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Variable Dynamic Assist Control on Haptic System for Human Adaptive Mechatronics

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***Abstract*— Based on a new concept of a human-in-the-loop system called *Human Adaptive Mechatronics*(HAM), an assist-control for a force/vision interactive haptic system is discussed in this paper. An assist-control scheme proposed here consists of a 'variable dynamics' unit and an online identifier of an operator's control characteristics. The former unit is realized by tuning an impedance of the haptic device's virtual model according to the identified operator's parameters. At a stage of the controller design, a human and a machine are considered as a plant and a controller respectively. A role of the controller is to tune dynamics of the machine so as to enhance operator's control performance. The tuning law is derived by utilizing a Lyapunov candidate function. We developed a HAM-haptic device test system, executed evaluation experiments with the apparatus, and analyzed the measured data. It was confirmed that the operator's characteristics can be estimated sufficiently and that operator's performance was enhanced by the variable dynamics assist-control.**

keywords: Human Adaptive Mechatronics, haptic interface, assist-control, variable dynamics, skill, online identification.

I. INTRODUCTION

An ultimate goal of haptic system research is a creation of new world that gives an intuitive interaction between humans and machines. Common modalities for this interaction include visual (for instance, virtual reality 3D-CG space), haptic (tactile sensing), proprioceptive (gravity imitation), and auditory (surround-sound control) data[1], [2]. So-called 'haptic system' usually treats these data sources simultaneously. Researchers in this field pay carefully attention to a design of whole system structure and a physical interface units so that the information can be transmitted adequately between humans and machines. Control system design is, however, not always paid sufficient attention. In other words, most haptic systems demand that a human gets used to manipulation of the haptic physical interfaces before he(she) can get the feel of the virtual space. Such machines do not adapt to a human, instead the machines implicitly demand that humans adapt to machines.

Changing topics from haptic research to control engineering one, several research activities concerning assist-control are being undertaken[3]. A typical technique to evaluate operator's skill is to check an error between actual motion and canonical one. A similar but more sophisticated method is to compare operator's response with an expert's behavior using a neural network scheme or fuzzy estimation[4]. Such comparisons of the human skill are dominant strategy of assist-control. These assist-control approaches, however, cannot reveal internal properties of an operator, and there is limit of the assist since such a machine cannot change the own characteristics. Roughly, these assists are indirect and conservative. For instance, a typical approach such that suppresses high frequency signals[3] is an *indirect* assist by keeping the stability of the whole human-machine system. Displaying of supplementary information[3] cannot change a human-machine closed-loop characteristic *essentially*. Summarizing above discussion, we think that a real aggressive assist-control that enhances human's operation has 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 a 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[5]. He also indicated that human control action contained considerable non-linearity and that humans have functions of an adaptation, prediction and optimization. In the 1960's, many models to express human control properties were introduced. Ragazz-ini[6] and Iguchi[7] 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 an optimal control for a VTOL aircraft[8]. 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[9], [10] and Smith predictor[11] are well known models of brain's control strategy. However these fruitful results have not spread to practical design of assist-control yet.

II. HUMAN ADAPTIVE MECHATRONICS

Against a background mentioned in the previous section, we proposed one realization of the system structure called 'Human Adaptive Mechatronics(HAM)'[12]. HAM is a new concept which was proposed in our university's research project, 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'. Figure

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1 shows an ordinary man-machine system and an example of a HAM-system. In existing system(upper part of the figure), a human has to learn the dynamics of the machine, i.e. a human estimates a machine model, then uses the estimated model as an inverse model for control. Because the machine does not change itself regardless of human skill, much time and effort is needed for human to become skilled. In the case of a HAM system (shown in the lower part of Fig.1), a human's skill is always estimated by a machine, and the machine supports a human by changing machine's characteristics(in the figure, 'virtual model' unit changes). In this paper, an assist-control to enhance human skill by changing the machine's dynamics is presented based on the above-mentioned idea.

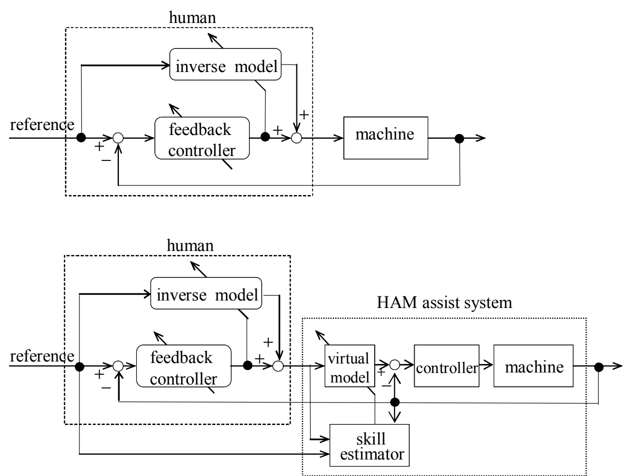

Fig. 1. Comparison of existing man-machine(upper) system and HAM system(lower)

This paper is organized as follows. In Section III, a developed haptic system is explained, and the virtual internal model control is described. The assist-control are described in Section IV. Section V shows experiments and their analysis. Section VI presents the conclusion.

III. HAPTIC TEST SYSTEM FOR HAM

A. System Structure of Apparatus

A haptic test system that we developed is shown in Fig. 2. This system can give appropriate visual information and feedback sense to an operator. The haptic device is made of a two degree-of-freedom planer xy-stage and a real-time monitor. The xy-stage is driven by linear DD-motors. The operator manipulates a grip attached to the xy-stage as he(she) looks at a monitor that displays a pointer corresponding to the grip's position in real time. Force added by an operator is detected by a sensor embedded between the grip and the stage. The x and y axis of the stage do not effect each other due to a mechanically independent design. Virtual internal model control changes the dynamic behavior as desired (the details are explained in subsection III-C). Computations are executed by a PC/AT 3GHz computer under real-time scheduling control. The control interval is 2 ms, and the movable range is about $62mm$ in both x and y directions.

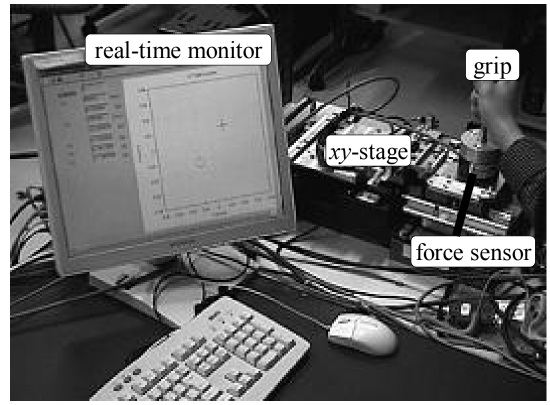

Fig. 2. Haptic test apparatus

B. Task Design for Verification

A point-to-point(PTP) control is a popular task for human-in-the-loop systems. Most material handling operations and hand motions fall into this category. Hence, we adopt a PTP-task for verification of the haptic test. In experiments, target's positions on a PTP task were changed at random so as to keep the distance from each last target to the next target constant. As soon as the target is displayed on the monitor, the operator moves the pointer to the target by manipulating the grip of the xy-stage. When position of the pointer is kept inside the target circle for 3 seconds, one PTP task(= one trial) is judged to be finished, and a new next target circle is displayed at random. The machine investigates operator's characteristics from the measured data and tries to support his(her) operation. In order to make an effort not to have influence of fatigue, 10 seconds rest on every 5 trials were given to subjects.

C. Virtual Internal Model Control

DD-motors of the xy-stage are controlled by local compensators designed using a virtual internal control method with impedance models. The stage is controlled so that it behaves like a virtual model having specified properties of mass, stiffness, and damping. Since the x and y-axis controllers can be designed separately thanks to the mechanical independence, subscripts of x and y are omitted in later discussion.

Dynamic equations of the stage and the virtual model are expressed as follows.

$$m_p \ddot{x}_p + d_p \dot{x}_p = f_h + f_a \quad (1)$$
$$m_r \ddot{x}_r + d_r \dot{x}_r = f_h, \quad (2)$$

where x_*, m_* and d_* are position, mass and viscosity, respectively. Here, for $*$, p means a plant for the stage, and r means the reference model that corresponds to the virtual model. f_h and f_a are a force added by a human and a driving force by an actuator. Defining an error as $e_r := x_r - x_p$, Eqs.(1) and (2) are transformed into

$$\frac{d}{dt}\begin{bmatrix} e_r \\ \dot{e}_r \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} e_r \\ \dot{e}_r \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \tag{3}$$

$$u := \frac{-d_r \dot{x}_r + f_h}{m_r} + \frac{d_p \dot{x}_p - f_h - f_a}{m_p}.$$

Minimizing the error in Eq.(3) makes the stage conform to a response of the virtual model described by Eq.(2). To compensate steady state error, an integral variable $\int e_r$ is taken into consideration in the state vector as follows.

$$\frac{d}{dt} e = Ae + Bu, \tag{4}$$

where

$$A := \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix},\ B := \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ e := \begin{bmatrix} \int e_r \\ e_r \\ \dot{e}_r \end{bmatrix}.$$

A feedback gain F is computed by a LQR method and a final form of the control law is obtained as follows.

$$f_a = \frac{m_p}{m_r}(f_h - d_r \dot{x}_r) + d_p \dot{x}_p - f_h - Fem_p \tag{5}$$

IV. HAM SYSTEM STRUCTURE AND STRATEGY

For an assist-control based on the HAM concept, 'an estimation of human control characteristics(step-1)' and 'assist by machine to human(step-2)' are necessary. Technically, the step-1 is a signal processing and a system identification. Once a form of a human transfer function is decided(if the discussion can be limited to linear case), the identification can be done by a least mean square approximation with an Auto-Regressive eXogenous input(ARX) model. An assist-control of the step-2 utilizes the results which is estimated at step-1, and effects interaction directly between human and machine by adding complemental input Details of this process are explained below.

A. Step-1. Identification of Human Controller

Three components in a voluntary motion using visual information can be considered: a brain controller, neuromuscular dynamics and reaction time delays. Control in a human is awfully complex because various kinds of compensators, such as a oculomotor control, a proprioceptive control and a neuromuscular control, are present[11]. Dynamics of a muscular are changed depending on the circumstance. The delay arises from the process of visual processing and recognition, and the transmission of neural signals from a brain to muscles. There is, however, a fairly large body of data that can be explained by a linear model plus time delay[13] when the operation is limited into narrow range. Moreover we guess that an effect of feedforward component in human controller is weak since hand-manipulation using a real-time monitoring depends on visual feedback information strongly. Therefore, a block diagram of a visual voluntary motion control is simplified into a feedback model as shown in Fig. 3. In the figure, r is a target position for a pointer, e_h is an error with respect to the target and u_h is a command computed by a brain controller. Here the 'plant' block is a xy-stage ,which has dynamic characteristics that are realized by the local virtual internal model control.

The operator measures the distance between a target and the pointer at a glance, and then a command to the muscles is computed in one's brain. Neuromuscular dynamics can often be approximated linearly by a first-order lag[14]. A simplest human controller is considered to be a PD controller[6]. Hence, the human transfer function $G'_h(s)$ can be considered as

$$G'_h(s) = \frac{K_d s + K_p}{Ts + 1} e^{-Ls}, \tag{6}$$

where K_p, K_d, T and L are a proportional gain and a differential gain of human brain controller, a time constant of the neuromuscular system, and reaction time delay, respectively. We have confirmed that the delay of this PTP task is almost constant regardless of the level of operator's skill. Hence, the time delay in Eq.(6) can be ignored for a purpose of identification, and the following model can be obtained.

$$G_h(s) = \frac{K_d s + K_p}{Ts + 1}. \tag{7}$$

Parameters K_p, K_d and T are estimated by a least-square method with a ARX-model that is transformed from Eq.(7) by a bilinear transformation(For the details, please see [15].)

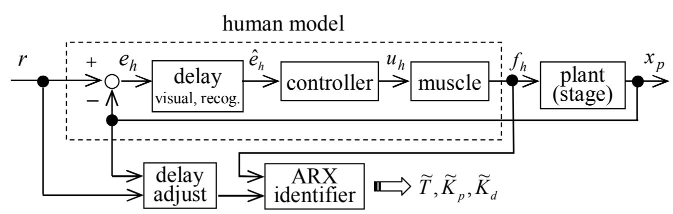

Fig. 3. Human control model and its identification

B. Step-2: Variable Dynamics Assist-control

An assist-control proposed here changes dynamics of the internal model on-line depending on operator's parameters. A block diagram of the assist-control is shown in Fig.4-(A). In the figure, r, y, e, v and f are, a positional reference, a position of the stage, the error, an output of a brain controller, and a force by a hand, respectively. And we assumed that (a) K_p, K_d and T are time-slowing changing parameters, and that (b) parameters of a machine m and b can be tuned. Assumption (b) is realized by a virtual internal model control, and note that m and b are operationable variables in this assist-control. Figure 4-(A) expresses a general human-machine system that includes a controller $(K_p + K_d)/(Ts + 1) =: C$ and a plant $1/(ms + b)s =: P$. We can consider conversely that the system consists of a plant C, of which parameters(K_p, K_d and T) change slowly, and a controller P, whose coefficients(m and b) are variable directly(Fig. 4-(B)).

Note that the output y of new controller P cannot be changed arbitrarily, and that only tuning of the controller's

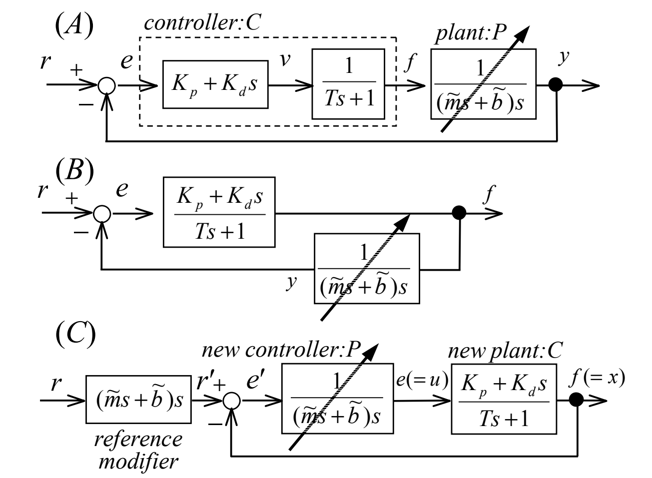

Fig. 4. Transformation of block diagrams for variable dynamics control

coefficients is possible. Transformation of the block diagram shown in Fig. 4-(B) yields a general feedback form as shown in Fig.4-(C). Below, in order to avoid misunderstanding owing to habits, characters for variables are changed as $f \to x,\ e \to u$. Then, the following equations are obtained.

$$x(s) = \frac{K_p + K_d s}{Ts+1}u(s) \tag{8}$$

$$u(s) = \frac{1}{(\tilde m s+\tilde b)s}e'(s) \tag{9}$$

$$e'(s) := r'(s) - x(s) \tag{10}$$

$$r'(s) := (\tilde m s + \tilde b)s \cdot r(s) \tag{11}$$

A purpose of the PTP task is a tracking such that $y \to r$ in the original block diagram shown in Fig.4-(B). This means that $e \to 0$, i.e. $u \to 0$, then Eq.(9) means that $e' \to 0$ as $t \to \infty$. Therefore choosing a Lyapnov candidate V as $V = \frac{1}{2}e'(t)^2$, the condition of convergence is investigated. It can be considered that a closed-loop system shown in Fig.4-(C) is almost stable under the assumptions of (a) and (b), hence it is not always necessary that $dV/dt < 0$ holds in order to keep the stability.

Lyapunov-like analysis is utilized to derive a update law of $\tilde m, \tilde b$. When a step input is chosen for $r(t)$ for a PTP motion, the response of $r'(t)$ given by Eq.(11) becomes almost impulse shape. The response, however, converges to zero rapidly, hence $\frac{d}{dt}r'(t) \simeq 0$ $(t \gg 0)$ holds. Then, a time-derivative of V is simplified and can be transformed as follows.

$$\begin{aligned}\frac{d}{dt}V(t) &= e'(t)\frac{d}{dt}e'(t) \simeq -e'(t)\frac{d}{dt}x(t)\\ &= -e'(t)\frac{d}{dt}\mathcal{L}^{-1}\left[\frac{K_p+K_d s}{Ts+1}\frac{1}{(\tilde m s+\tilde b)s}e'(s)\right]\\ &= -e'(t)\left(\frac{K_p - K_d/T}{\tilde b T - \tilde m}\cdot\phi\left(t,\frac{1}{T}\right)\right.\\ &\quad\left.+\frac{K_p - K_d\tilde b/\tilde m}{\tilde m - T\tilde b}\cdot\phi\left(t,\frac{\tilde b}{\tilde m}\right)\right),\end{aligned} \tag{12}$$

where function $\phi(t,\alpha)$ is

$$\phi(t,\alpha) := \int_0^t e^{-\alpha(t-\tau)}\cdot e'(\tau)d\tau. \tag{13}$$

It is necessary for each term in Eq.(12) to be negative in order to satisfy $dV/dt < 0$ as long as possible, Therefore, the following conditions can be derived.

$$\frac{K_p - \frac{K_d}{T}}{\tilde b T - \tilde m} > (<) 0 \quad if \quad e'(t)\phi(t,\frac{1}{T}) > (<) 0 \tag{14}$$

$$\frac{K_p - \frac{K_d \tilde b}{\tilde m}}{\tilde m - T\tilde b} > (<) 0 \quad if \quad e'(t)\phi(t,\frac{\tilde b}{\tilde m}) > (<) 0 \tag{15}$$

Conversely, if parameters do not fulfill the above inequality conditions, variable parameters $\tilde m, \tilde b$ are tuned so as the unsatisfied condition will be recovered. Now, the following intermediate variables are defined.

$$\delta_1 := \eta_1\cdot(\tilde b T - \tilde m) \tag{16}$$

$$\delta_2 := \eta_2\cdot(\tilde m - T\tilde b) \tag{17}$$

$$\eta_1 := \mathrm{sgn}(K_p - \frac{K_d}{T})\cdot\mathrm{sgn}\left(e'(t)\phi(t,\frac{1}{T})\right) \tag{18}$$

$$\eta_2 := \mathrm{sgn}(K_p - \frac{K_d\tilde b}{\tilde m})\cdot\mathrm{sgn}\left(e'(t)\phi(t,\frac{\tilde b}{\tilde m})\right) \tag{19}$$

Considering signs of a numerator and a denominator of Eq.(14) and signs of $\tilde m$ and $\tilde b$ gives the following update law.

$$\tilde b[t+\Delta] \leftarrow \tilde b[t] + k_1\sigma(\delta_1)\eta_1\cdot|e| \tag{20}$$

$$\tilde m[t+\Delta] \leftarrow \tilde m[t] - k_2\sigma(\delta_1)\eta_1\cdot|e| \tag{21}$$

where k_1 and k_2 are positive constant parameters, Δ is a control interval, brackets in above equations mean a discrete-time point, and a function σ is defined as

$$\sigma(\delta) = \begin{cases} 0 & \delta > 0 \\ |\delta| & \delta < 0 \end{cases}.$$

The other update law is derived from Eq.(15) in same manner.

$$\tilde b[t+\Delta] \leftarrow \tilde b[t] - k_3\sigma(\delta_2)\eta_2\cdot|e| \tag{22}$$

$$\tilde m[t+\Delta] \leftarrow \tilde m[t] + k_4\sigma(\delta_2)\eta_2\cdot|e| \tag{23}$$

Equations (20) $\sim$ (23) are summarized into the following parameter update law.

$$\begin{bmatrix}\tilde b\\ \tilde m\end{bmatrix}_{[t+\Delta]} = \begin{bmatrix}\tilde b\\ \tilde m\end{bmatrix}_{[t]} + \begin{bmatrix}k_1 & -k_3\\ -k_2 & k_4\end{bmatrix}\begin{bmatrix}\sigma(\delta_1)\eta_1\\ \sigma(\delta_2)\eta_2\end{bmatrix} \tag{24}$$

On the implementation, these parameters are updated under the following practical limit to ensure adequate action.

$$\underline{b} < \tilde b < \bar b, \quad \underline{m} < \tilde m < \bar m, \tag{25}$$

where $\underline{b}, \bar b, \underline{m}$ and $\bar m$ are constant. Here parameters k_i are chosen as they satisfy $k_1k_4 - k_2k_3 \neq 0$. Integral computation described in Eq.(13) is executed by using the following alternative online recursive computation.

$$\phi[t,\alpha] = e^{-\alpha\Delta}\phi[t-\Delta,\alpha] + e'[t]\Delta \tag{26}$$

Since Eq.(11) cannot be computed directly, an approximation as $(\tilde{m}s+\tilde{b})s \sim \frac{(\tilde{m}s+\tilde{b})s}{(0.01s+1)^2}$ is used, and the response is computed by the Eular integration with the state-space model which is derived via controllable canonical form. K_p, K_d and T are identified on every PTP-task and are updated according to an appropriateness of the identification result.

V. EXPERIMENT AND ANALYSIS

A. Online Identification of Human Controller

For a design of a virtual internal model control of the xy-stage, the initial parameters were chosen as $\tilde{m}[0] = 50\ [kg]$, $\tilde{b}[0] = 50\ [Ns/m]$. We assumed that the two direction separation of human control characteristics is possible, because nonlinearity depending on the geometrical position of hand is weak due to the narrow movable range of the grip. Hence, the identification was performed using only x-component response data. An input for the identification is an error between the current position and the target one. The output is a force filtered through a 36Hz LPF. The time-delay effect is compensated by sifting the measured input signal at every PTP motion. The data was decimated by a factor of 10 for an identification, i.e. identification sampling time is 20 ms. One result of the identification is shown in Fig. 5. The solid curve is a simulated step response that is computed using an identified human controller model and virtual stage's dynamics model. In this case, the identified parameters $K_p = 779.0, K_d = 288.0, T = 0.18$ and the time delay $= 0.406$ were used in simulation. Since a response of the identified model resembles to the actual response, it can be said that the dentification process was reasonable.

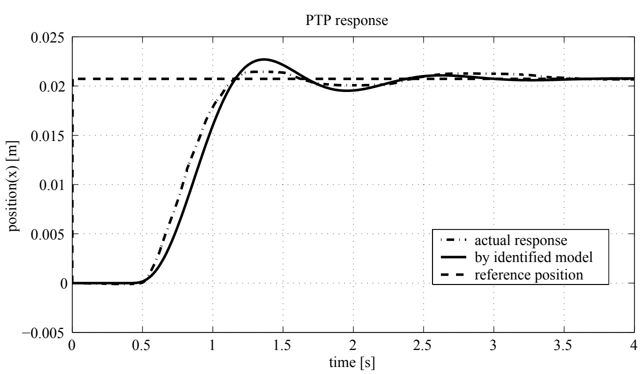

Fig. 5. Comparison of responses of PTP task

B. Verification of Effect of Assist

Before the assist-control was applied to a subject, a learning trials were given to him sufficiently so as to become an expert[1]. The learning trials were executed under fixed parameters which are same values as initial ones of an assist-control. In other words, a subject who mastered the operation sufficiently against the fixed internal model was prepared.

[1] We judged that his performance was expert after no further improvement could be confirmed.

Parameters of the update law in Eq.(24) were chosen as $k_1 = k_4 = 1 \times 10^{-4}, k_2 = k_3 = 2 \times 10^{-4}$. Figure 6 shows evolution of settling time, which is calculated as the time taken for the pointer to reach the target circle. When three seconds passed after the pointer was kept staying inside the circle, we judged the pointer was stopped by the operation. The value of y-axis is the time from which the three seconds was subtracted. The dots show the raw data, and the solid line shows the evolution of trend obtained by moving average computation against 5 PTP tasks. We can recognize that the settling time was decreasing. Figure 7 shows an evolution of the accumulation errors $\int |e(t)|dt$ of each trial. The dashed line is the raw value, and the solid line is the result of the moving average. It can be confirmed that the error was decreasing and that response of PTP operation was improved. Figure 8 shows the evaluation of tuned parmeters $\tilde{m}$ and $\tilde{m}$.At the beginning of trials, the values were constant, because we enabled the assist-control after $50sec$. After about $150sec$, $\tilde{m}$ was saturated at the lower limit value that is limited by mechanical safety. The reason is that the update law (24) cannot guarantee a convergence of the parameters yet. It is necessary to consider conditions which can avoid monotonic increasing as a future work. Results of the experiment, however, showed that the proposed assist-control works well, and it can be said that the total performance of whole human-machine system can be enhanced by changing the machine itself.

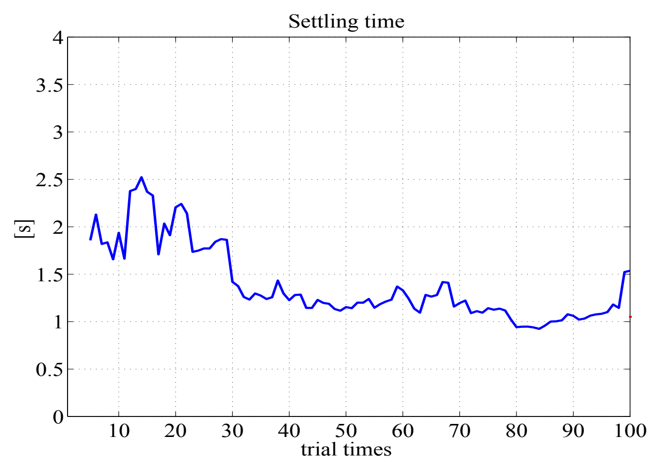

Fig. 6. Evolution of settling time

VI. CONCLUSION

For a force-feedback haptic interface system, a new assist-control adapting to a human to enhance the control performance was proposed based on a concept of Human Adaptive Mechatronics(HAM). The strategy consists of an identification of an operator's control characteristics and an automatic tuning of dynamic property of the machine. The tune is done by changing impedance parameters of a virtual internal model for the machine. An update law of the tune was derived by utilizing Lyapunov stability concept. By

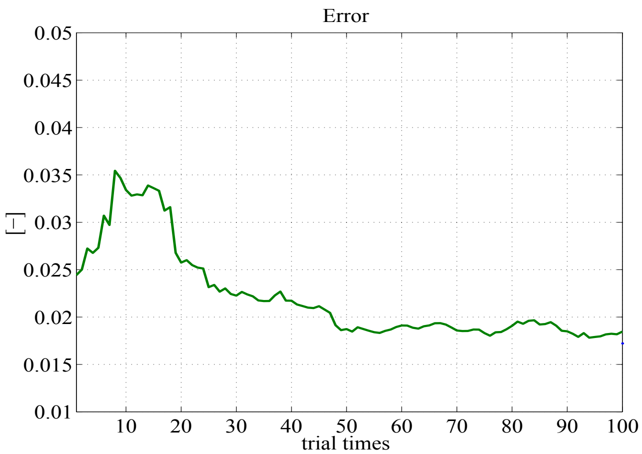

Fig. 7. Evolution of error

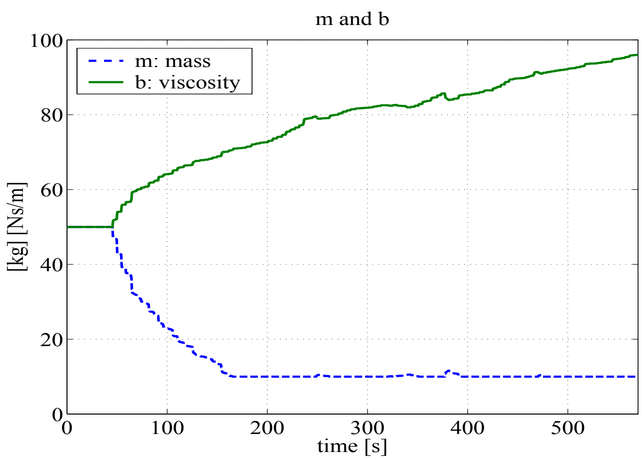

Fig. 8. Evolution of tuned parameters

using the developed haptic 2-DOF test system, it was shown that proposed assist-control works effectively.

An approach proposed here is merely the beginning of our research. Many issues that should be resolved remain before us. As the example, a tuning law mentioned in this paper cannot guarantee a convergence to constant values without reaching to the safety limit. Strictly speaking, a human is considered as unknown system and the behavior is also unknown. Hence other method that can cope with such abnormal operation may be needed additionally. We would like to report further results in future.

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References

[1] V. Hayward, S.R. Astley M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre, "Haptic Interfaces and Devices," Sensor Review, vol.24, no.1, pp.16–29, 2004.

[2] S.P. DiMaio, S.E. Salcudean, C. Reboulet, S. Tafazoli and K. Hashtrudi-Zaad "A virtual excavator for controller development and evaluation," in *proc. of the IEEE International Conference on Robotics and Automation*, pp.52–58, 1998.

[3] M. Yoneda, F. Arai, T. Fukuda, K. Miyata, and T. Naito, "Operational Assistance for Straight-line Operation of Rough Terrain Crane," in *proc. of IEEE International Conference on Systems, Man, and Cybernetics(SMCf99)*, vol.IV, pp.IV27–IV32, 1999.

[4] M.C. Nechyba, and Y. Xu, "Human Control Strategy: Abstraction, Verification and Replication," IEEE Control Systems Magazine, vol.17, no.5, pp.48–61, 1997.

[5] A. Tustin, "The Nature of the Operator's Response in Manual Control and its Implications for Controller Design," Journal of Instn. of Elect. Engrs., vol.94, Part.IIA, pp.190–202, 1947.

[6] J.R. Ragazzini, "Engineering Aspects of the Human Being as a Servo-Mechanism," *Meeting of the American Psychological Association,* 1948.

[7] M. Igutsi, "Human-Machine sytem," Kyo-ritsu publishing(in Japanese), 1970.

[8] S. Baron, D.L. Kleinman, and W.H. Levison, "An Optimal Control Model of Human Response Part II: Prediction of Human Performance in a Complex Task," Automatica, vol.6, pp.371–383, 1970.

[9] D.M. Wolpert, and M. Kawato, "Multiple paired forward and inverse models for motor control," Neural Networks, vol.11, pp.1317–1329, 1998.

[10] M. Kawato, "Internal models for motor control and trajectory planning," Motor systems, pp.718–727, 1999.

[11] R.C. Miall, D.J. Weir, D.M. Wolpert, and J.F. Stein, "Is the Cerebellum a Smith Predictor ?," Journal of Motor Behavior, vol.25, no.3, pp.203–216, 1993.

[12] K. Furuta, "Control of Pendulum: From Super Mechano-System to Human Adaptive Mechatronics," in *proc. of the 42nd IEEE Conference on Decision and Control,* Maui, Hawaii USA, Plenary, pp.1498–1507, 2003.

[13] D.L. Kleinman, S. Baron, and W.H. Levison, "An Optimal Control Model of Human Response Part I: Theory and Validation," Automatica, vol.6, pp.357–369, 1970.

[14] A. Phatak, H. Weinert, I. Segall, and C.N. Day, "Identification of a Modified Optimal Control Model for the Human Operator," Automatica, vol.12, pp.31–41, 1976.

[15] K. Kurihara, S. Suzuki, F. Harashima, and K. Furuta, "Human Adaptive Mechatronics(HAM) for Haptic System," in *proc. of the 30th Annual Conference of the IEEE Industrial Electronics Society(IECON'04)*, Busan, Korea, in CD-ROM, 2004.

[16] S. Suzuki, K. Kurihara, K. Furuta, and F. Harashima, "Assistance Control on Haptic System for Human Adaptive Mechatronics," Advanced Robotics, vol.20, no. 3, accept.