Differentiation of Input-Output Relations to Facilitate User's Correct Awareness of Operating Mode of Automated Control System

Yukio Horiguchi, Ryuichi Fukuju and Tetsuo Sawaragi

Abstract— **This study investigates a practical guideline on human-machine interaction design to facilitate human operator's correct awareness of the actual operating state of an automated control system in their joint activity. Based on the comprehension that a human being is a "proactive" agent who would affect the external world to obtain new cues to foster its understandings, the mapping structures between the human operator's input operations and the machine's response behaviors, i.e., the *input-output relations*, may be one of the dominant characters that can explain the operator's awareness of the machine's operating state. From this perspective, we speculate that different control modes with similar input-output relations should be easily mixed up with one another since interactions mediated by those relations would intimate a same mode. This hypothesis was verified through an experiment using a driving simulator that examined drivers on their recognitions of the operating mode of ACC (Adaptive Cruise Control) while driving with it. Another experiment confirmed that a human-machine interaction design to differentiate modes in their input-output relations could successfully reduce mode confusion errors.**

I. INTRODUCTION

Computerized systems performing complicated work operations consist of lots of digitized states and transition rules as the internal mechanisms to control their behaviors [1]. "Modes" represent that interpretation of a sequence of human actions by those systems is *variant* depending on the situation, and thus they are a significant source of confusions and thus errors since they introduce unnecessary restrictions and complexities into human-machine interfaces [2]. Although many problems and tragedies modes are involved with have been widely recognized [1], [3], elimination of modes, which is expected as the best way to prevent those troubles, is usually improbable. An alternative means is to prepare some effective feedback information about the operating state of the system because *mode errors* [4], [5] stem from the user's inappropriate analysis of the situation. To make automated control systems effective 'team players' in a human-machine joint activity, it is required for them to "make pertinent aspects of their status and intentions obvious to their teammates" [6]. As far as automation with multiple modes, the mode being selected for performance is one of the essential part of such information, and thus it should be communicated to and shared with the human operators for certain; otherwise the disagreement between the operators' awareness and the actual mode would cause various unexpected events that should demand superfluous cognitive resources of the people involved [7].

Y. Horiguchi and T. Sawaragi are with Department of Mechanical Engineering and Science, Graduate School of Engineering, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, Japan {horiguchi & sawaragi}@me.kyoto-u.ac.jp

R. Fukuju was with the same affiliation as the other two authors when he engaged in this work, but he is currently with Toyota Motor Corporation

To address this design issue of effective "communication" modalities, we have to understand what kind of properties characterize our awareness of modes well. In this respect, we place a significance on those information channels closely associated with user actions, by virtue of "proactiveness" of users who would take *proactive* actions to construct the appropriate interpretation on their situation [14]–[16]. Accordingly, response behaviors of the mechanical system to a particular sequence of user operations should acquire more importance in their communications. The term *input-output relation* (of the system from the user's point of view) is here intended to denote the mapping structure between user's input actions and machine's response behaviors. With this mapping structure employed on its theoretical basis, a comprehensible guidline on human-machine interaction design is proposed here, with a simple estimation method of possible confusions the users may make on the current mode of automated control systems they are required to work with. Our basic idea is that as the users depend on the system's response behaviors to some extent as valuable cues to sense its state, different modes which have the same input-output relations are hard to be distinguished by them. Such behaviors do not differentiate those modes in their available feedback information. It can be considered that the modes which share such properties as likely to be mixed up with one another and thereby easily confusing the users.

The idea mentioned above is validated through an experiment using a driving simulator with Adaptive Cruise Control (ACC) implemented, in which drivers are queried as to the current mode of the ACC system to collect the probability distributions of mode confusion to be compared with what has been estimated. In addition, it is also examined whether purposefully designed input-output relations can contribute to the improvements of the drivers' awareness of situation (i.e., the system's mode) through another experiment.

II. BASIC IDEAS

A. Definition of Input-Output Relation

Visible structures of a device, composing its *system image* [5], have a strong influence on the perceiver's comprehension of its functions. All the structures characteristic of the system are, however, not on the surface in general, and some portion of the important information may be hidden. Therefore, people make good use of interaction with their work environment to obtain new cues for certain recognition [8]–[10]: they can proactively work on the object so as to uncover something hidden from the responses induced by their actions (e.g., shaking a box provides the practitioner with some new information on what is inside it); or, they can bring and implement some regularities in their work environment to make up alternative resources to the invisible. In those contexts, what is fed back to the actor in response to his action holds a great significance for his interpretation of the surrounding and ongoing situation.

In a human-machine joint activity, it is not the user's principal task to administrate and keep track of the machine's mode. They are the additional, derived from a compelling occasion that he has to work together with the machine with multiple modes in it. Accordingly, they might become competitors of the user's principal tasks in his cognitive resources such as sensory channels. Even if the ongoing status of the system is correctly presented in the display unit, the information will neither be delivered to nor exploited enough by the user when some sensory feedback on modes compete with those task-specific resources [11]. This has directed our attention to response behaviors of the computerized system to a particular sequence of user operations, which are *manifest* resources for situation awareness because he executes those actions with a particular intent and thus his attention naturally covers the area of the sensory feedbacks. Here the term *input-output relation* is intended to denote a mapping structure between user's input actions and machine's response behaviors, and we try to employ this mapping structure on a conceptual basis of a new evaluation scheme of human-machine interfaces to facilitate the users correctly aware of the system's modes.

Meanwhile, mapping structures inducing any mode transactions are not regarded as *input-output relations* because they are not direct sources of information about the ongoing state of mechanical systems. Interaction resulting from such mapping structures tells only what the "previous" mode is. Just user operations not changing properties of the system behavior are intended.

B. Estimation Method of Possible Mode Confusion

The estimation method proposed here employs the degree of similarity in input-output relations of a mechanical system on the possibility of mode confusions, and it consists of the following processes:

1) At the level of mechanical behaviors the users can distinguish, all the relevant input-output relations implemented in the target system are listed.
2) All the modes of the system are represented in a vector form, i.e., *mode vectors*, whose components denote whether or not individual options of the input-output relations listed above are effective in each mode.
3) Distances among the mode vectors, i.e., the inter-mode distances, are calculated as representing the degrees of dissimilarity among the modes.

Fig. 1. The driving simulator and the button controllers to manipulate the ACC system.

III. Experiment of Driver's Awareness of ACC Modes

The proposed model was validated through an experiment using a simplified driving simulator in which Adaptive Cruise Control (ACC) was implemented as an automated control system. In the experiments, the driving simulation is frozen at selected times, and drivers were queried as to the current mode of the ACC system to collect the probability distributions of mode confusion in their driving.

A. Driving Simulator with ACC Function

Fig. 1 shows the driving simulator used to the experiments, which employs Logicool GT FORCE Pro as the steering wheel controller for driving. Four different button controls mounted inside the wheel are the means to manipulate the ACC behaviors.

One of the basic functions of ACC is to drive the car precisely at the speed the driver has set. But, while another car is detected in front of it, the system tries to control the own car to follow that lead car as keeping a safe distance between them by adjusting the traveling speed appropriately. In cases where the driver wants more speed, he can override the automatic control by footing hard the gas pedal. These intelligent behaviors of the car are realized with various control modes and transitions among them. Fig. 2 illustrates all of the modes and transition conditions in the ACC system implemented in the driving simulator. In this *machine model* [1], the directed links in full line represent the mode transitions the driver can initiate by himself while the broken lines represent the automatic transitions the ACC system covertly activates after its own discretion on the driving situation. The labels attached to these links explain the conditional events for the mode transitions.

There are six different control modes included in this ACC system, i.e., idle, armed, canceled, override, constant-speed and car-following, all of which are hierarchically organized in terms of common transition events. The behaviors

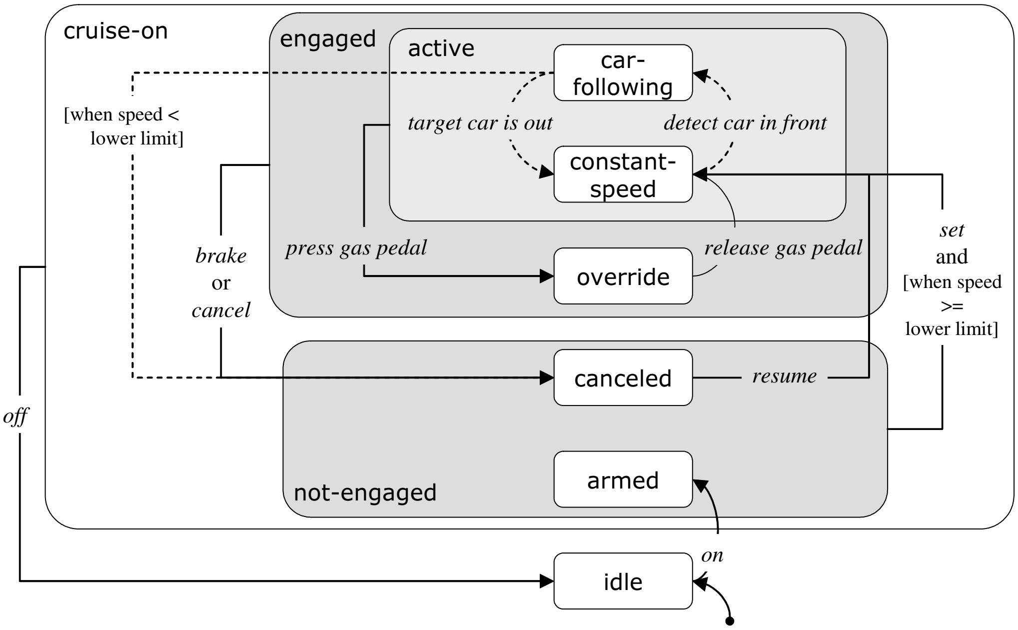

Fig. 2. The modes and their transitions constituting the ACC system implemented in the driving simulator.

of these individual modes are summarized as follows:

- Idle is the state where the cruise control is not employed for use, and pressing the "on" button will arm the ACC system.
- The system in armed is waiting for the driver's cue to activate the cruise control. When the speed of the own car is faster than or equal to 30km/h (corresponding to the lower limit of the cruise speed for automatic control), the "set" button is effective to take the car to constant-speed immediately. Its cruise speed is set to the vehicle speed at the *set* event.
- The car in constant-speed drives precisely at the set speed. The driver can change the cruise speed by pressing the "accelerate" and "coast" buttons while the ACC system is in engaged. When the system detects another car in front of it, which is traveling slower than its cruise speed, this car will be locked on to (i.e., the lead car) for the car-following mode.
- The cruise control in car-following tries to keep a safe distance between the two cars. Once the lead car gets out of its vigilance area, the system unlocks the car and then goes back to constant-speed.
- Whenever the driver wants more speed while ACC is active (i.e., in constant-speed or car-following), he can override the automatic control by footing hard the gas pedal. If he releases the gas pedal, the ACC system will become active to be in constant-speed again.
- While in engaged, pressing the brake pedal or the "cancel" button will take the system to canceled. This mode is almost same with armed but different in that the "resume" button is effective only in the former, which can re-activate the cruise control with the previously set speed. By the condition of [when speed < lower limit], ACC will be canceled from car-following automatically.
- Regardless of where the system is, the "off" button will always make it idle.

Fig. 3. The indicators on the state of the ACC system.

TABLE I
THE WAY TO INDICATE THE OPERATING STATE OF THE ACC SYSTEM

Mode	Indicators
idle	Nothing displayed
armed	Car-icon [blue]
canceled	Car-icon [blue] and cruise-speed
constant-speed	Car-icon [yellow] and cruise-speed
car-following	Car-icon [yellow], cruise-speed and lead-car
override	Car-icon [red] and cruise-speed

The ongoing state information of the ACC system, such as the current mode and the reference values for automatic control, is always available through several indicators displayed in the instrument panel (Fig. 3). As listed in Table I, the

$$
\begin{aligned}
&\qquad\qquad\quad\;\; ① \quad ② \quad ③ \quad ④ \\
\mathit{Mode}[\textsf{idle}] &= {}^{T}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1) \\
\mathit{Mode}[\textsf{armed}] &= {}^{T}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1) \\
\mathit{Mode}[\textsf{canceled}] &= {}^{T}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1) \\
\mathit{Mode}[\textsf{constant-speed}] &= {}^{T}(0\ 1\ 0\ 1\ 1\ 0\ 1\ 0) \\
\mathit{Mode}[\textsf{car-following}] &= {}^{T}(0\ 1\ 0\ 1\ 1\ 0\ 1\ 0) \\
\mathit{Mode}[\textsf{override}] &= {}^{T}(1\ 0\ 1\ 0\ 1\ 0\ 1\ 0)
\end{aligned}
$$

Fig. 4. Definition of the mode vectors for the ACC system: the boxes with circled numbers represent the corresponding options in the input-output relations involved.

TABLE II

EUCLIDEAN DISTANCES AMONG THE MODE VECTORS, I.E., THE *inter-mode distances*.

	idle	armed	canceled	constant-speed	car-following
armed	**0**				
canceled	**0**	**0**			
constant-speed	2.83	2.83	2.83		
car-following	2.83	2.83	2.83	**0**	
override	2	2	2	2	2

color of a car-shaped icon (car-icon), digital numbers lighted to represent the set speed (cruise-speed), and bar icons to indicate a capture of a lead car (lead-car) are combined to express the different control modes correctly.

B. How to Encode Modes into Vectors

All the modes of the ACC system were encoded into vectors (i.e., *mode vectors*) that are represented by 0s and 1s. Each component of the mode vectors describes whether or not a particular behavior will be made by the system in response to an operation given by the user. Fig. 4 lists all the vectors to represent the modes in Fig. 2. The followings are the four different input-output relations to be considered here:

① Which is the response behavior of the system to the driver's *footing the gas pedal*, accelerating the vehicle or not?

② Which is the response behavior of the system to the driver's *releasing the gas pedal*, decelerating the vehicle or not?

③ Which is the response behavior of the system to the driver's *pressing the "accelerate" button*, incrementing the set speed or not?

④ Which is the response behavior of the system to the driver's *pressing the "coast" button*, decrementing the set speed or not?

All the alternatives described above are represented by either ${}^{T}(1\ 0)$ for an affirmative option or ${}^{T}(0\ 1)$ for a dismissive option.

TABLE III

RESULTANT PROBABILITIES (%) OF MODE CONFUSIONS.

	idle	armed	canceled	constant-speed	car-following
armed	**8.3**				
canceled	**6.9**	**12.2**			
constant-speed	0	1.0	**6.3**		
car-following	0	0	1.0	**12.0**	
override	0	4.1	4.3	4.3	0

Table II presents the Euclidean distances among the mode vectors, i.e., the *inter-mode distances*. Based on the hypothesis that modes with same input-output relations are easily mixed up with one another, confusions in a group of modes whose inter-mode distances are zero are expected to be made at high frequencies, such as {idle, armed, canceled} and {constant-speed, car-following}.

C. Experimental Setup

In the experiments, test subjects drove a car on the virtual urban roads in simulation. Each driver performed a ten-minute drive with the ACC system along the specified course including many traffic lights. So as for the drivers to make use of the ACC functions as much as possible, some additional rules were imposed to their driving (e.g., the ACC should be turned *off* when stopping for a red light). During a ten-minute drive, several intermittent breaks intervened minutely, in which the simulation was frozen for about three seconds. At that time, the display screen was blanked, and then the drivers were queried as to which was the current mode of the system they guessed. As well as the individual answer to the query, the actual mode of the ACC system, the previous adjacent mode and transition event, and the reference values for the automatic control (e.g., the set speed) were logged at every time.

Before their main tests, all the subjects had been instructed on the modes and the transition events of the ACC system as well as how to use the system. Another ten-minute drive with no interventions was prepared for their rehearsal runs.

D. Results

Three hundreds and three sets of test data were acquired from the experiment with 35 test subjects, and the total percent error rate in their answers was 19.5% (59 failure cases). Table III shows the resultant probabilities of mode confusion organized for all the combinations of modes. This result confirmed a decided tendency that all the combinations with no inter-mode distances scored higher frequency of confusions than others. As to these two different variables, i.e., the inter-mode distance and the probability of mode confusion, the correlation coefficient between them are calculated from the variable values in Table II and III, and it is -0.83 as indicating a strongly negative correlation. These

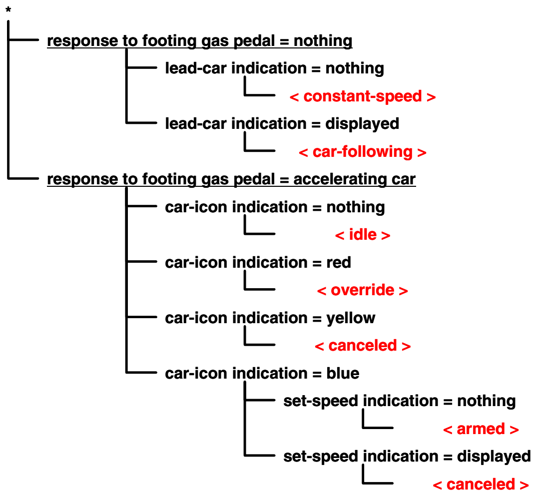

Fig. 5. Decision tree generated by C4.5 algorithm to explain the judgments made by the test subjects on mode of the ACC system.

results prove the validity of our hypothesis and estimation method on mode confusion.

In addition to this comparison, we applied C4.5 algorithm [13] to the case data of all the judgments made by the subjects. The purpose of this data processing is to generate a rational explanation of their judgments in terms of information theory. The class of the data corresponds to the mode the subjects had answered while the attributes relate to the input-output relations and the display indicators as follows.

- response to footing gas pedal: nothing or accelerating
- response to releasing gas pedal: nothing or decelerating
- response to resume/accelerate: nothing or set-speed up
- response to set/coast: nothing or set-speed down
- set-speed indication: nothing or displayed
- car-icon indication: nothing, blue, red, or yellow
- lead-car indication: nothing or displayed

Fig. 5 shows the decision tree generated by C4.5 algorithm. What is interesting here is that the judgment on the system's response behavior to footing gas pedal, i.e. the input-output relation ①, appears at the root of this decision tree. This result explains of the subjects' awareness of mode strongly affected by this property of the interface to the automated system. It also suggests that the degree of the effect onto the driver's awareness should vary among the input-output relations implemented in the experimental system.

On the other hand, confusions between constant-speed and canceled in Table III can not be explained in terms of their inter-mode distance. Our prospect on this phenomenon focuses on the drivers' awareness of their own *brake* operations. These two modes are connected in part through the *brake* event, that is, the ACC system in constant-speed will go into canceled after footing the brake pedal. Fixed-based driving simulators can not provide the drivers with the feeling of speed, and thereby make it harder for them to recognize their own brake operations. We consider this

$$
\begin{array}{rl}
 & \quad\;\; ① \quad\; ② \quad\; ③ \quad\; ④ \quad\; ⑤ \\
Mode[\mathsf{idle}] = & {}^{\mathrm{T}}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1) \\
Mode[\mathsf{armed}] = & {}^{\mathrm{T}}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1) \\
Mode[\mathsf{canceled}] = & {}^{\mathrm{T}}(1\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 1) \\
Mode[\mathsf{constant\text{-}speed}] = & {}^{\mathrm{T}}(0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0) \\
Mode[\mathsf{car\text{-}following}] = & {}^{\mathrm{T}}(0\ 1\ 0\ 1\ 1\ 0\ 1\ 0\ 0\ 1) \\
Mode[\mathsf{override}] = & {}^{\mathrm{T}}(1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 1)
\end{array}
$$

Fig. 6. Definition of the mode vectors for the ACC system with the modified input-output relations.

kind of uncertainty in evaluating their own behaviors as one of important causes of errors in discriminating these two different modes. In fact, there were 7 cases out of the total of 9 confusions between constant-speed and canceled which had the *brake* as their previous transition events.

IV. Improving Driver's Awareness of Modes by Modifying Input-Output Relations

The result of the previous experiment confirmed a considerable effect of the input-output relations of a target system on our recognition of its control mode. Even if the system's mode is correctly represented in the display unit, that information will neither be delivered to nor utilized enough by the user, especially in the case where it competes in cognitive resources with his primary task (e.g., the visual channel already busy for driving). In relation to this issue, it is examined here whether purposefully designed input-output relations can contribute to the improvements of the drivers' situation awareness.

The target problem is set to eliminate the mode confusion between constant-speed and car-following, which had the second highest probability of occurrence as already shown in Table III. It is suggested by the proposed method to broaden the distance between these two different mode vectors. For this purpose, a new input-output relation should be introduced in addition to the alternatives from ① to ④. As a new option, the following behavioral difference was introduced by applying a function of the steering wheel controller to generate force feedback effect.

⑤ Which is the strength of the reactive force the driver feels when *turning the wheel* slightly, hard one or soft one?

The strength of the reactive force that the driver feels when he is operating the steering wheel is variable depending on the current mode of the ACC system. The option ⑤ modifies the mode vectors as shown in Fig. 6, and the distance between constant-speed and car-following becomes 1 from 0 (see Table IV).

Two hundreds and thirteen sets of test data were acquired from the second experiment with 17 subjects in the same task condition as the previous experiment. As the result, 13.5% of error rate (29 failure cases) was scored in total in the subjects' answers of modes recognized. Table V shows the resultant probabilities of mode confusions disaggregated.

TABLE IV
MODIFIED INTER-MODE DISTANCES.

armed	**0**				
canceled	**0**	**0**			
constant-speed	3	3	3		
car-following	2.83	2.83	2.83	**1**	
override	2	2	2	2	2
	idle	armed	canceled	constant-speed	car-following

TABLE V
RESULTANT PROBABILITIES (%) OF MODE CONFUSIONS IN THE CONDITION OF THE MODIFIED INPUT-OUTPUT RELATIONS.

armed	**8.3**				
canceled	**6.9**	**10.9**			
constant-speed	0	0	**4.2**		
car-following	0	0	3.1	**2.5**	
override	0	0	4.3	4.3	0
	idle	Armed	canceled	constant-speed	car-following

As compared to Table III, it is obvious that the performance of mode discrimination between constant-speed and car-following was remarkably improved as the error rate decreased from 12.0% to 2.5%. This result confirms that input-output relations purposefully designed to increase the inter-mode distances can effectively support the users' awareness of the state of the automation thereby to reduce the probabilities of mode confusions.

V. CONCLUSION

This paper has proposed a new method to estimate possible mode confusions a human user may make when he is working with an automated control system which has multiple control modes. Focusing on the awareness improved through interaction, input-output relations of the system from the user's point of view were introduced as the conceptual basis. Based on this idea, all the modes are encoded into vector forms from the perspective of their input-output relations, and then the distances among the vectors are utilized as the indexes to estimate the likelihoods of mode confusions.

The proposed method was validated through the experiments using a driving simulator with ACC implemented. The ACC system has 6 different modes and a complex transition structure among them, and the drivers were queried as to which is the current mode of the system during their driving. The resultant probability distributions of mode confusion were compared with what had been estimated by the proposed method, successfully proving the validity of the estimation method and its basic idea. Another experiment successfully confirmed purposefully designed input-output relations can contribute to the improvements of the drivers' awareness of modes.

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REFERENCES

[1] Degani, A., *Taming HAL: Designing Interfaces Beyond 2001*; Palgrave Macmillan, 2004.

[2] Raskin, J., *The Humain Interface: New Directions for Designing Interactive Systems*; ACM Press, 2000.

[3] Sarter, N.B., Woods, D.D. and Billings, C.E., "Automation Surprises," (G. Salvendy, Ed.) *Handbook of Human Factors & Ergonomics*, Wiley, 1997.

[4] Norman, D.A., "Categorization of Action Slips," *Psychological Review*, Vol. 88, 1981, pp. 1–15.

[5] Norman, D.A., *The Psychology of Everyday Things*, Basic Books, 1988.

[6] Klein, G., Woods, D.D., Bradshaw, J.M., Hoffman, R.R. and Feltovich, P.J., "Ten Challenges for Making Automation a "Team Player" in Joint Human-Agent Activity," *IEEE Intelligent Systems*, Vol. 19, No. 6, 2004, pp. 91–95.

[7] Woods, D.D. and Patterson, E.S., "How Unexpected Events Produce an Escalation of Cognitive and Coordinative Demantds," (P.A. Hancock and P.A. Desmond, Eds.) *Stress, Workload and Fatigue*, Lawrence Erlbaum Associates Inc., 2000.

[8] Kirsh, D. and Maglio, P.P., "On Distinguishing Epistemic from Pragmatic Action," *Cognitive Science*, Vol. 18, 1994, pp. 513–549.

[9] Kirsh, D., "The Intelligent Use of Space," *Artificial Intelligence*, Vol. 73, 1995, pp. 31–68.

[10] Kirlik, A., "The Ecological Expert: Acting to Create Information to Guide Action," *Proceedings of Fourth Symposium on Human Interaction with Complex Systems*, 1998, pp. 15–27.

[11] Sellen, A.J., Kurtenbach, G.P. and Buxton, W.A.S., "The Prevention of Mode Errors through Sensory Feedback," *Human Computer Interaction*, Vol. 7, No. 2, 1992, pp. 141–164.

[12] Endsley, M.R., "Direct Measurement of Situation Awareness: Validity and Use of SAGAT," (Mica R. Endsley and Daniel J. Garland, Eds) *Situation Awareness Analysis and Measurement*, Lawrence Erlbaum Associates, 2000, pp. 147–173.

[13] Quinlan, J. R., *C4.5: Programs for Machine Learning*, Morgan Kaufmann Publishers, 1993.

[14] Horiguchi, Y. and Sawaragi, T., "Design of Shared Communicational Modality for Naturalistic Human-Robot Collaboration in Teleoperating Environment," *Proceedings of The Fifth International Conference on Knowledge-Based Intelligent Information Engineering Systems & Allied Technologies*, 2001, pp. 854–858.

[15] Horiguchi, Y. and Sawaragi, T., "Naturalistic Human-Robot Collaboration Mediated by Shared Communicational Modality in Teleoperation System," *Proceedings of The Sixth International Computer Science Conference on Active Media Technology 2001*, 2001, pp. 24–35.

[16] Horiguchi, Y., *Design of Co-Adaptive Interface System for Supporting Joint Task by Human and Machine Autonomies*, Ph.D Thesis of Kyoto University, 2005.