Overview of Human Adaptive Mechatronics and Assist-control to Enhance Human's Proficiency

Satoshi Suzuki*, Katsuhisa Furuta**, and Fumio Harashima***

* 21st Century COE Project Office, Tokyo Denki University(TDU), Tokyo, Japan
(Tel : +81-3-5280-3590; E-mail: ssuzuki@ham.coe.dendai.ac.jp)
**Department of Computers and Systems Engineering, TDU, Saitama, Japan
(Tel : +81-492-96-2911; E-mail: furuta@k.dendai.ac.jp)
***Department of Electrical Engineering, TDU, Tokyo, Japan
(Tel:+81-3-5280-3590, E-mail: f.harashima@ieee.org)

Abstract: Human Adaptive Mechatronics(HAM) is a new concept which was proposed in our university's research project sponsored by Japanese Ministry of Education, Sports, Culture, Science and Technology(MEXT), and is defined as ``intelligent mechanical systems that adapt themselves to the user's skill under various environments, assist to improve the user's skill, and assist the human-machine system to achieve best performance''. In this paper, the concept and key-items of HAM are mentioned. And the control strategy to realize a HAM human-machine system is explained in the case of physical-interface system, i.e. haptic system. The proposed assist-control of a force-feedback type haptic system includes online estimation of a operator's control characteristics, and a `force assist' function implemented as a change in the support ratio according to the identified skill level. We developed a HAM-haptic device test system, executed evaluation experiments with this apparatus, and analyzed the measured data. It was confirmed that the operator's skill could be estimated and that operator's performance was enhanced by the assist-control.

Keywords: Human Adaptive Mechatronics, haptic interface, proficiency, assist-control, online identification.

1. INTRODUCTION

In most existing human-machine system, humans have to learn to operate machines and improve their skills, because the ordinary machines aren't designed to assist the operator to improve the skill and to play best performance adapting to the environment. Several research activities concerning so-called assist-control are being undertaken in especially automotive industry, however true skill-assistance has not been achieved yet. A typical technique to evaluate operator's proficiency is to check the error between actual and canonical motion by using a neural network scheme or fuzzy estimation[1]. These assist-controls approaches, however, cannot reveal internal properties of a operator, and it is difficult to discuss the total stability and performance of human-machine system. Additionally, most traditional techniques of assist-control are conservative. Input limitation and suppression of high frequency signals[2] are typical approaches. Displaying of supplementary information is also used, but these techniques do not improve characteristic of the original closed-loop system directly. Real positive assist-controls that enhance human operation by considering the human control axiom have not yet been established.

On the other hand, research on human control characteristics has a long history. It is said that Tustin tried first to express the human control model in 1940s when classic control theories were systematized. He utilized a linear transfer function to model human action and proposed linear servo control[3]. In the 1960's, many models to express human control properties were introduced. Ragazzini[4] modeled the human as a PID controller and indicated that humans are time-variant systems having randomness and claimed that we should pay attention to differences among individuals. The work of Baron in 1970 showed good agreement between theory and experiment in a scheme of optimal control for a VTOL aircraft[5]. Recently, thanks to collaboration with brain science and system engineering, research on brain has become more active and human's cerebration logic is being elucidated. The feedback / feedforward model [6] and Smith predictor [7] are well known models of brain's control strategy. The former model proposes that human brain tends to change from 'feedback' to 'feedforward' by learning. The latter model says that human brain forms models of delays caused by neural signal transmissions and recognition and utilizes them to make controllers in his(her) brain. However these fruitful results have not spread to practical design of the assist-control yet.

2. HUMAN ADAPTIVE MECHATRONICS

Given the background in the previous section, we propose one realization of the system structure called `Human Adaptive Mechatronics(HAM)[8,9]. HAM is a new concept that was proposed in COE(Center of Excellence) research project in Tokyo Denki University, and the project is sponsored by Japanese Ministry of Education, Sports, Culture, Science and Technology(MEXT) from 2003 to 2007. The 18 professors and associate professors are promoters of this project, and several research staffs and post doctoral fellows are doing research belonging to the COE project. To improve the relation between a human and a machine, the mechatronics should pay attention to the human and adapt to the operator's skill level assisting the operation. To design such mechatronic system, new discipline of HAM should be developed, which may be covered by the following fields:

1) Modeling human and machine dynamics. Especially the variable constraints should be considered.
2) Modeling the operation base on skill, rule, knowledge, decision combining event and dynamical systems.
3) Modeling of the psycho-physical characteristics of human operator
4) Development of Mechatronic systems supporting human operation not only assisting control action but also providing proper data and knowledge for understanding the situation and giving better decision

The research of HAM consists of Mechacronics and Human. The Mechatronics is made of Mechanical, Electrical, Information Technology, Systems and Control Engineering. The Human discipline consists of psychology and medical engineering. The schematic diagram of HAM is shown in Fig.1.

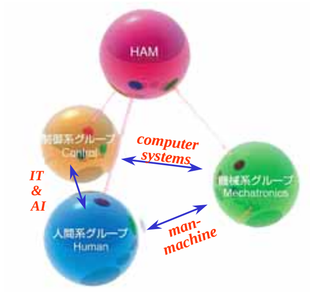

Fig.1 Schematic diagram of HAM project

3. HAM-HAPTIC INTERFACE

There are various kinds of approaches concerning a human-machine system. Even if a scope is limited into our COE project, several control strategies already have been proposed; a hybrid(continuous-time and discrete-time) system approach[10], in which stabilization of whole system by discontinuous switching of controllers is considered, a various control time-interval system approach[11], a state-transition model approach[12] expressing statuses of an operator, and a robot, and an environment in discrete way. In this paper, we introduce an assist control of a haptic system, in which an operator manipulates a machine by using the control stick. As one method to achieve a HAM system, we propose a human-machine structure including two kinds of interfaces (Fig.2). One is the *Human Adaptive (HA)-mechanical unit* which is a mechanical part of the interaction between the mechanical device and human's muscle-skeleton system. The HA-mechanical unit supports the learning process intuitively via physical feeling. Another is a *HA-display unit*, which gives helpful visual information to human for the support. A HAM core-engine observes human motions, estimates the skill level, and adjusts own characteristics/information via above two HAM units according to the operator's skill.

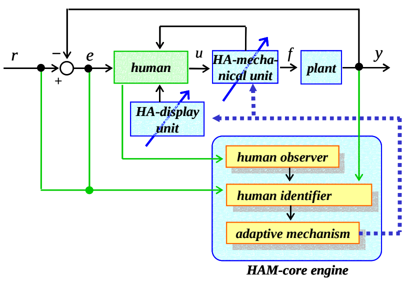

Fig. 2 Conceptual block diagram of HAM

To design a system in order to enhance human ability, it is necessary to consider what model can express human control characteristics adequately. In our present study, we assumed that human controller consists of a variable FF/FB component (like a Kawato-model) and a time-delay compensator(like a Smith predictor) as shown in Fig. 3.

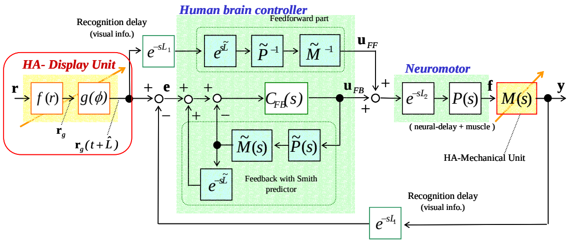

Fig.3 Human control model with HA-units

Based on this basic human-machine structure, a system to be treated is modified according to each focus point of research. Section 4 and 5 explain the HA-mechanical unit and the HA-display unit, respectively

To evaluate the proposed ideas and control methods, we developed a haptic test system shown in left of Fig.4. The test system is made of a two-dimensional positional *xy*-stage and a real-time monitor, which can display the position of the stage . Operator manipulates a grip attached to the *xy*-stage as he(she) looks at the real-time monitor. The force from the operator is detected by a sensor. In order to suppress inherent characteristics such as frictions, nonlinearities and variances of viscosity, actuators of the *xy*-stage are controlled by local compensators designed by a virtual internal control method with impedance models [13].

Fig.4 HAM test system with haptic device

4. PHYSICAL INTERACTION ASSIST BY HA-MECHANICAL UNIT

A point-to-point(PTP) task was chosen for verification of a proposed method using the HA-mechanical unit, because the PTP task is popular in many human-in-the-loop systems. Most material handling operations by cranes and transporters are classified into this kind. In order to support human operation from a machine side, the following process is necessary.

phase-1 estimation of human characteristics
phase-2 quantification of the human skill
phase-3 assist control from a machine to a human

Phase 1 is the cognition of a human behavior on the machine side. This process can be translated to the signal processing and the system identification problem. At the phase 2, the machine quantifies the skill level from the data of phase 1. In case of PTP task, ideal parameters can be assumed to be known *a priori*. Then, the quantification is done by comparison of ideal parameters and the identified parameters of human. At the phase 3, the machine decides how machine itself gives supports to a human according to the estimated skill level.

4.1 Phase-1: Identification of human controller

Human measures a distance between a target and a current marker by glance and then a command to his(her) muscle is computed in his(her) brain by using his(her) own controller. In this process, there are always delays caused by neural transmissions and recognitions.

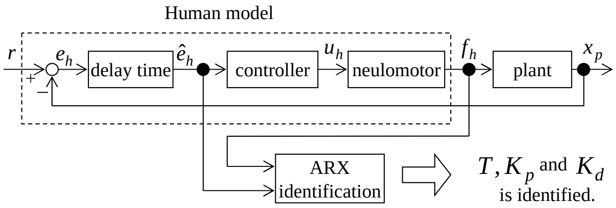

Fig.5 Human model and its identifier

These elements are assumed to be summarized as one element of time-delay for simplicity. The neuromotor corresponding to dynamics of the muscle is assumed to be first order system [14]. Then, a human-machine system treated here can be modeled as shown in Fig.5.

In the figure, r [m] is a target's position, u_h is a command computed by a human controller, e_h [m] is an error between the target and the stage's position, and f_h [N] is force generated by the human muscle. The *xy*-stage is moved directly by human manipulation f_h. Here the 'plant' block corresponds to the stage controlled by the impedance local control. Note that we cannot measure u_h normally since u_h corresponds to neural signal to the 'muscular cell'. On the other hand, f_h can be measured by a force sensor. Hence, we try to identify a transfer function from $\hat{e}_h$ to f_h in order to estimate characteristic of human controller. We assumes that the operator executed the PTP task without discontinuous switching of controllers since each task is done in relatively short time. Additionally, a PD control structure was chosen as most simple formation. Shortly, it is assumed that human controller and the nuelomotor are expressed by $K_d\,s+K_p$ and $1/(Ts+1)$, respectively, where K_p and K_d are a proportional differential gains, and T is a time constant. Then, human transfer property $G_h(s)$ is summarized as follows.

$$G_h(s) = \frac{K_d s + K_p}{Ts+1} \tag{1}$$

The response function is identified by using a parametric ARX model. Bilinear transformation $s \cong 2/\Delta \times (1-z^{-1})/(1+z^{-1})$ to Eq.(1) yields a discrete impulse transfer function $G_h(z^{-1})$:

$$G_h(z^{-1}) = \frac{b_1 z^{-1} + b_0}{a_1 z^{-1} + 1} \tag{2}$$

$$a_1 := (-2T+\Delta)/(2T+\Delta) \tag{3}$$

$$b_0 := (2K_d + K_p\Delta)/(2T+\Delta) \tag{4}$$

$$b_1 := (K_p\Delta - 2K_d)/(2T+\Delta), \tag{5}$$

where Δ is a sampling interval, and z^{-1} is a time-shift operator. Eqs.(3)-(5) give following equations.

$$T = (1-a_1)\Delta/(2a_1+2) \tag{6}$$

$$K_p = (2T+\Delta)(b_0+b_1)/2\Delta \tag{7}$$

$$K_d = (2T+\Delta)(b_0-b_1)/4 \tag{8}$$

If a_1, b_0 and b_1 are identified from the ARX model by using the input/output response, the time constant and gains are determined by Eqs.(6)-(8).

4.2 Phase-2: Quantification of human skill

We defined skill-level parameters of the PTP task by perturbation from the ideal reference trajectory, because the reference can be designed so that it is ideal by considering the physical meanings (minimum acceleration, small overshoot, time optimal, less saturation of input , and so on). Additionally, considering difference between a human's controller and an ideal controller may enable to quantify human skill more precisely. For the later assistant control, the following assist ratio $\alpha[i]$ which corresponds to human skill index is defined.

$$\alpha[i] = w_1\left|\bar{e}_t - e_t[i-1]\right| + w_2\left|\bar{T}_c - \tilde{T}_c[i-1]\right| + w_3\left|\bar{K}_p - \tilde{K}_p[i-1]\right| + w_4\left|\bar{K}_d - \tilde{K}_d[i-1]\right|, \tag{9}$$

where i is the number of trial, $e_t[i]$ is an error computed by

$$e_t[i] = \int_{t_s[i]}^{t_e[i]} \sqrt{(r_x[i]-x_p(t))^2 + (r_y[i]-y_p(t))^2}\,dt, \tag{10}$$

$r_x[i]$ and $r_y[i]$ (= constant for i-trial) are reference positions of the i-th task and $x_p(t)$ and $y_p(t)$ are the *xy*-stage's positions of x and y directions. $t_s[i]$ and $t_e[i]$ are the start and the end time, $\bar{e}_t$ is an minimum error constant performed by an expert. $\bar{K}_p, \bar{K}_d$ and $\bar{T}$ are ideal parameters of an expert, $w_1,\dots w_4$ are weighting factors, and $\tilde{K}_p[i], \tilde{K}_d[i]$ and $\tilde{T}_c[i]$ are operator's parameters identified by using Eqs(6)-(8).

4.3 Phase-3: Design of assist control

Since the target position is known *a priori* and the dynamic characteristic of mechanical of the *xy*-stage can be tuned by the impedance control as desired, ideal control force that yields adequate PTP motions can be computed by using above-mentioned information and models. Therefore, we propose parallel type assistance control structure shown in Fig.6. An assist using an ideal control force is changed according to the skill-level $\alpha(0 \le \alpha \le 1)$.

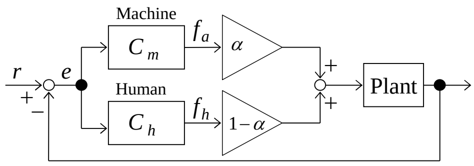

Fig.6. Parallel type assistant control

A situation of support-free (i.e., $\alpha = 0$) means finish of learning. Describing C_h and C_m as the operator's controller and the machine's one, the input control law that should be added to the mechanical parts is given as follows.

$$u = (\alpha \cdot C_m(s) + (1-\alpha)\cdot C_h(s))\cdot e \tag{11}$$

4.4 Evaluation by Experiment

The monitor of the PTP-task is shown in Fig.7(left). As soon as a target(reference location) is displayed on the monitor, the operator moves the pointer(= grip's location) to the target by manipulating the haptic device When position of the pointer can be kept inside the target circle for a few seconds, one PTP task is judged to be finished, and new next target circle is displayed.

A transfer function of the operator's characteristic was identified in real-time by the method mentioned in section 4.1. The input signal is the positional error against the target point, and the time-delay effect is compensated by sifting the measured input signal every step. The output signal is the force that is filtered through a 36Hz LPF. One result is shown in Fig.7(right). The solid line (identified) is a simulated data computed by using an identified human controller model. The identified gains K_p=779.0, K_d=288.0, T=0.18 and *Time delay=0.406[s]* were used in the simulation. The response of the identified model resembles to the actual response one. It can be said that the identification is done sufficiently on-line.

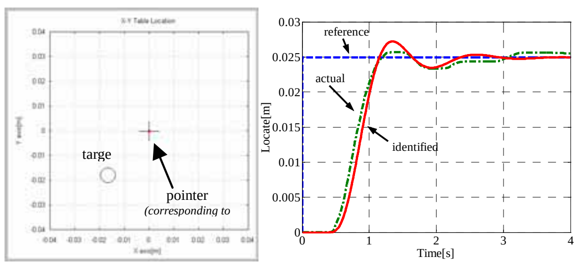

Fig.7 Display of PTP task(left) and Comparison of an actual response and an identifies model's response(right)

4.5 Verification of assist effect

A comparison experiment was executed to investigate the effect of the assistant control. The 50 PTP tasks were imposed on three examinees; two beginners and one expert. One of beginners manipulated the machine without the assist-control (this case is called 'beginner-A' simply). Another beginner executed same operation under the assist-control (this case is called 'beginner-B'). The expert operated the machine under same condition (this case is called 'expert'). The experiment result is shown below. The dotted line is beginner-A (no assist). The solid line is beginner-B(assisted). The dot-dash line is the expert.

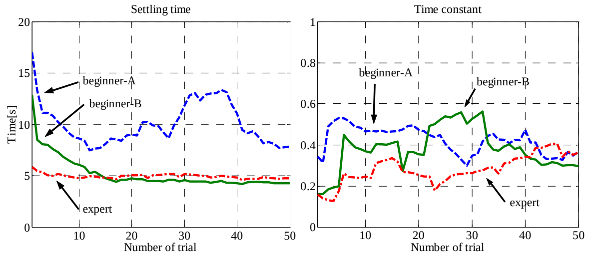

Fig.8 Settling times and time-constant

The left graph in Fig.8 shows a settling times which are duration times by when the pointer has reached into the target circle (the radius is $\pm 0.002m$) and the pointer keeps staying in the inside of the target circle for 3 seconds. The settling time of the expert is smaller than the case of the beginner-A. It is difficult for the beginner-A to make the pointer stay inside the circle because of lack of the friction by the impedance control, since the dynamics of the *xy*-stage is tuned as non-easily manipulation intentionally. From this experimental result, it is found that the settling-time is a significant index to check operation skill. The right graph in Fig.8 shows the time-constant of the operator's transfer characteristic. The value of the expert is smaller than the cases of beginners. Since time-constants of beginners are relatively big, it seems that the slow dynamics of operator's hand causes non-quick operation.

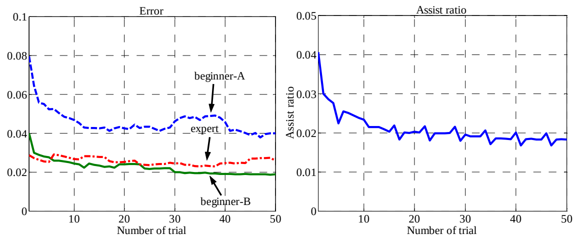

Fig.9. Error and assist ratio

The left graph in Fig.9 shows an error-index computed by Eq.(10). The beginner-A is biggest among the three cases. From the view point of errors, it can be said that the beginner-B, who is supported by the machine, got use to the PTP task. The right graph of Fig.9 shows the evolution of the assist ratio of beginner-B. The decreasing means that the beginner-B is getting used to the operation of the machine. These facts say that the assisted beginner mastered the operation in relative short time like an expert.

5. VISUAL ASSIST BY HA-DISPLAY UNIT

5.1 Basic strategy of HA-display assistant

Let me explain the process on the HA-display by using Fig. 3. Now *r* is a reference signal given to a operator, and he (she) tries to coincide *y* to *r*, where *y* is a position of the machine. It is said that human brain forms models of delays $\tilde{L}$ and dynamics including machine $\tilde{M}(s)$ and own body part $\tilde{P}(s)$ by learning. And human controls all human-machine system by a feedforward control with the learning models finally. Taking this hypothesis into consideration, the second assist-control proposed is a method which acts on these human internal models by adding a reference signal whose dynamics and time-delay are modified. In the figure the HA-display unit modifies $r(t)$ to $r_g(t+\hat{L})$, where $\hat{L}$ is a time-delay for assistance. A function *f* modifies amplitude of the reference signal, and a function *g* adjusts the time-delay, i.e. phase. *f* and *g* are functions such that *f.g*=1 holds after the operator has finished mastering the manipulation sufficiently. The strategy is summarized as follows.

(a) Assist of the learning of positional pattern

Geometric characteristic of trajectories generated by human is analyzed statistically. A guide of motion modified by the statistical result is displayed to the operat or. This operation is realized by a function *f*.

(b) Assist of the learning of time-delay

Time-delay is estimated by comparing a reference and a h uman operating trajectory. The guide of motion is displayed in advance by considering the estimated time -delay. This operation is realized by a function *g*.

5.2 Repetitive task and skill

Repetitive action is needed for human to learn something. From a view of brain science, the learning is considered as shifting information from the working-memory of a brain to the long-term memory. Repetitive action promotes the shifting. This axiom is valid both on the learning of knowledge and on body motion. As a simplest repetitive test of a voluntary motion control, we treat a task of tracking to a moving target along a circle.

Figure 10 is a geometric relation of the repetitive task. Moving points *P,R* and *G* are a pointer manipulated by a operator, a reference marker, and a guide marker which assists the operator, respectively. The marker *R* moves at an angular velocity of ω_0 (=const) along the circle of which radius is r_0(=const). The pointer *P* is moved according to a position of the grip of *xy*-stage. The operator is ordered to chase the marker *R* by using the pointer *P* and to draw a perfect circle. The guide marker *G* moves ahead of the marker *R* in order to show the adequate trace line for the operator. In short, the marker *G* is a support element by the HAM assist-control, and the movement is modified according to the operator's skill level. Let's describe the polar coordination expressions (angle, radius) of points *P,R* and *G* as $(\theta_p, r_p), (\theta_r, r_r)$ and (θ_g, r_g) respectively. An angle of phase-lag of marker P against marker R is denoted as $\phi_p = (\theta_r - \theta_p)$. An angle of the phase-lead of the marker *G* against the marker *R* is denoted as $\phi_g = (\theta_g - \theta_r)$. Benefit of the repetitive task proposed here is geometrical separation of the time-delay and the dynamics into the phase and the radius. This enables easy analysis[15].

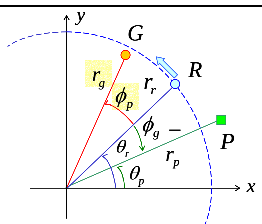

Fig.10 Geometric relation of repetitive motion

Definitions of several variables are shown below. First of all, a history of the marker *P*'s radius on *i*-th laps is described as

$$r_p[i]=[r_{p,1},r_{p,2},\cdots,r_{p,360}]\in R^{1\times 360} \quad (12)$$

where $r_{p,j}$[i] means a radius at θ_p=*j* degree of *i*-lap. The average radius trajectory from all *N*-laps is defined as follows.

$$a_{rad}=\sum_{i=1}^{N}[r_{p,1[i]},r_{p,2[i]},\cdots,r_{p,360[i]}]/N \quad (13)$$

The variance is computed as

$$v_{rad}=\sum_{i=1}^{N}[(r_{p,1[i]}-a_{rad,1})^2,\cdots,(r_{p,360[i]}-a_{rad,360})^2]/N \quad (14)$$

In the case of phases, the average a_ϕ and the variance v_ϕ are defined in similar ways.

5.3 Assistance strategy by HA-display

Human's voluntary motion includes a kinematics properties of limbs and individual characteristics. When repeatability of the motion that is suffered from these characteristics is strong, it can be guessed that variance of the operated trajectories is small. On the other hand, when the operator is still a beginner and he is paying efforts to learn it, it seems that the variance of the resultant trajectory is large. Hence, we guess that skill level can be judged by the check of the variance. Small variance, however, does not always mean the finish of correctly learning. For instance, when an operator has learned one fixed pattern wrongly, value of the variance is plausible small incorrectly. In this case, the machine should give the operator advices that are useful to improve his operation.

When the variance is large, it is better to avoid interference from a machine to an operator because the interference may be disturbance to the operator. The detail procedure is shown below.

1. Cyclic motion of the pointer-*P* is measured and the *N* laps of trajectories are memorized(Below we count *N*-laps data as 'one set data').
2. Averages and variances $a_{rad}, a_\phi, v_{rad}, v_\phi$, of the radius r_p and the phase ϕ_p are computed.
3. The trajectory of the guide marker *G* is obtained by modifying the reference marker *R*'s trajectory according to the level of v_{rad} and v_ϕ.
4. At the next set, the marker *G* is moved by referring the trajectory computed at the step-3. And the operator manipulates the pointer *P* by seeing the movement of the marker *G*.
5. Return to above stpe-2. At the next set, new guide trajectory is computed by updating the one-set former guide trajectory.

Concerning the radius direction, the marker *G* is moved in opposite direction of the averaged radius in proportion to an error between the average and the reference. The radius sequence of the marker *G*, $r_g=[r_{g,1},\cdots,r_{g,360}]$ is computed as

$$r_{g,i}=r_0-k_{1rad}\cdot h(v_{rad,i}\,|\,k_{2rad},k_{3rad})\cdot(a_{rad,i}-r_0), \quad (15)$$

where $h(v\,|\,a,b)$ is a smooth monotonic decreasing function defined as

$$h=1/(1+\exp(-a(v-b))), \quad (16)$$

and $k_{1rad}..k_{3rad}$ are positive parameters. Function (16) emphasizes an update ratio in Eq.(15) when variance $v_{rad,i}$ is small. The other correction law of a phase-sequence for the marker *G* is computed in same manners.

5.4 Experimental result and its analysis

For design of an impedance control, the virtual model's parameters of mass, viscosity and stiffness were chosen as 30kg, 30N.s/m and 0, respectively to obtain a bit difficult control feeling intentionally. Parameters of the repetitive task are chosen as $\omega_0=2\pi/5$ rad/s and r_0=0.02 m. Display scale of the real-time monitor is about 5. Parameters of the HA-display's correct law are chosen as k_{1rad}=10, k_{2rad}=5, k_{3rad}=0.5, $k_{1\phi}$=10, $k_{2\phi}$=5 and $k_{3\phi}$=0.5 by trial and error after checking a maximum variance of test-run. Total 10 set tests (1 set=6 laps) were imposed on an examinee. Ten seconds rest was given to the operator after each set was finished. Data of each first laps was not used to eliminate a transition response. The assistance sequences are updated on each set. Two beginners executed two kinds of tests: one is with the assist-control and another is without the assist-control.

The result is shown in Fig.11. The upper and the lower graphs indicate accumulated error-indexes of the radius and the phase. Those indexes are computed by the following equations.

$$s_{rad}=\sum_{j=1}^{359}\left(r_{p,j}-r_0\right)^2\cdot\pi/180$$

$$s_{phi}=\sum_{j=1}^{359}\phi_{p,j}^2\cdot\pi/360$$

About the radius, there was no difference between two cases(upper graph), but the phase error of the assisted examinee was decreasing significantly faster than the non-supported case(lower graph). It can be said that the assisted operator's skill is enhanced because the error is decreasing as the number of count increases.

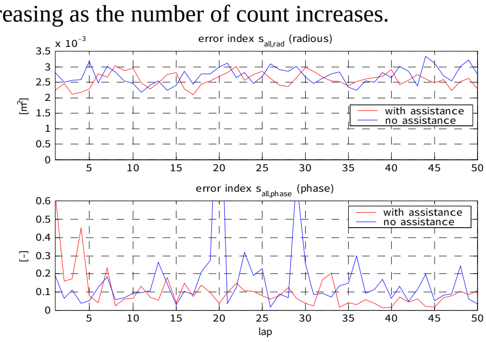

Fig.11 Accumulated tracking errors

Figures 12 and 13 show the evolution of variance in the assisted case and the non-assisted case, respectively. On each figure, the upper and the lower graphs correspond to v_{rad} of the radius and v_ϕ of the phase. The *x*-axis is an count of the laps, *y*-axis is the angle and the vertical axis is values of the variances. In Fig.12, the tall mountains at the range of 1-5 laps of v_{rad} (upper graph) mean that the learning process is still in trial and errors mode. As the lap increases, the shape of the mountains becomes flat, and this means that the repeatability of the cyclic motions increases. In the lower graph of the phases, similar tendency can be confirmed and it can be said that the proficiency was promoted.

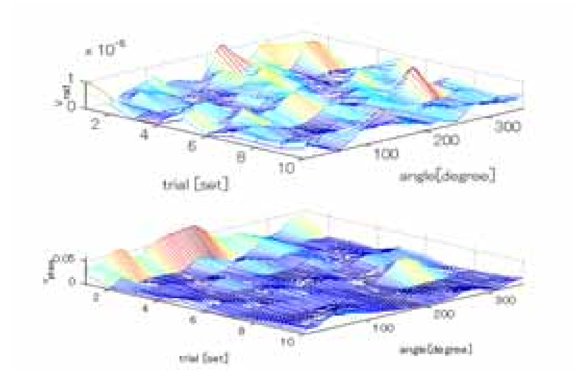

Fig.12 Evolution of variance (assisted case)

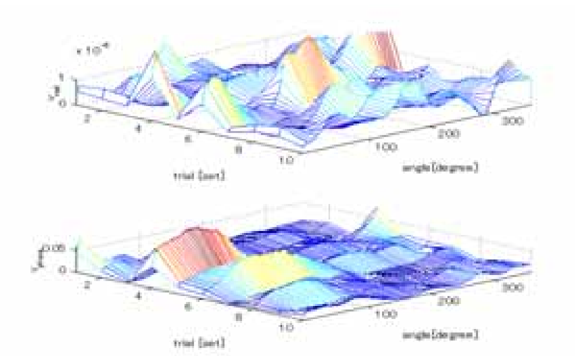

Fig.13 Evolution of variance (non-assisted case)

Other result without support is shown in Fig.13. Especially the variances of the radius did not decrease after the trial was repeated. The operator could not master the manipulation sufficiently.

Above-mentioned results claim that the assistance by the HA-display is effective. The number of the examinees was, however, small, hence the statistical credibility is not sufficient. In future, additional experiments and analysis are necessary.

6. CONCLUSION

A new control system structure including a human-adaptive (HA) mechanical unit and a HA-display unit was proposed as a Human Adaptive Mechatronics(HAM) human-machine system. One design of a HA-mechanical unit, which estimates the human's skill and assists him, was proposed. The quantification is performed using an online identification by assuming that the human's dynamics consist of two system transfer function blocks: a brain controller and neuromuscular dynamics. The assist-control proposed has three components: an ideal control model, an internal virtual model, and a mixer that adjusts ratio between human and machine. The mixer changes the ratio of support force based on an ideal machine's operation and human's direct manipulation.

And the other method: HA-display unit that modifies information indicating to the operator was shown. We introduced a cyclic motion test to deal with both dynamics and time-delay separately. Effectiveness of the visual guide that adapts operator's manipulation was shown by experiments.

As a future research, dynamic time-delay compensation, expansion to nonlinear system, analysis of processes of the learning should be solved. We would like to tackle them at next research stage.

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