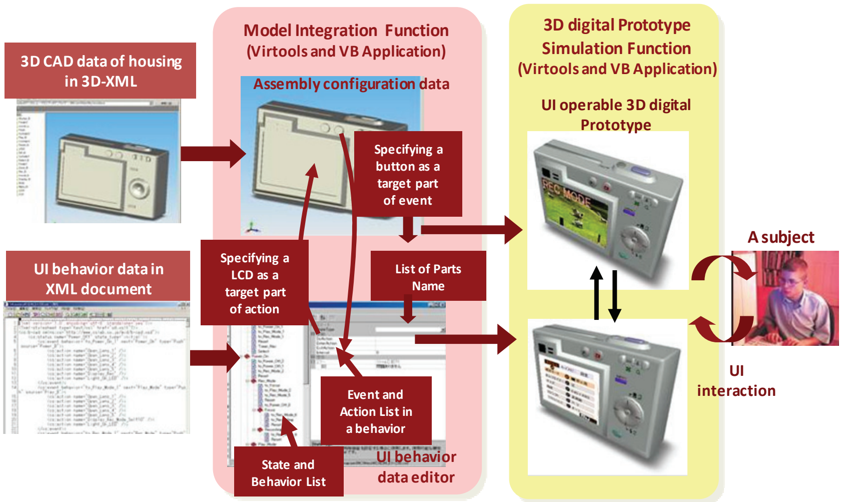


Figure 5. Model integration function.

a UI behavior modeling function to help designers create and modify the model. As shown in Figure 4, the modeling function is implemented a commercial visual editor (MS/Visio), and the UI behavior can be input and manipulated in an intuitive way by the designers.

3.2 Integrating the UI model with the 3D CAD model

In case of evaluating usability of an appliance whose UI elements are placed on multiple surfaces of the housing, the 3D digital prototype where UI simulation can work is indispensable to the user test. For building the 3D UI operable digital prototype, we used the Virtools[17] which is a commercial Web3D tool.

The CAD data of the housing is imported to the authoring tool from 3D-CAD systems (CATIA, Solidworks, etc.) in the format of 3D-XML[18]. The 3D-XML is a universal lightweight XML-based format for sharing of 3D CAD model. The format includes the assembly and each part has its own unique part-name. In the model, a 3D object which is a source of an event or be a destination of an action is modeled as a single part. A button, a switch knob, a LCD screen and a LED are typical examples of these objects.

As shown in Figure 5, in the Virtools authoring tool, an interaction designer links events and actions of the UI behavior model to "messages" of the tool. A message consists of a unique message-name, part-name and message-type of the Virtools. For an example, an event of "button_1_pushed" in the behavior model is tied to a message consisting of "message-1" (message-name), "button-part-1" (part-name) and "on_clicked" (message-type) in the Virtools. Consequently the operation makes all logical links between the messages in the Virtools and events or actions in UI behavior data.

3.3 Modeling of User Test Tasks

In the user test, a subject is asked to complete a set of task by operating the UI, and actual operations for the task are analyzed to evaluate the usability. In the standard [19], a *task* is defined as "the activities undertaken to achieve a goal". The goals and tasks are set by usability professionals before test.

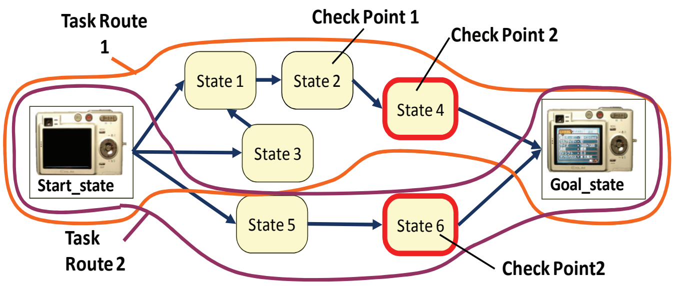


Figure 6. Test task model.

In the environment, we designed a "test task model" and make a logical link between the task model and the UI behaviour model to automate the usability evaluation. Figure 6 shows the test task model. A *task* consists of a start state, goal state and a list of *task route*s. And a *task route* consists of a list of *checkpoint*s. A checkpoint is a certain state where a correct sequence of UI operation must pass. A start state and a goal state refer to the *state* in the UI behaviour model.

Generally multiple correct operations of the UI exist to achieve a goal. So in the test task model, multiple task routes are allowed in one task. Moreover, lower and upper bounds for the number of input operations or an allowable elapsed time between every two neighbouring checkpoints are also defined. And if actual time of a subject's operation stays within a range between these bounds, the operation is judged to be correct. In this way, usability professionals can adjust a range of correct UI operations in the task when determining the number of error operations and the task completion.

We developed a tool where a usability professional can interactively set the tasks. To define the task, he/she has to only pick up the start state, goal state and checkpoints on the screen of the Visio. A short text indicating a goal of the task to the subjects during the test is also input. The defined tasks are exported to a XML document of the test task data.

Figure 7. 3D digital prototype simulation function and test task display function.

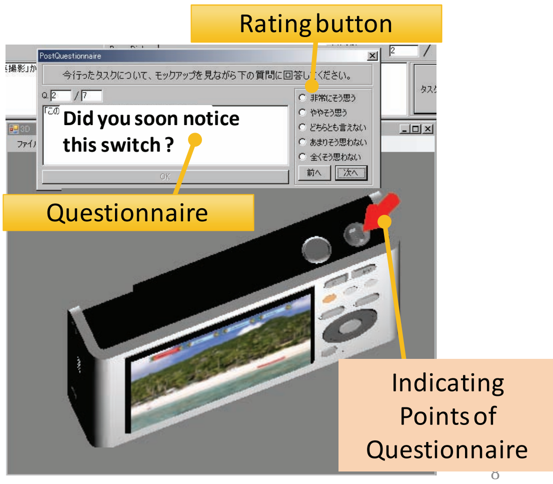


Figure 8. Digital questionnaire execution function.

4 TESTING FUNCTION

After making the logical links, the UI behavior model is read by the 3D digital prototype simulation function which is implemented by the Visual Basic, and the 3D CAD model is sent to the Virtool player. We build a special function in the Virtool player so that it can send and receive messages to/from the UI simulator using the inter-process communication. The simulator executes state-transition of UI in response to an incoming message, and generates another message to the player according to an action described in the behavior model. The message sent makes the status of UI on the 3D CAD model changed such that “another menu appears” and “an LED is turned on” etc. In this way, the working UI-operable 3D prototype is built.

Shown in Figure 7, at the beginning of every new test, the test task display function indicates a goal of each task of the test in the form of an imperative sentence. “Switch shooting mode from still to video” and “set the self-timer for 20sec” are typical examples of the goal. The goal is indicated on one window of the screen just above the 3D digital prototype. The test subject is asked to attain the indicated goal by operating the UI of the 3D digital prototype.

During the UI operation by a subject, the event logging function records an actual sequence of state-transitions caused by the subject’s operations on the digital prototype as a list of combinations of state, event, action and behavior together with their time stamps. The function outputs these data to an event log data file in the XML format. At the end of every test, the event logging function compares the actual sequence of state-transitions with all of the pre-defined task routes and allowable number of operations and elapsed time between checkpoints, and judges whether the operation of the subject is correct or not.

If the operation is judged to be wrong, a digital questionnaire is automatically indicated on another screen, and a portion on the 3D digital prototype related to the questionnaire is pointed by the digital questionnaire execution function as shown in Figure 8. The subject is asked to answer to the questionnaire. The questionnaire execution function sequentially indicates each item of the questionnaire with the portion indicated on the 3D digital prototype as shown in Figure 8. The subject is asked to answer to each item of the questionnaire, for example *“Did you soon notice this button?”*, by rating his/her impression in five grades; “*Strongly agree*”, “*Agree*”, “*Yes and No*”, “*Disagree*” and “Strongly disagree”. The subject inputs this evaluation by clicking one of the radio buttons placed on the indicated screen. The answer is automatically stored, in the system and the ones from many subjects are summarized to clarify what needs improvement in the design. and the answer is automatically stored and further analyzed to clarify causes of the wrong operations in the usability assessment function. The detail of this digital questionnaire is explained in the section 5.3.

5 USABILITY ASSESSMENT FUCNTION

5.1 User Performance Measures

The usability assessment function investigates the event log data by comparing it with the test task data and UI behavior model. The function outputs measures of usability assessment as a result of the analysis. The analysis process can be done automatically.

The test results analyzer compares the event log data from the subject’s operation with the test task data and UI behavior specification, and outputs measures of the user performances. We adopted the following three measures based on three basic notions of usability (effectiveness, efficiency and satisfaction) defined in [19]; 1) number of events inputted in each task and in each subject, 2) elapsed time in each task and in each subject, and 3) personal task achievement ratio.

5.2 Operational Log Analysis Chart

An actual sequence of operations by a subject is compared with the one of correct task routes defined in the test task data, and the result of the comparison is graphically displayed in the form of “operational log analysis chart” on the lower part of the screen.

Figure 9 shows the notation of this operational log analysis chart. Each rectangle shows a state, and a line between two rectangles does a transition between states. A left-most rectangle in the chart indicates a start state, and a right-most rectangle does a goal state. The upper most horizontal white

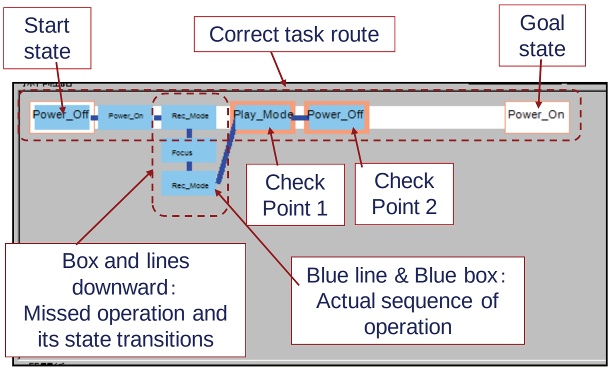


Figure 9. Operational log analysis chart.

straight line indicates transitions (behaviors) on a correct task route, and every rectangle with orange edges on this line except both ends corresponds to each checkpoint. While the blue rectangles and blue lines indicate actual operation sequence of the subject. If a subject does UI operations whose elapsed time or number of events between two neighboring check points exceeds the predefined bounds, the tool judges that a subject did a wrong operation on the UI, and draws additional blue rectangles and blue lines in downward direction corresponding to these wrong operations.

Therefore, as a depth of the chart becomes larger, the examiner of the user test can easily recognize that the subject did more missed operation in this task.

5.3 Digital Questionnaires

The operational log analysis chart can clarify particular states in the UI specification where many subjects did the wrong operations. However, the chart itself cannot provide enough information that enables a UI designer to identity the cause of the wrong operations and to redesign the UI specification in order to improve the user performance. To solve the problem, the digital questionnaire execution function is developed to analyze missed operations and to identify real cause of them. The structure of the digital questionnaires is built based on an extension of the cognitive walkthrough method which is dedicated by the HCI (Human Computer Interaction) model.

5.3.1 Cognitive Walkthrough

The cognitive walkthrough (CW) is a usability inspection method where analysts are asked to simulate the user's cognitive behavior and answer a series of evaluation questions for each step of a task [20]. It detects the usability problems in the UI design by presuming the cognitive behavior path which the expected users will take to accomplish given tasks. To presume the user's behavior path, the professionals themselves instead of the users answer the questionnaire which is built based on the behavioral model of the user in the cognitive science. Therefore the cognitive walkthrough is effective to clarify what is the cause of the wrong operations and what needs improvement in the UI design.

The cognitive walkthrough is one of the most appropriate usability evaluation methods for the initial design stage of UI

Table 1. Extended HCI model and the questionnaires.

Cognition Process of Extended HCI Model	Items of questionnaires based on Extended HCI [Hori & Kato 2007]	Items of questionnaires used in our system
Formation of Intension of manipulation	Does the user try to accomplish the correct action ?	Did you easily understand what you should do for the appliance by reading the task ?
Perception of objects	Can the user perceive the object to be manipulated ?	Did you soon notice this [*input element name*]?
Interpretation of objects	Can the user understand that the perceived object is the correct object ?	Did you soon understand that you should operate this [*input element name*] ?
Perception of actions	Can the user perceive his/her actions of manipulation ?	Did you soon understand how you should operate this [*input element name*] ? (by pushing, sliding etc.)
Interpretation of actions	Can the user come up with actions of manipulation which should be applied to the object ?	N.A.
Execution of actions	Can the user certainly execute the correct action?	N.A.
Perception of the effect	Can the user notice the change of the state ?	Did you soon notice that the state of this [output element name]changed by your operation?
Interpretation of the results	Can the user understand what state the system is after the state change ?	Did you easily understand how the state of the appliance changed as a result of the operation by observing the state change of [*input element name*] ?
Evaluation of the results	Can the user understand that he/she advances toward the solution of the task by observing the system state ?	Did you soon understand whether your operation is correct or not by observing the state change of [*input element name*] ?

development. However, the quality of the evaluation greatly depends on the knowledge of the professionals, and the method sometimes misses a part of the problems in the design if only the usability professionals execute the walkthrough. For eliminating the drawback, it is desirable that the end users are directly involved in the walkthrough in addition to the professionals.

However, the form of the questionnaires currently used in the walkthrough are built for the professionals and are very general and abstract; for example, "*Will the user associate the correct action with the effect to be achieved?*". These questions are difficult to answer properly unless one has expertise in cognitive science and/or usability evaluation. To that end, the questionnaire used in the improved walkthrough should be more specific so that end users can easily understand when the cognitive walkthrough is used along with the user test.

5.3.2 Digital Questionnaires

By considering the above discussion, we implemented a function of executing "digital questionnaires" in our testing functions to identity causes of the wrong operations and what needs improvement in the design based on answers returned from the users who use our UI-operable 3D digital prototype.

To construct the digital questionnaires, we first introduced the extended HCI (Human-Computer-Interaction) model. The extended HCI model [21] is an extension of the CW method whose questionnaire are formulated based on an extended model of Norman's HCI[22] that explicitly distinguishes between object and action, and perceiving and understanding. The questionnaires were used for the usability evaluation of the Web site. The questionnaires based on the extended HCI

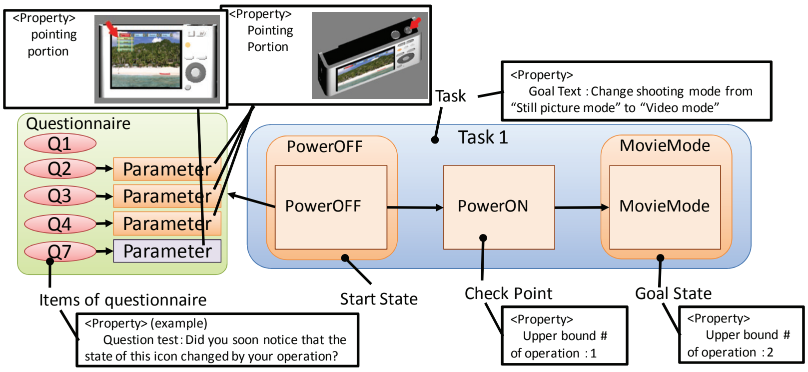


Figure 10. Modeling of the task and the questionnaire.

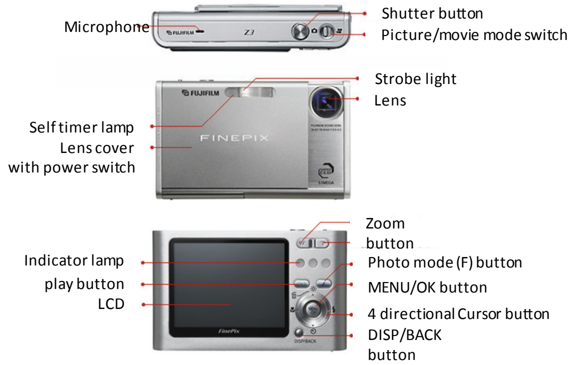


Figure 11. The appliance for the user test.

model are easier to understand for the end users as shown in Table 1.

The items in the questionnaire based on the extended HCI model still have abstract expressions, so we further make these items take more specific and concrete expressions to the user tests of information appliances so that the end users can understand them more easily on the digital prototype as shown in the Table 1. For example, an item in the questionnaire of the extended HCI model which examines perception of the object to be manipulated is expressed as "*Will users be able to perceive the object to be manipulated?*", and we changed it to more specific one "*Did you soon notice this button?*" when applying the questionnaire to the test of a digital camera.

Moreover, we also implemented an indicating function that automatically points to an actual 3D object corresponding to "*this button*" or "*here*" on the 3D digital prototype when indicating a certain item in the questionnaire on the screen as shown in Figure 8. These functions enable end users involved in the test to understand each item of the questionnaire more easily, and also enable usability engineers to save a quite bit of manpower for constructing the questionnaire in the system.

This proposed digital questionnaire enables many end users to take part in the cognitive walkthrough evaluation and to answer the questions by actually manipulating the 3D digital prototype whose UI can work as same as the final appliance does. This feature can greatly increase the reliability of the user test's results.

For defining the questionnaire, the usability professional assigns one questionnaire to a check point in the UI behavior model as shown in Figure 10. The professional also specifies a particular portion on a UI screen image or a part in the 3D model of the housing to be indicated on the 3D prototype. The standard template of the questionnaire is predefined as a stencil with standard properties in the Visio, and the engineer can past the stencil to the particular task which is graphically displayed in the Visio, and input the sentence of a question in the property value.

6 EXPERIMENTS OF USABILITY ASSESSMENT

6.1 Task Setting

Results of user tests using the UI operable 3D digital prototype (hereafter referred to "3D-DP"), a 2D UI software prototype (2D-DP) and a physical prototype were compared

Figure 12. 3D digital prototype (a) and 2D UI software prototype (b).

with each other to investigate the effectiveness of the 3D-DP. A compact digital camera (Fuji FinePix-Z1) on the market shown in Figure 11 was selected for a user test. We used the real camera for the test as a substitute of the physical prototype. The 2D-DP was modelled using Protobuilder [2] which is a commercial UI prototyping tool. In this tool, the simulation of UI is executed in 2 dimensional. Figure 12 shows the 3D-DP ((a)) and the 2D-DP ((b)).

In the user tests, these three types of prototypes (3D-DP, 2D-DP and the real camera) were operated by 37 subjects, and their test results were evaluated. We defined the following three kinds of tasks which consist of frequently-used operations of the digital camera;

- Task 1: Setting a self-timer to 2 sec

This task is to change a mode of shooting from manual shooting to self-timer, and to set the timer value to 2 seconds. To complete this task, the user first has to open the lens cover on the front side to turn on the power, then to flip the camera to operate several buttons on the back side.

- Task 2 : Switching picture/movie mode

This task is to switch the mode from picture mode (default setting) to movie mode and to enable shooting movies. To complete this task, the user has first to open the lens cover on the front side, to manipulate a picture/movie mode switch on the upper side, to operate some buttons on the back side and to make sure of icons indicated on the corner of the LCD screen. The user has to sequentially operate switches and buttons which are placed on multiple sides of the prototype in this task.

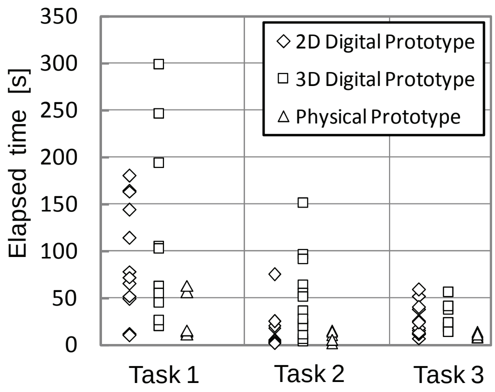


Figure 13. Elapsed times of the user test.

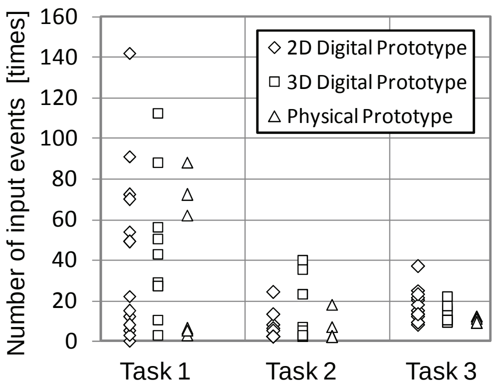


Figure 14. Numbers of input events of the user test.

- Task 3 : Changing a mode of scene selection

This task is to switch a mode of the scene selection. There are several modes in the list such as "portrait", "manual" and "scenery" etc. The task is to switch a mode from "manual" to "scenery". To complete this task, the user has to operate larger number of buttons only on the back side than the task 1 and 2 and to make sure of icons indicated on the corner of the LCD screen.

6.2 Comparison of Performance Measures depending on Type of Prototypes

As the measures of usability assessment, we adopted three measures; an elapsed time and the number of input events to complete the task.

Figure 13 shows a comparison of the elapsed time of each subject among the type of the prototypes. Figure 14 does the number of input events.

As shown in Figure 13, the average elapsed times of the 2D-DP and the 3D-DP are about four or five times as large as that of the physical prototype. And the variances of the elapsed times of these digital prototypes are much larger than that of the physical prototype. Especially, there is a considerable difference of elapsed time between the 3D-DP and the physical prototype. This is because the subjects must rotate, translate and scale the 3D-DP during executing the test by moving a mouse, and the move took extra operation time.

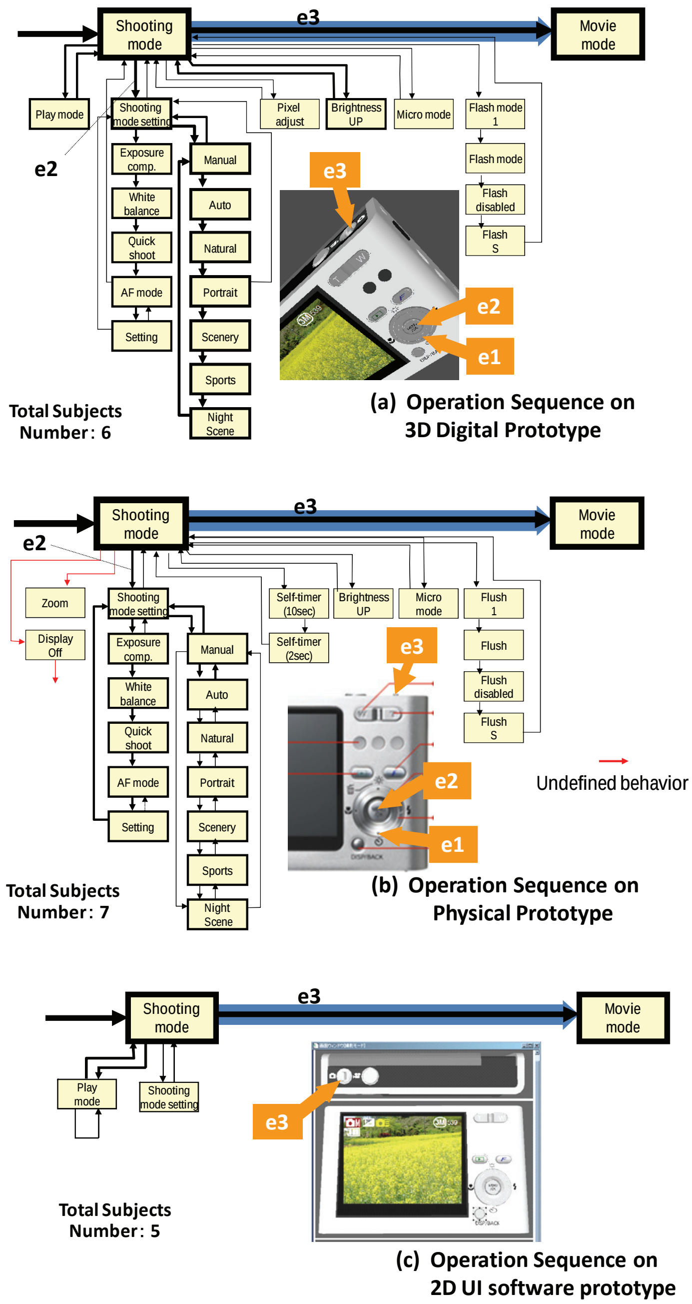


Figure 15. Summarized operation log analysis chart.

From this analysis, it is difficult to accurately evaluate the elapsed time of UI operation using either 2D-DP or 3D-DP.

On the contrary, as shown in Figure 14, as for the number of input events, the difference of their average and the variance among the types of the prototypes is relatively smaller than that of the elapsed time. Moreover the difference of the number of input events is not so significant between the 2D-DP and 3D-DP as that of the elapsed times.

However, only from these simple comparisons of the number of input events, it is impossible to decide that the patterns of the user's UI operation for the three tasks of the digital prototypes are similar to that of the physical prototype.

Therefore, we investigated the patterns of the UI operations including the missed one of all subjects in greater detail using the operational log analysis chart of all subjects. The result of the investigation is described in the next section.

6.3 Comparison of Operational Patterns

To investigate of the difference of operational patterns of the UI among the digital prototypes and the physical prototypes, we extracted an actual sequence of operations including missed operations done by each subject, and put the sequences of all subjects together in each type of prototype.

To analyze the summarized sequences of operations, they are schematically drawn as a "summarized operational log analysis chart" shown in Figure 15. This chart can be made by superimposing an operational log analysis chart of one subject onto ones of the other subjects. In this summarized chart, the notation of correct and missed operations is as same as the one in the personal version described in section 5.2. But the width of a line on the chart is promotional to the number of subjects who passed over the state-transition corresponding to the line. Therefore, more subjects passed over routes of operation are displayed as wider lines.

Figure 15 shows the summarized operational log analysis charts for the task 2 in case of the 3D-DP (Figure 15-(a)), the physical prototype (Figure 15-(b)) and the 2D-DP (Figure 15-(c)). Comparing Figure 15-(a) and Figure 15-(b), it is clear that the critical state where many subjects stepped to missed operations and the pattern of missed operations after the critical state in case of the 3D-DP are very similar to those of the physical prototype. Especially, the 3D-DP and the physical prototype were identical to each other in the critical state of "Shooting mode" where about a half of subjects stepped to the wrong ways. This is because the button for correct input (e1) is placed very close to the one for wrong input (e2) shown in Figure 15, and many subjects pushed the wrong button (e2) instead of the correct one (e1).

On the contrary, comparing the charts of the 3D-DP (Figure 15-(a)) and the physical prototype (Figure 15-(b)) with the one of the 2D-DP (Figure 15-(c)), the patterns of the UI operations are significantly different with each other. Most of the subjects did correct operations at the "Shooting mode" state on the 2D-DP, but many subjects did wrong operations on the 3D-DP and the physical functional prototype at the same state.

In order to complete the task 2 at the "Shooting mode" state, a small changeover switch (shown as "e3" in the pictures of Figure 15) must be operated. The switch changes the shooting mode from the picture mode to the movie mode, and is placed on the top side of the housing. However in the 3D-DP and the physical prototype, many subjects could not notice this small switch on the top side when they paid attention to the other buttons and the LCD display on the backside during the test.

On the other hand, as shown in the Figure 12-(b), in the 2D-DP, the top and the back side of the housing is displayed at the same time on one image, and the switch (e3) can be easily noticed by most of the subjects even if they pay attention to the other buttons and the LCDs on the backside.

Obviously from this result, in 2D-DPs, all buttons, switches and indicators which are originally placed on multiple sides of the physical prototype are simply displayed on a single screen for convenience. This simplification enables subjects to easily find indicators and to operate buttons faster than in case of the physical prototype, and also enables subjects to complete the task more easily than in the real operating situation. Therefore, in a user test using 2D-DP, the UI designers may overlook the problem of the usability of the UI where many subjects make mistakes in the operation.

6.4 Improvement of UI design based on Digital Questionnaires

Next, we identified the cause of the wrong operations of the subjects, and improved the UI design based on the he summarized operational log analysis chart for the task 1. The summarized chart for the task 1 shows the facts that;

- At the "Rec_Mode" state, many users took the wrong path aiming to the "Shooting mode" state instead of the correct path to the "Time_2sec" state, and
- Even at the "Timer_2sec" state which is a goal of the task, many users still continue operating the UI.

So we examined the answers from the subjects for the digital questionnaires which were indicated at the "Rec_Mode" and the "Time_2sec" state. As shown in the Figure 16, the answers at the "Rec_Mode" suggest that many subjects noticed existence of the object to be manipulated (a down cursor button), but did not notice that they could complete the task by manipulating this object. On the other hand, the answers at the "Timer_2sec" state suggest that the subjects could notice the change of the system status caused from their operations but could not know whether they correctly accomplished the task or not. This means that a small white icon displayed on the LCD shown in Figure 16 could be noticed by many subjects, but did not enable them to notice that the self-timer settings had already been set to 2 sec. From these answers, we finally identified that shape and color of the timer icon in current design need to be improved.

Based on the suggestion, as shown in the Figure 17, we redesigned shape and color of the time icon to the new ones so that the background color becomes conspicuous and timer value is explicitly displayed. An additional test was executed

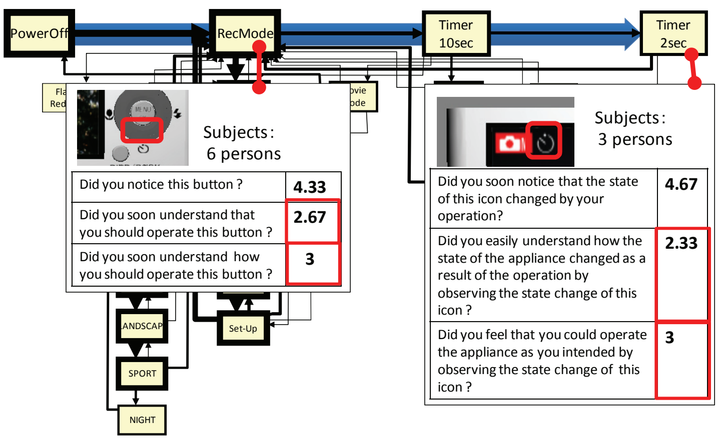
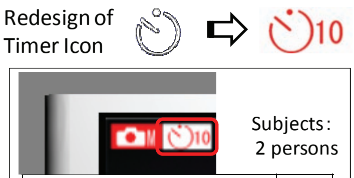


Figure 16. Average rating for the digital questionnaires for task 2 in the original UI design.



Did you soon notice that the state of this icon changed by your operation?	4
Did you easily understand how the state of the appliance changed as a result of the operation by observing the state change of this icon ?	4
Did you feel that you could operate the appliance as you intended by observing the state change of this icon ?	3.5

Figure 17. Average rating for the digital questionnaires for task 2 in the modified UI design.

using the 3D-digital prototype with the redesigned icon. The result of the test showed that two of four subjects could complete the task 2 without wrong operations. And the rest could also complete the task, although they took some wrong operations.

The results shows that the digital questionnaire is effective for identifying the problem and for clarifying what needs improvement in the UI design even if we use the UI-operable 3D digital prototype in the user test of information appliances.

7 CONCLUDING REMARKS

A computer-supported environment for testing and usability assessment for human centered-design of information appliances was proposed. In the environment, UI-operable 3D digital prototypes can be designed and used for user tests instead of physical prototypes, and the test results can be automatically analyzed. A function of graphically displaying user's operational history helps the designers identify which portions in the UI specification induce wrong operations of users. A function of indicating digital questionnaire based on cognitive walkthrough method also enables them to reveal causes of the wrong operations and to clarify point of redesign.

From the user test results using the UI-operable 3D digital prototype and physical prototype, it was shown that the UI operable 3D digital prototype could replace the physical functional prototypes in the usability assessment of information appliances. The results also showed that the digital questionnaire along with the 3D digital prototype is very effective for identifying the problem and for clarifying what needs improvement in the UI design.

In our future study, similar experimental studies have to be executed for broader range of information appliances to verify the effectiveness of UI operable 3D digital prototype. The cost-effect analysis for the digital prototype should be also done precisely and quantitatively.

REFERENCES

[1] ISO13407, 1999, "Human-centred design processes for interactive systems".
[2] Protobuilder, http://www.gaio.co.jp/product/dev_tools/pdt_protobuilder.html.
[3] RAPID PLUS, http://www.e-sim.com/products/rapid_doc/index-h.htm.
[4] Lin, J., et al., 2000,"DENIM: Finding a tighter fit between tools and practice for web site design", *Proceedings of Human Factors in Computing Systems: CHI 2000*, Vol.2, No.1, pp.510-517.
[5] Landay, J.A. et al., 2001,"Sketching Interfaces: Toward more human interface design", *IEEE Computer*, Vol.34, No.3, pp.56-64.
[6] Avrahami, D., et al.,2002,"Forming Interactivity: A Tool for Rapid Prototyping of Physical Interactive Products", *Proceedings of the ACM Symposium on Designing Interactive Systems*, pp.141-146.
[7] Lee, K.P., 2003,"User-Participatory Testing Using Web", *Proceedings of HCII 2003*
[8] Viewpoint, http://www.viewpoint.com/pub/technology/
[9] VRML97, 2002, "Functional specification and VRML97 External Authoring Interface (EAI)", *ISO/IEC 14772-1:1997 and ISO/IEC 14772-2*
[10] Kuutti,K., et. al., 2001,"Virtual prototypes in usability testing", *Proceedings of the 34th Hawaii International Conference on System Sciences*, Vol.5.
[11] Bruno, F., et al., 2005, "A new approach to participatory design: usability tests in virtual environment", *Research in Interactive Design*, Vol.1, Springer, VC200560.
[12] Verlindern, J., et al, 2004, "Qualitative comparison of Virtual and Augmented Prototyping of Handheld Products", *Proc. of International Design Conferences*, pp.533-538.
[13] Nam,T-J., 2005, "Sketch-Based Rapid Prototyping Platform for Hardware-Software Integrated Interactive Products", *Proc. of CHI'05*, pp.1689-1692.
[14] Takahashi, H., et al., 2007, "Augmented Reality System for Development of Handy Information Device with Tangible Interface", *Lecture Notes on Computer Science*, Vol. 4563, pp.564-573.
[15] Aoyama,H. et al., 2006, "Development of system using mixed reality technology for evaluating designability and operability of product", *Research in Interactive Design*, Vol.2, Springer, WoIM2006188.
[16] Horrocks I., 1998, *Constructing the User interface with Statecharts*, Addison-Wesley.
[17] Virtools: www.virtools.com
[18] 3D XML: www.3ds.com/3dxml.
[19] ISO9241-11,1998,"Ergonomic requirements for office work with visual display terminals (VDTs) – Part 11: Guidance on usability"
[20] Polson, P., G., Lewis, C., Rieman, J. and Wharton, C.,1992,"Cognitive walkthroughs: a method for theory-based evaluation of user interfaces", *International journal of Man-Machine Studies*, Vol.36, pp.71-73.
[21] Hori, M. and Kato, T., 2007, "A Modification of the Cognitive Walkthrough Based on an Extended Model of Human-Computer Interaction (in Japanese)", *Trans. Information Processing Society Japan*, Vol.48, No.3, pp.1071-1084.
[22] Norman, D. A.,1986, "Cognitive engineering" In D. A. Norman and S. W. Draper (Eds.), *User Centered Systems Design: New Perspectives in Human-Computer Interaction*, pp.31-61, Hillsdale, NJ: Lawrence Erbaum Associates.