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## Consideration of skill improvement on remote control by wireless mobile robot

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### Abstract

This paper considers the quantification of skill progress in order to measure a remote operational skill online. This method is very important to make a support system adapting to operator. This support system is called as Human Adaptive Mechatronics (HAM) System, and HAM was done as Center of excellent(COE) project promoted by Japan Society for the Promotion of Science.

Many approaches exist to attain this goal and human skill level depends on many factors such as condition, equipment and environment of operation. Therefore we first pay attention to delay time during the machine operation in order to aim at the acquisition of evaluation quantity on state of skill and we examine relationship between skill level and input/output delay time. For this analysis, we utilize a tele operated robot system to obtain data. We experiment with a simple task in which we operate a wireless mobile robot(WMR) with pinhole camera in order to reach the goal through the two check points. It is necessary that human operates machine by using image information from display monitor in the tele operation system. We analyze the correlation between operation date and WMR position based on these data. Next, we especially investigate a change of operational skill progress on curve path using data measured by simple task and analyze the data because curve control of tele operating robot only based on display is difficult to the operation in straight line path for human. For this purpose, we identified a delay of response with operation data based on ARX (AutoRegressive model with eXogenous input) model by using position and attitude data of the robot and then we analyze relationship and progress of skill level by using these data. A system operated by human can be considered as a closed loop system, and human can be regarded as controller in the system(3; 4). Furthermore, we classify operators into groups by correlation between delay time and total time of operation and area of stability poles and total time. And we analyze data by data of distance, total time and curvature and decide effective and important factors to skill level for each group. As these results, we consider skill parameter of tele-operations.

### 1. Introduction

We are living a comfortable life by using various gadgets of mechatronics products now. We use many machines in our work or life today and we usually operate the machines. There is not only simple machine system, such as cleaning machine, but also complex machine system, e.g. airplane system. Mechatronics is a key technology in our today's society. Mechatronics

is known as the discipline integrated by mechanical, electrical and information technology and has been used to produce advanced artifacts used in modern society. The main issue of the mechatronics, however, is how to control the machine effectively. Mechatronics has been developing to design integrated systems that consider human and environment, recently. It is easy for me to manipulate the simple machine but it is difficult that we use a complex machine system safely. It is usually demanded that human learn an operation of the machine. Long term and much effort are needed to become skilled for human in many cases. The reason is that the operation system of the machine is not easy for human. Then an error motion causes unstable action of system even if the system with controller is stable(5). One of the reasons is that the machine does not adjust itself regardless of the human skill. That is, the ordinary machines were not designed to assist human to improve one's skill. Human can adapt to machine, sometimes make trouble in human-machine systems. To improve this wrong relation, mechatronics should pay attention to human skill level and adapt to the operator's skill ability assisting the operation.

Human Adaptive Mechatronics(HAM) is an intelligent mechanical system that adapts to human skill under various environments, improves human skill, and assists the operation to achieve best performance of the human machine system(1). In this new kind of human machine system, human factor has to be taken into consideration for the motion control design. The mechanical model of the skill-based human operation includes the various psychophysical limitations inherent in the human operator. Kleinman studied the dynamics characteristics of pilots(2). Generally, the beginner operator makes a mistake enough. On the other hand, the expert operates very well. For the reason, it is very important that the machine system can adapt the human skill. Our motivation of research is to find how we get good skill under this background. For the purpose, we make an experiment in this paper.

In considering a human as a control system, the system is treated as cascade of inherent part of reaction of time delay and lag attributed to the neuromuscular system where time delay comes from the various internal delay associated with visual or central process. Furthermore, it is aimed that the predictor models the human's compensation for his/she inherent time delay. This prediction is interpreted as Smith predictor(6). However, this delay time of controller for system can not be excluded from the response. This means that the delay time of operation can not be changed by training. Furthermore, mismatch of time delay causes the stability of operation (12) and the response is slow in the movement. Then we think that the delay time is important element of human operation. For this consideration, we first investigate the relation between the delay time and progress of operation using a WMR in simple experiment. Subjects operate the WMR with pinhole camera to reach a goal through two check points in the experiment. They manipulate by only using image of pinhole camera under the assumption that human regulates his/her delay time between input signal and output response. In this experiment, the input signals make position and angle of joystick and the output responses are measured by other camera system. The operation signal of robot is analog so that this signal gives linearity between joystick positions or angles and velocity signals of WMR. We can feel the linear response between joystick operation and WMR moving and we do not sense the time delay because of quick response. We analyze the position and velocity of WMR and the operation log of joystick. We calculate correlation with start input signal and the response of WMR to the input. From the correlation data, relation between time to goal and the distribution of delay time. Next, using the data based operation data on curve, we identify a delay of response by using ARX model. Since operation in this experiment is more difficult than in straight path, we consider that the operation data in curve include delay of response.

The subjects are classified into some groups by using data based on the relationship between maximum stability pole of ARX and operation time and between delay time and the operation time. Furthermore, detail analyses are done to the subject by whom each group has a strong correlation in each relation and we multilaterally examine the delay of response and the relation of the advancement of the operation.

This paper is organized as follows. In section II, tele operation control system of machine and response delay of human operation in the system is introduced. We explain an experimental system that consists of tele operated wheeled mobile robot and measurement system in section 3. In this section, we first introduce a test field of experiment and manipulation. Section 4 explains an analytical method of the experiment data. First of all, we examine each delay time of seven subjects based on operational data of WMR. We use of the data operated in a special environment in order to examine the relation between response delay and operation mistake. These data were measured in the situation which the wall is near. Next, the delay of the operation based on a curve running data is shown by using ARX model. The subjects are being classified into some groups and these data are analyzed by using Independent component analysis in this section. Last section 5 is conclusion and discussion.

## 2. Human model and skill in tele operation control system

Our motion control system is composed of the brain, the outside environment, and the body. The brain corresponds to the control center, and the body receives information with the outside and acts actually. Therefore the skill level of human operation has relation to an environment and equipment of operation strongly and this relationship is greatly important in the analysis of the motion control system. To achieve a desirable motion control corresponding to the environment, an internal model of external dynamics that consists of the body and the environment is needed(10). On the other hand, there are transmission delays of the nervous system in our sense and movement. This delay has the range from 300ms to 10ms and the delay in the feedback loop makes the system unstable. Therefore, to do a smooth and fast motion, the decrease of the influence of the response delay is important and the forecast of environmental change into action is needed (11). A mechanism to compensate to time delay is explained as so-called Smith Predictor. In the machine operation that should consider time delay, there is a tele operation system(6). In the case of tele operation system, real time camera image is significant for the judgment and the response of the visual feedback is late. Thus it is important to adjust the delay for good motion control. Fig. 1 shows a block diagram of a system to which human does a tele operation of machine. While this method is to cognitive steady process, these modeling methods tend to become subjective because the method needs analysts cognitive judgment. Based on this viewpoint, we consider two type skills such as cognitive and operation skills are needed to operate a machine system and we examined the relation between environment recognition and process of operational skill in tele operated system(8). From this result, cognitive skill have little relevancy in simple task of machine manipulation and operation skill is more important than cognitive skill for adult. In an operation task of a machine, on the other hand, the delay in operation affects the results.

In the system by which human operates a machine, the machine can be considered and the plant and human be regarded as a compensator. When delay time is in the closed system, the effect of control input appears late and a high gain makes the feedback system unstable(12). The time delay  $e^{-sL}$  does not change a gain of system but only change a phase of system and decrease in time delay  $L$  increases a stability margin of phase. From this result, the time delay shows the possibility of control performance in tele operation system.

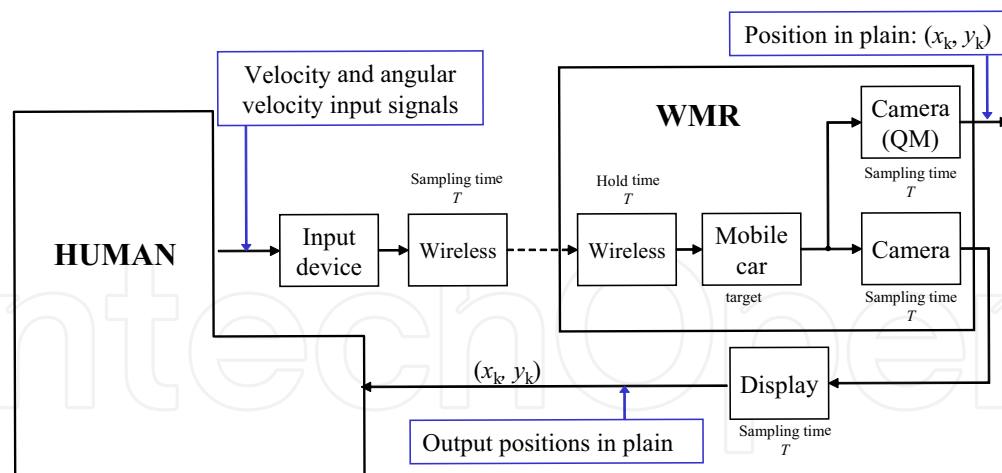


Fig. 1. Block diagram of human/machine system

### 3. Experiment for data acquisition for analysis

#### A. Test field

In order to analyze time delay based on the data between velocity command  $v$  and the actual translational velocity of WMR, the data is calculated from position data of the WMR measured by stereo vision tracking system; Quick Mag. The WMR used in this experiment is shown in Fig. 2(left). The driving device is used by stepping motor and a pinhole camera is mounted forward in order to give the operator the front image of the WMR. A joystick is used to operate this WMR. This joystick signal is analog so that signal gives linearity between joystick positions or angles, and velocity signals of the WMR. We can feel the smooth response from joystick operation to WMR motion. The test field is a small maze that consists of block-wall, start point, goal point, and several check points. Operator manipulates the WMR by seeing the image from the camera, and moves the WMR from start point to goal point passing the intermediate check points by using joystick. Right of Fig. 2 shows the test field. In this experiment, operator has to manipulate the WMR by only using image information of position and movement. We investigate the correlations such as the correlation coefficients between delay time of angular velocity, pole estimated ARX based on angular velocity data and total time by using the data from a start position of analysis to goal shown in Fig. 4. This area is narrow and subjects have to turn to go into the goal in this place. Therefore, many subjects can not operate a wheeled mobile robot (WMR) well in this place. From this reason, we consider that rotation operation in narrow place is more difficult than the straight advancement operation and analyze the angular velocity data of this area. We evaluate skill by total time of each trial. Before the experiment, subjects were permitted to see the test field, and were demanded by an experimental instruction so that they might operate the WMR to the final goal as fast as possible. Ten trials were imposed to each subject. Position and rotation of the WMR is measured by a real time visual motion capture system: QuickMag with sampling time 16[ms].

#### B. Operation signal of wheeled mobile robot

An operator manipulates a joystick by using front-back direction  $y$  and rotational angle  $z$ . Fig. 3 shows operation of the joystick. Translational velocity and rotational velocity are computed as

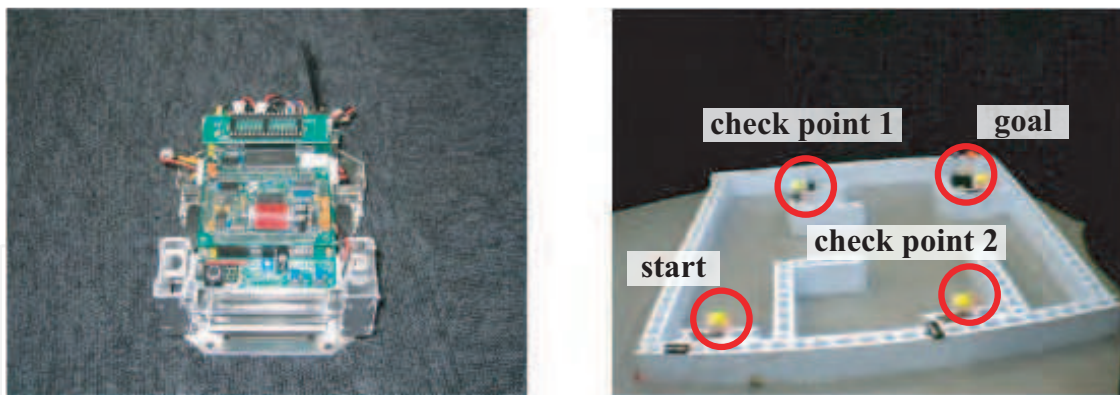


Fig. 2. Wheeled mobile robot(left) and maze test filed(right)

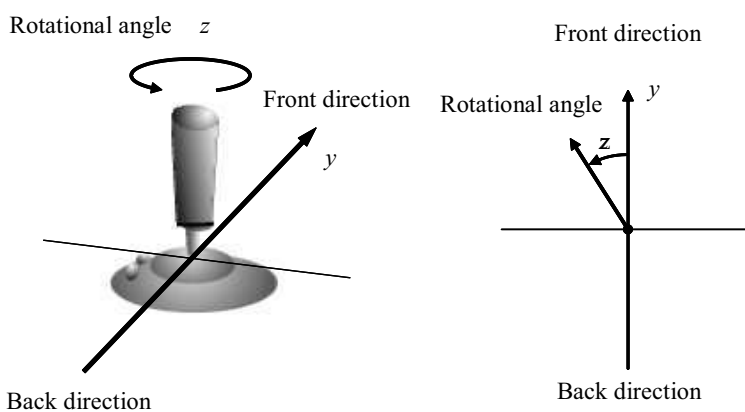


Fig. 3. Joystick movement

$$v(t) = \begin{cases} \text{sign}(y(t)) \left( \frac{v_{max} - v_{min}}{1000 - 400} (|y(t)| - 400 \cdot \text{sign}(y(t))) + v_{min} \right) & \text{if } 400 \leq |y(t)| \leq 1000 \\ 0 & \text{if otherwise} \end{cases} \quad (1)$$

$$\omega(t) = \begin{cases} \text{sign}(z(t)) \left( \frac{\omega_{max}}{800} (|z(t)| - 200 \cdot \text{sign}(z(t))) \right) & \text{if } 200 \leq |z(t)| \leq 1000 \\ 0 & \text{if otherwise} \end{cases} \quad (2)$$

where  $v_{max}[m/s]$ ,  $v_{min}[m/s]$  and  $\omega_{max}[deg/s]$  are given by 0.5, 0.125 and  $(v(t) - v_{min}) / 90$  respectively and these values are tuning parameters. Using these input signals, the velocity of right and left wheel such as  $v_r(t)$  and  $v_l(t)$  of WMR are calculated by

$$v_r(t) = \frac{2v(t) + 90\omega(t)}{2}, v_l(t) = \frac{2v(t) - 90\omega(t)}{2} \quad (3)$$

This joystick has free area in position and angle and the input signal gives as 0 in the area. The operator of robot is analog so that this signal gives linearity between joystick positions or angles and velocity signals of WMR. Then operator can feel the linear response between joystick operation and WMR moving and he does not sense the time delay because of quick

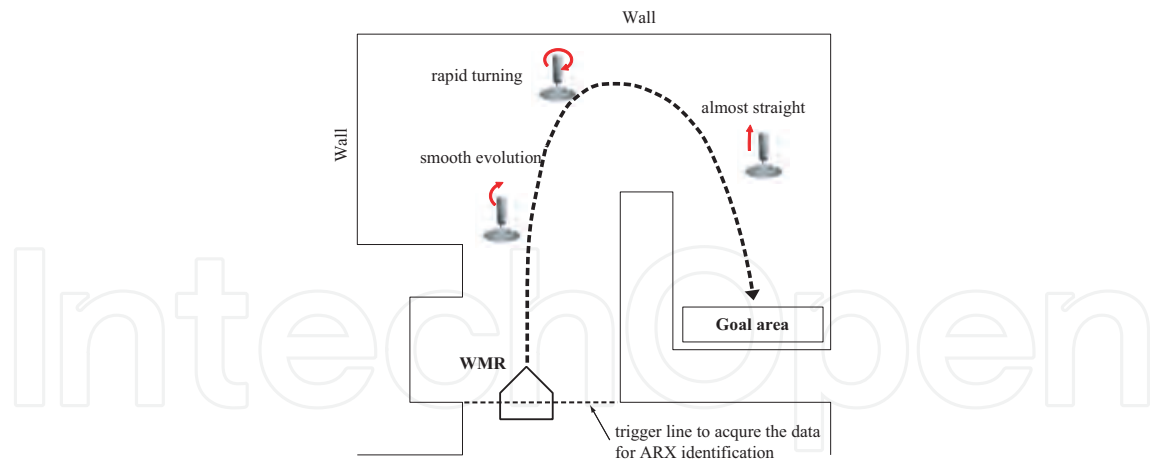


Fig. 4. Operation track of WMR from start position of analysis to goal area

response. The output responses are measured by QuickMag in this experiment. The subject tried this operator 10th times. We define the progress of skill as arrival time. Because of the definition, the subject were demanded to reach the goal as soon as possible before this experiment. We calculate the correlation between input signal and output response by using these experiment data. In this experiment, we assume that operators tend to predict the motion of WMR through the image information and he/she adjusts the delay time of output response. Under the assumption, we think that changing of delay time can use the estimation of skill level and investigate the tendency of decrease of goal time with concentration of time delay. The operation time is used to judge the skill level in this experiment. Then we understand that the faster the goal WMR can be arrived at, the more he/she became good at his/her operation.

#### 4. consider of relationship between skill level and response delay time

##### 4.1 Analysis based on data between checkpoints

We first searched the delay times between input signals and output responses based on the data for position and direction of the center of gravity. A male participated in this experiment. In this experiment, we used the positive changing date and counted the number of delay time(7). The data varying from 0 to nonzero number and relating the response of WMR to the input signal can be found. Using this idea, we calculated correlation data of input  $u(t)$  and output  $y(t)$  such as

$$\lim_{t \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} u(t) y(t + \tau) d\tau \quad (4)$$

The input data such as joystick position, angle and direction of WMR are given by digital data. Then we calculate the correlation as the number of  $\sum_{l=-0}^T u(k)y(k-l) \neq 0$ . Fig. 5 gives a result of reaching time. (1) is the total time from start to 1st check point, (2) and (3) experiment the total time from 1st check point to 2nd check point and 2nd check point to goal. (4) is time to total operation time. These results indicate that operation decreases with increase the step of operation. We consider that operator tends to manipulate the handle of joystick well and that skill level in 10th experiment is higher than in 1st experiment.

Fig. 6 to 13 show the results for number and rate of delay time of velocity. Fig. 6 and Fig. 7 give the results of delay time of velocity and rate of delay time in 1st operation. The data in the

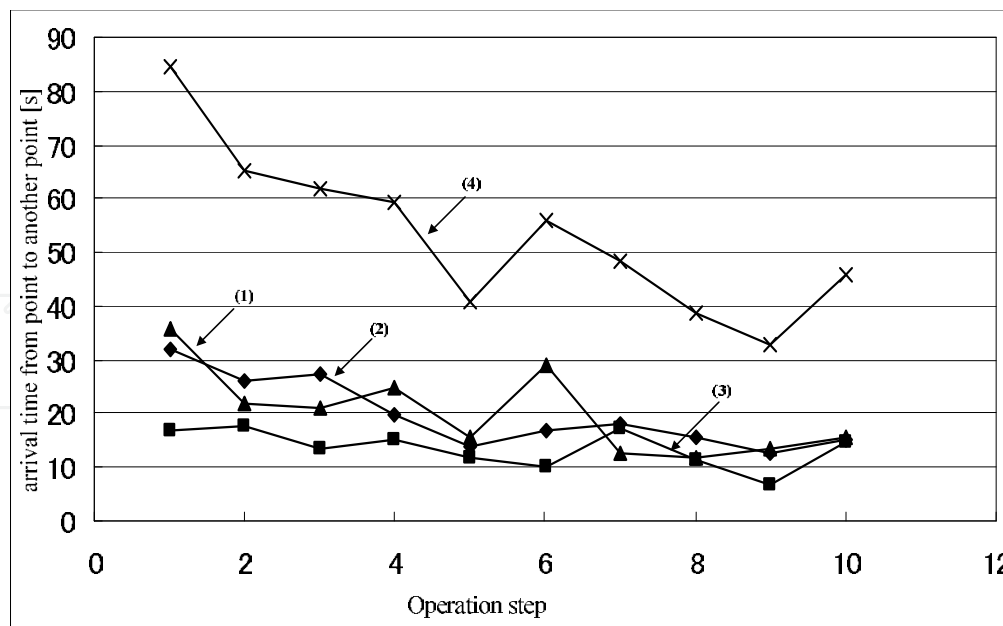


Fig. 5. Arrival time from point to another point;(1) start to point 1, (2) point 1 to point 2,(3) point 3 to goal

first operation show that delay time distributes wide range such as about 150ms to 800ms and there are two peaks at near 300ms and 500ms. On the other hand, we can find out the features in Fig. 8 and Fig. 9 that range of delay time is closer than first result and the time concentrates two times such as 300ms and 500ms. By comparison with 1st operation, improvement of operation makes the distribution small.

Fig. 10 to 13 present the result of delay time in angular velocity. These times are faster than time for velocity because we move joystick in operation of angular velocity. These results also give that the range of delay time changes. In first operator, the delay time appeared over two times exist in near 200ms to 350ms and the delay time over same times concentrate near 350ms in the 10th operation. We consider from these data that human does not accustom him to operation with image of camera and he can not estimate next move of WMR. Then he hardly operate joystick at good timing and he has many delay time. Otherwise he learns good timing through many operations and the delay in 10th experiment does not expand wildly. We think the distribution of delay time relates with skill level.

#### 4.2 Analysis on progress process of operational skill level by ARX model

Next, we analyze a progress process of operational skill level by ARX model given by equation(5). Operated robot and operating environment used the same one as experiment of section 4.1. Moreover, the inadequate data set was rejected from the identification process to keep reliability of the identification, because inadequate data set, e.g. collision against a wall, does not include correct movement of WMR to operational command.

In this example, seven adult male participated in this examination, whose age range are 22 to 24. subjects are demanded to reach a goal as fast as possible. For the reason, we consider that information of the total time can be used as index of skill-level. Results of total time of the subjects are shown in Fig. 14. These results indicate that total time of subjects monotonically decreases as trial increase. we can consider all subjects have improved the operation level from these results. The data estimated delay time by ARX is the same as the data used in



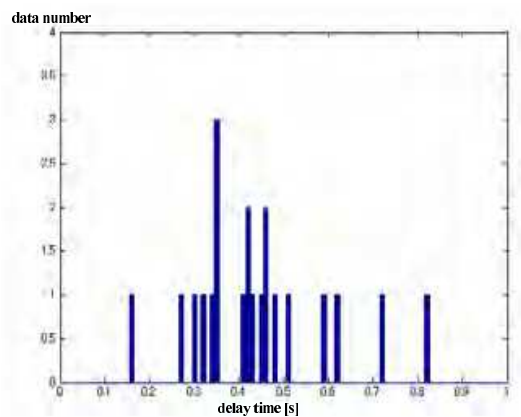


Fig. 6. Result of delay time for velocity in 1st operation

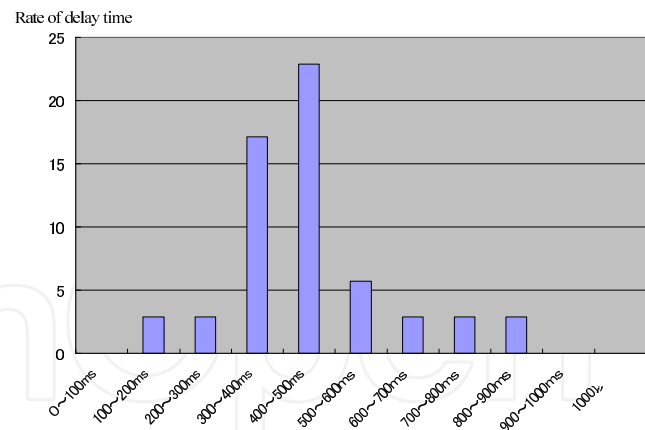


Fig. 7. Rate of delay time for velocity in 1st operation

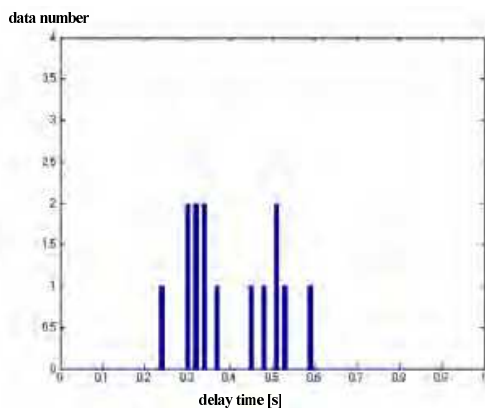


Fig. 8. Result of delay time for velocity in 10th operation

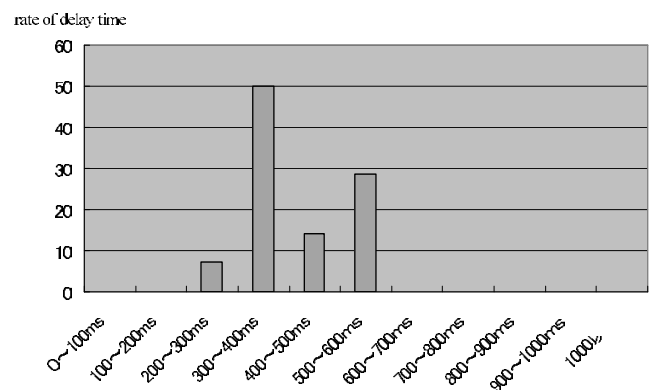


Fig. 9. Rate of delay time for velocity in 10th operation

section 4.1. That is, the input signals are given by (1) and (2) and the output is actual translation velocity of a WMR that is computed from position data measured by a QuickMag. Using data given in experiment, time delay is estimated by searching minimum identified error by equation (5) with identified parameters. The orders,  $n$  and  $m$  are specified as both 5 because the suitable value can be decided by using loss function given as  $\sum_i^{N/2} \epsilon^2(i, \theta)$  where  $\epsilon$  is computed by prediction error and  $N$  and  $\theta$  are a number of data and data vector, respectively(9).

### 4.3 Validity of ARX model

Human characteristic of tele operation system is estimated by using ARX model with delay in this paper. ARX model is given by

$$y(t) + a_1y(t-1) + \dots + a_ny(t-n) = b_0u(t-L) + b_1u(t-L-1) + \dots + b_mu(t-L-m) \quad (5)$$

where  $n$ ,  $m$  are degree of an ARX-model, and  $L$  is time delay. Similarly, for rotation model, the input is angular velocity of a WMR. The characteristic of seven subjects were analyzed by

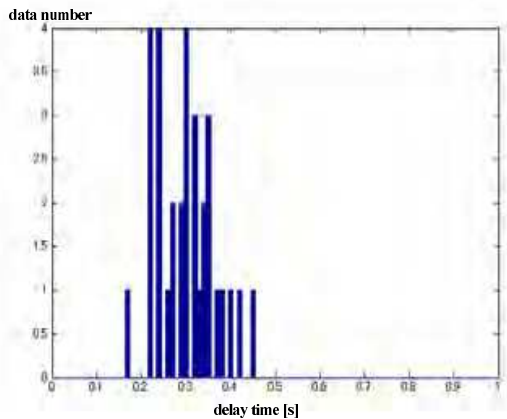


Fig. 10. Result of delay time for angular velocity in 1st operation

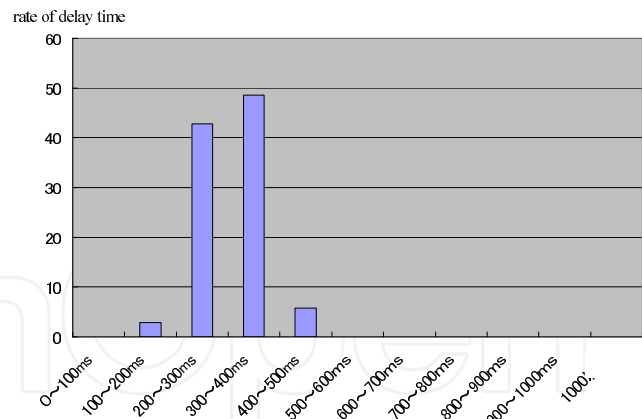


Fig. 11. Rate of delay time for angular velocity in 1st operation

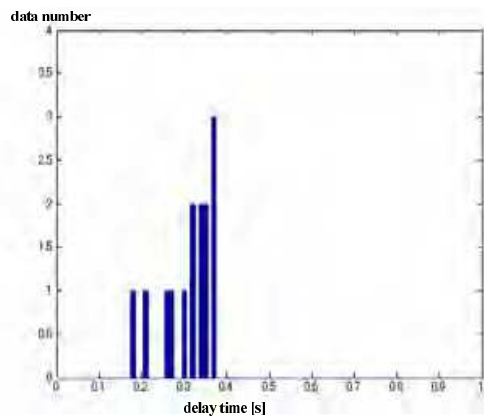


Fig. 12. Result of delay time for angular velocity in 10th operation

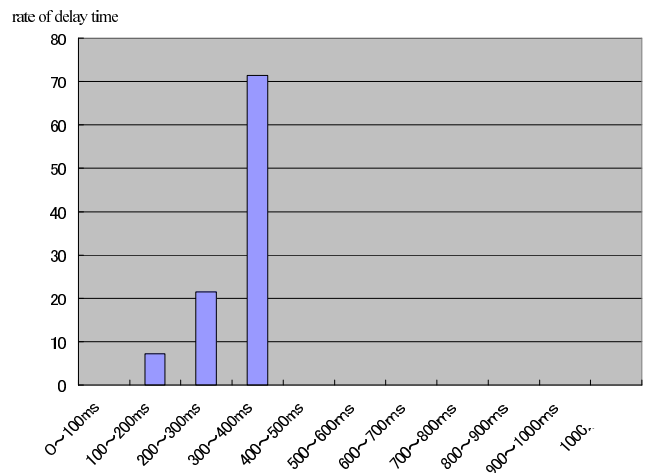


Fig. 13. Rate of delay time for angular velocity in 10th operation

using ARX model based on experiment data. This experiment field is shown in Fig. 4. First of all, we examine validity of ARX as human operation model. We compare output data with estimated data made by ARX. Although straight course can confirm forward scenery from a front camera, a forward situation in the curve course changes one after another through a front camera. For the reason, an operation of WMR in the curve course is more difficult. Since rotational operation is difficult and skill progress of each operator is different, we investigated not the translational velocity data but the rotational velocity data. The operational signal is calculated based on another data by using this ARX model after a coefficient of ARX model was estimated by using the data of curve path. That is, the data from a start position to goal shown in Fig. 4 are used for estimation of ARX model. The validity of this model is examined by the difference between an output of ARX and an actual output. Fig. 15 shows angular velocity that measured by QuickMag and estimated by ARX model, where x-axis and y-axis are an operation time and angular velocity. The large difference is not seen from Fig. 15 in the output, and the model also reproduces operation change well. Furthermore Human are usually stability controller and the ARX which is a model of human operation had to be steady.

Fig. 16 shows zeros and poles of the ARX model. This result of Fig. 16 shows that poles are in stable area and the model is stable. On the other hand, zeros are on the circumference of one in radius and the position of zeros affects an operational performance. As a result, we can find that ARX model is reasonable as an estimated model.

#### 4.4 Analysis on delay time and stability pole of ARX

The data measured from the start point of the curve to goal point is used for the analysis based on ARX model. Fig. 4 shows the measure point. There is a wall and subjects have to start rotational motion in this area. This area is narrow and subjects have to turn to go into the goal in this place. Therefore, many subjects can not operate WMR well in this place. From this reason, we consider that rotation operation in narrow place is more difficult than the straight advancement operation. We think that the skill of operation appears more clearly in difficult operation areas, and we use the angular velocity data observed in this place. The Values as the correlation coefficients between delay time of angular velocity, poles of estimated ARX based on angular velocity data and total time  $A_{\omega}$  are used for the data analysis. Using these values, we try to classify the subjects into two groups. Table 1 and table 2 show the two groups. According to the correlation coefficients  $l_{\omega}$  and  $\sigma_{\omega}$ , A and D have positive correlation for both coefficients. These subjects have a tendency such that operation mistake such as collision to wall decrease with operation number and these subjects tend to be able to operate WMR well. On the other hand, subject C has negative correlation coefficients  $\sigma_{\omega}$  and  $l_{\omega}$ . The subject has few operation mistakes in the first operation. However, the subject makes a lot of mistakes since second operation. This subject tends to reach goal as fast as possible since second examination. Subjects E, F and G have positive correlation coefficient  $\sigma_{\omega}$  but negative correlation coefficient  $l_{\omega}$ . They have the same tendency as the subject A and D. Then the coefficient correlation,  $p_a, p_g$ , between delay time and poles to subject A and G, who have

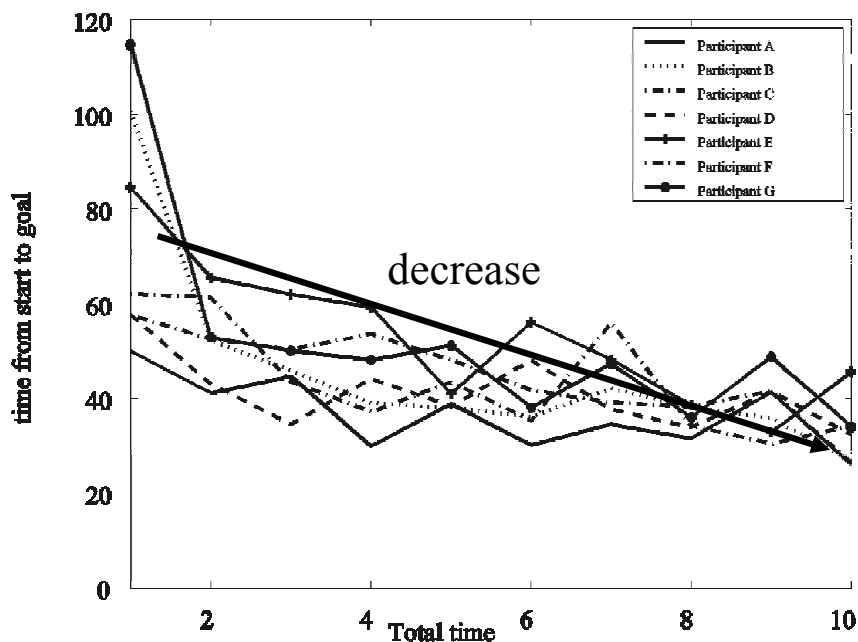


Fig. 14. Total time on each trial

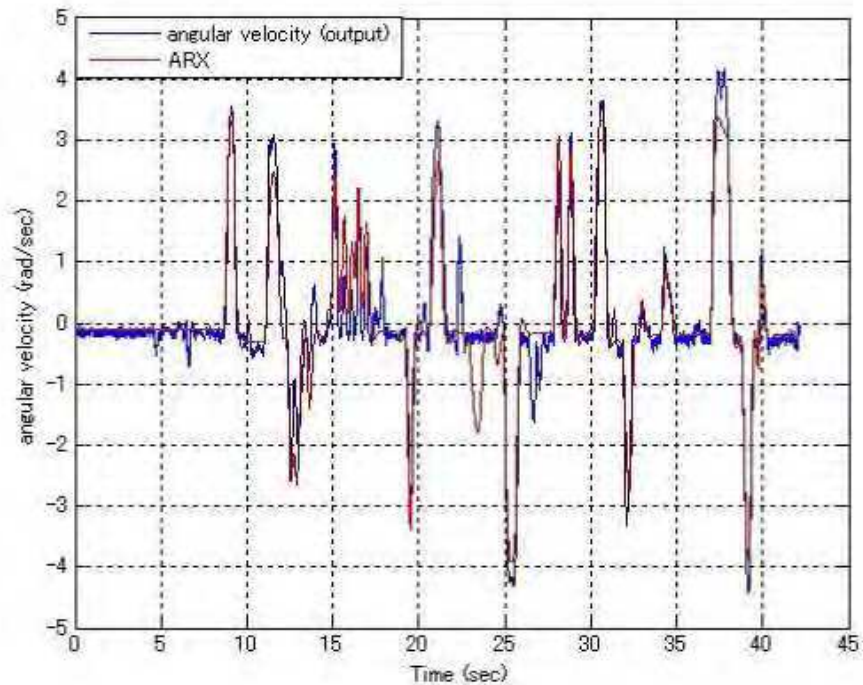


Fig. 15. Measured angular velocity of WMR and simulated response with estimated ARX model output

a maximum and a minimum correlation  $l_\omega$  in the group (A,D) and (E,F,G). The correlation coefficients to A and G are computed as  $p_a = 0.35$  and  $p_g = 0.50$ , respectively.  $p_g$  is larger than  $l_\omega$  of G. Fig. 18(lower) shows the tracking path of WMR of subject G. Subject G tends to turn WMR smoothly without stopping around corner of maze. As the change to smooth path, the skill level of subject G progresses clearly. The progress of operation can also judge from the result of collision number shown in Fig. 20. The delay times of subject G shows in Fig. 19(lower). Therefore, subject G tends to decrease delay time with stability and the operation is steady as a result. On the other hand, for subject A,  $l_\omega$  is larger than  $p_a$ . The delay times of subject A shows in Fig. 19. The result shows that the delay time is larger in first trial. The correlation coefficient  $l_\omega$  of subject A by using data from second to tenth trial is computed as  $-0.036$ . In the operation since the second times, it can be said that the operation is steady. The feature can be found from Fig. 18. However, Results of Fig. 19 show that delay time and pole of angular velocity does not decrease monotonically. We consider that subject tends to do a same operate, so that the coefficients do not decrease. It can be confirmed that the operation track of WMR has the same tendency as straight line and rotation shown in Fig. 18(upper). On the other hand, subject C has negative correlation coefficients  $\sigma_\omega$  and  $l_\omega$ .

Next, the subjects A,B,C and D are also examined from the views of the values as (i) total time and variation of delay time, (ii) total time and kurtosis of delay time and (iii) total time and skewness of delay time. The subject A and D show the feature of  $l_\omega > 0$  and  $\rho_\omega < 0$ , and the B and C have  $l_\omega > 0$ ,  $\rho_\omega < 0$  and  $l_\omega > 0$ ,  $\rho_\omega < 0$ , respectively. Table 3 and table 4 show these values. For the values (i), (ii) and (iii), the other subjects except B do not have all positive values. However The definite feature of operation can not be found from these values. Then we investigate data from another viewpoint again.

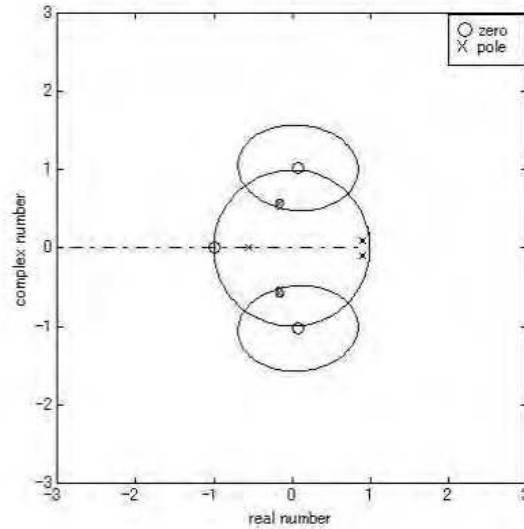


Fig. 16. Zero (○) and pole (×) of estimated ARX model

We classify the seven subjects by relationship between delay time and total time and by between maximum stability pole and total time. Fig. 27 indicates the relationship of the correlations. x axis is correlation coefficient of delay time and total time, and y axis is a greatest stability pole of ARX and total time. The subjects experimented ten times and sum of operation time was recorded. Results in Fig. 27 indicate that subjects can be divided into two groups. A group 1 includes C and D and B, F, and G are elements of a group 2. A group 1 shows the subjects have positive correlation. On the other hand, group 2 tends to a negative correlation. Subject A shows a tendency of increase, but regarded as the other group so that a rate of increase is different from group 1. In addition, subject E is included in both group 1 and group 2, but we include E into group 1 this time. We analyze the following terms two groups by using input and output data from 2nd point to goal, i.e., (i) distance from 2nd point to goal, (ii) operation time, (iii) the number of time that curvature has more than 5 and (iv) a rate of operation time from 2nd point to goal to total operation time. Fig. 28 and Fig. 29 are results on (i) to (iv) for subjects in group 1 and 2. Group 1 tend to decrease (i), (ii) and (iii) according to increase of experimental number of times. On the other hand, the curvature of subjects F and G in group 2 do not vary and their distance do not tend to decrease. For these results, the subjects in Group 1 which have positive correlation come to progress their manipulation skills because their stability and delay time of response are decreased with experiments times.

$l_\omega > 0$	subject A ( $l_\omega = 0.57$ ) subject D ( $l_\omega = 0.17$ ) subject B ( $l_\omega = 0.02$ )
$l_\omega < 0$	subject C ( $l_\omega = -0.6$ ) subject G ( $l_\omega = -0.14$ ) subject F ( $l_\omega = -0.11$ ) subject E ( $l_\omega = -0.003$ )

Table 1. Classification table by delay time of angular velocity

$\sigma_\omega > 0$	subject G ( $\sigma_\omega = 0.42$ ) subject F ( $\sigma_\omega = 0.35$ ) subject A ( $\sigma_\omega = 0.34$ ) subject D ( $\sigma_\omega = 0.24$ ) subject E ( $\sigma_\omega = 0.021$ )
$\sigma_\omega < 0$	subject C ( $\sigma_\omega = -0.51$ ) subject B ( $\sigma_\omega = -0.15$ )

Table 2. Classification table by pole of angular velocity

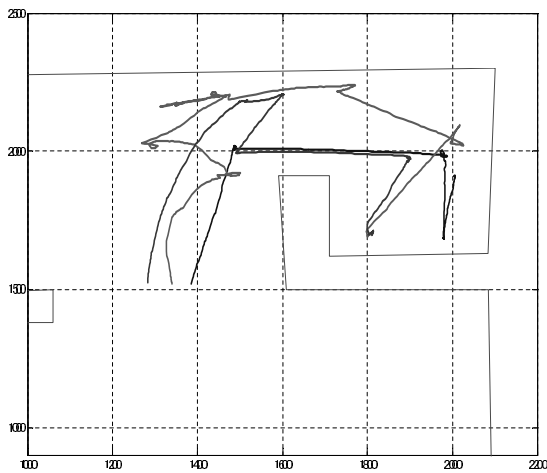


Fig. 17. Operation trajectory of subject A; 1th (blue), 5th (green) and 10th (red) trial

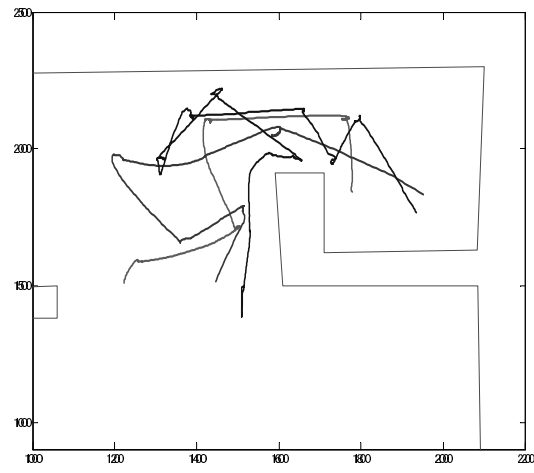


Fig. 18. Operation trajectory of subject G; 1th (blue), 5th (green) and 10th (red) trial

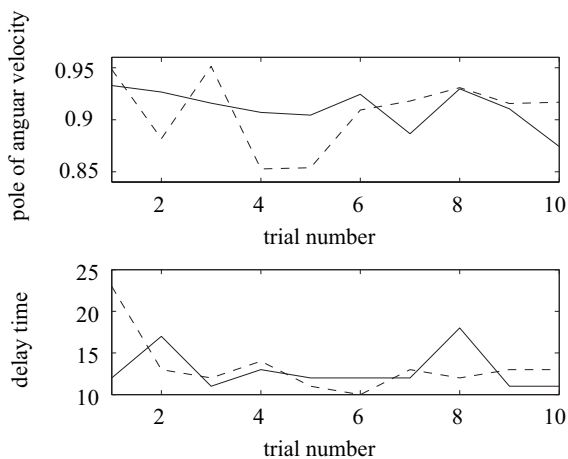


Fig. 19. Pole of angular velocity(upper) and delay time (lower) subject A (dashed line) and G (solid line)

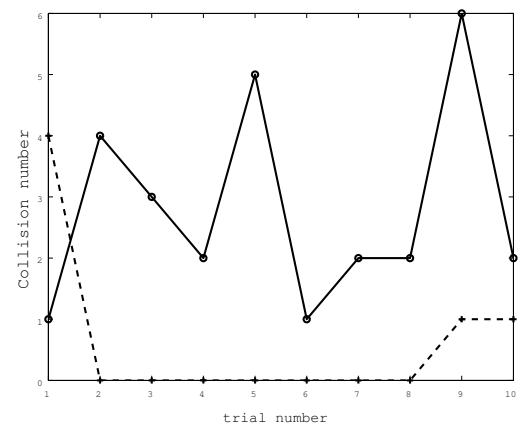


Fig. 20. Collision number of subject: A (solid line) and subject G (dashed line)

We consider that they can arrive at the goal only by a small number of turn operations. The subjects in Group 2 with negative correlation have the feature that stability margin tend to become more large with operation times, the response time, however, does not decrease. So we consider they tend to do useless operation, so that the distance and delay time does not decrease. Next, we examine each correlation value of these elements; i.e. (i) and (ii), (i) and (ii), (ii) and (iii). Each value is included in table 5. The each correlation of (i) and (ii) and (ii) and (iii) shows high values. We notice this result, and we demonstrate each operation path of C,D and G by using data from 2nd point to goal. Fig. 31 to Fig. 32 are results of operation path. When the operation times increases, each operation of subject D and C tends to be steady. On the other hand, The subject G of group 2 does not operate WMR stably every time. Fig. 18 is the result of operation of G. Moreover progress of operation differs in the subject C and D. D can rotate WMR at curve well and his path is smooth, but C does many useless manipulations. Furthermore as shown in table 1 and 2, it is important point that both  $l_{\omega}$  and  $\rho_{\omega}$  of C are positive.

	A	B	C	D
(i)	-0.330	-0.588	0.200	0.102
(ii)	0.138	0.506	-0.049	0.396
(iii)	-0.238	0.510	0.303	-0.190

Table 3. Correlation between total time and each data of velocity

	A	B	C	D
(i)	-0.160	0.006	0.020	0.090
(ii)	-0.067	0.335	-0.160	0.067
(iii)	-0.450	0.267	0.536	0.031

Table 4. Correlation between total time and each data of angular velocity

(i) total time and variation; (ii) total time and kurtosis; (iii) total time and skewness

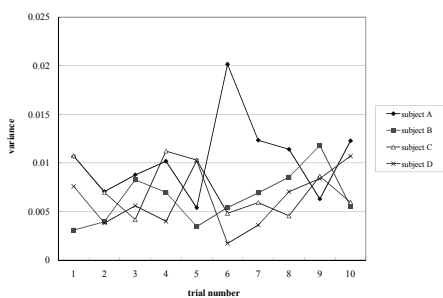


Fig. 21. Variation of delay time of velocity

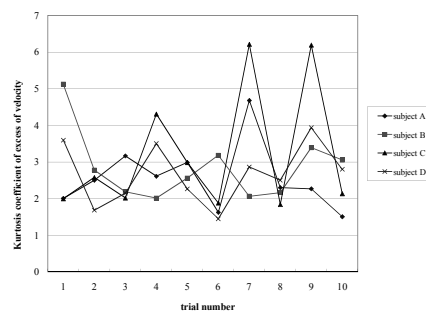


Fig. 22. Kurtosis of delay time of velocity

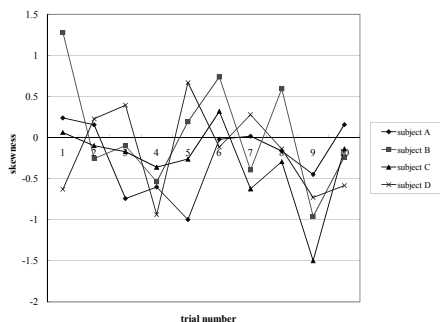


Fig. 23. Skewness of delay time of velocity

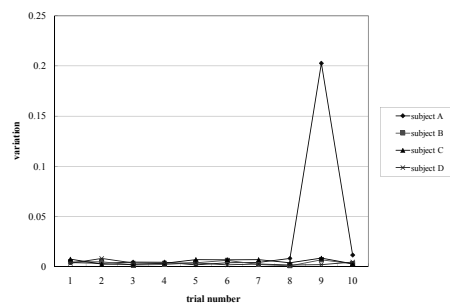


Fig. 24. Variation of delay time of angular velocity

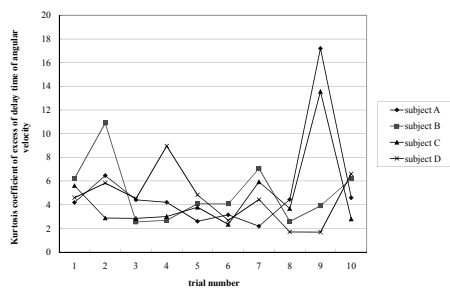


Fig. 25. Kurtosis of delay time of angular velocity

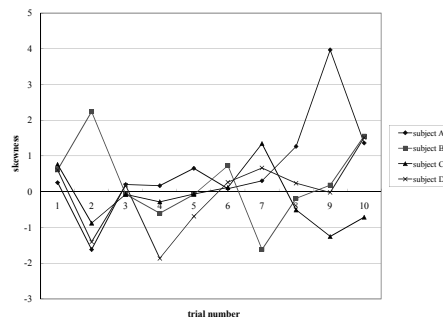


Fig. 26. Skewness of delay time of angular velocity

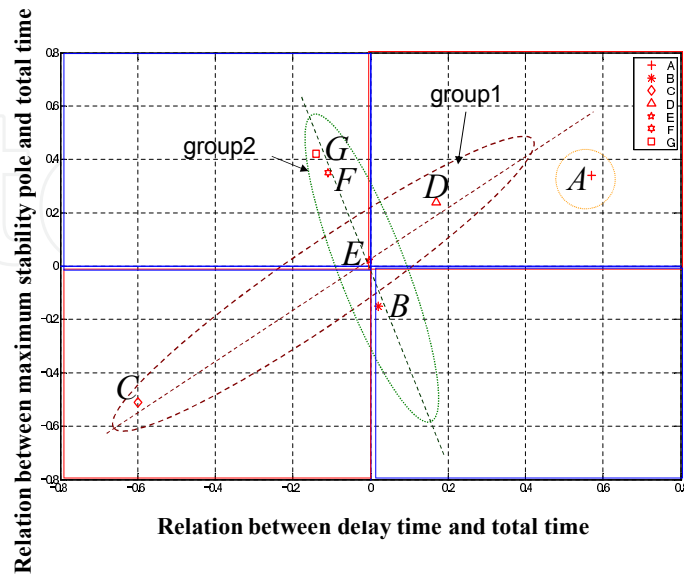


Fig. 27. Relation between delay time, maximum stability pole and total time

Table 5 Correlation of trajectory distance , path time and curvature on curve path

	Distance and time	Curvature and distance	Curvature and time	
C	0.81	0.76	0.93	g roup 1
E	0.93	0.8	0.92	
D	0.9	0.65	0.67	
B	0.83	0.77	0.86	g roup 2
F	0.8	0.87	0.85	
G	0.95	0.94	0.96	
A	0.64	0.49	0.53	

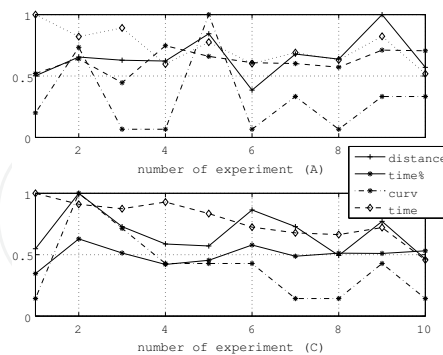


Fig. 28. Results of (i) – (iv) with subjects A, C; (i) distance (solid line), (ii) normalized operation time solid line with \*), (iii) curvature (dot-dash line), (iv) normalized total time dashed line



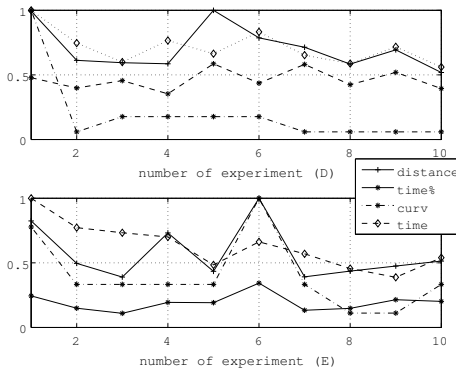


Fig. 29. Results of (i) – (iv) with subjects *D, E*; (i) distance (solid line), (ii) normalized operation time solid line with \*, (iii) curvature (dot-dash line), (iv) normalized total time dashed line

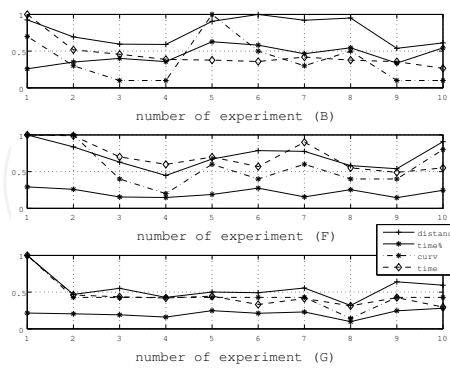


Fig. 30. Results of (i) – (iv) with subjects *B, F, G*; (i) distance (solid line), (ii) normalized operation time solid line with \*, (iii) curvature (dot-dash line), (iv) normalized total time dashed line

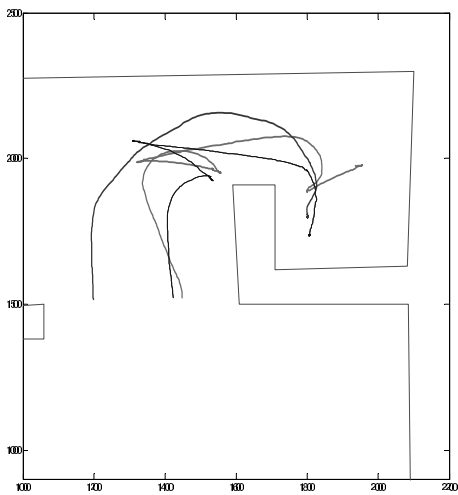


Fig. 31. Operation trajectory of subject *D*; 1th (blue), 5th (green) and 10th (red) trial

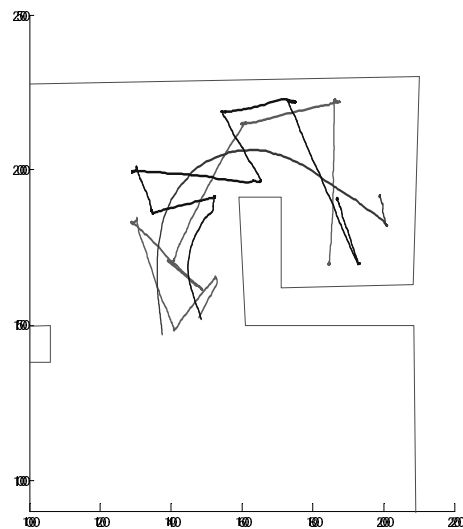


Fig. 32. Operation trajectory of subject *C*; 1th (blue), 5th (green) and 10th (red) trial

## 5. Conclusion

We analyzed correlations such as the correlation coefficients between delay time of angular velocity, pole estimated ARX based on angular velocity data and total time. We can classify the subjects into two groups for each coefficient based on the correlation coefficients  $l_\omega$  and  $\sigma_\omega$ , where  $\sigma_\omega$  and  $l_\omega$  signify the coefficient between pole of ARX, delay time of angular velocity and total time, respectively. One group has positive correlation for both coefficients. On the other hand, One in the other group has negative correlation coefficients  $\sigma_\omega$  and  $l_\omega$  and the other subjects in the second group have positive correlation coefficient  $\sigma_\omega$  but negative correlation coefficient  $l_\omega$ . They have the same tendency as the some subjects in first group. Next, we analyzed the coefficient correlation,  $p_a, p_g$ , between delay time and poles of subjects who have same tendency in both group. We found the following tendency based on the correlation coefficients to the subjects in two groups;

- (1) Decrease of delay time tends to the stability of operation.
- (2) Operation track has the same tendency when  $l_\omega$  is larger than  $p_a$ .

Furthermore, we classified 2 groups by correlation of coefficient with operation time and we considered the skill levels of the groups based on rotation manipulation and time from 2nd pint to goal. The results indicates that the group that tends decrease of response delay decreased a path distance and manipulation time also. For these results, the response delay is one of feature for skill level and the quantity is useful for inference of skill level.

## Acknowledgments

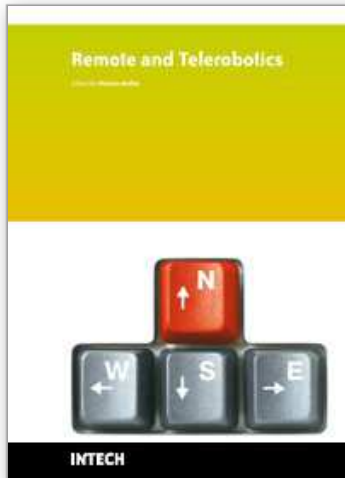
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Any book which presents works about controlling distant robotics entities, namely the field of telerobotics, will propose advanced technics concerning time delay compensation, error handling, autonomous systems, secured and complex distant manipulations, etc. So does this new book, Remote and Telerobotics, which presents such state-of-the-art advanced solutions, allowing for instance to develop an open low-cost Robotics platform or to use very efficient prediction models to compensate latency. This edition is organized around eleven high-level chapters, presenting international research works coming from Japan, Korea, France, Italy, Spain, Greece and Netherlands.

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