Output Feedback Adaptive Controller Model for Perceptual Motor Control Dynamics of Human

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1. Introduction

The construction of collaborative human-machine system is being recognized as an important technology from the viewpoint of human centered assisting system development (Takahashi and Ikeura, 2006; Yamada and Utsugi, 2006). While such assisting systems aim at partial replacement of control task or an amplification of control power, those have insufficiency in order to achieve the accurate maneuvering, where human performs as a main controller in the human-machine system. For the purpose of improvement of the maneuvering performance and the response of human-machine system, authors have developed a new compensator named as "collaborater", which can support the collaborative work of human and machine (Ohtsuka et al., 2007, Ohtsuka et al., 2009). The model of human response behavior is required to design the collaborater and the collaborative assisting system, but it has been difficult to construct an accurate model of human perceptual motor control system (e.g., limb and muscle). Kleinman et al. applied optimal control theory to develop a model of human behavior in manual tracking tasks (Kleinman et al., 1970). Their model contains time delay, a representation of neuromotor dynamics, and controller remnant as limitations.

Recently, Furuta considers that the analysis of human control action is one of fundamental problems in the study of human adaptive mechatronics (Furuta et al., 2004). From such a viewpoint, in the authors' previous study, Delayed Feed-Forward (DFF) Model has been used for describing human's hand-tracking motion with visual information (Ishida and Sawada, 2003). The DFF model can realize the characteristics that the limb motion, with prediction of target position, makes the predicted value to minimize the transient error in the considering frequency range. However, for the non-cyclical target value and/or the controlled machine output, it has been resulted in that the DFF model has an insufficient reliance because of the shortage of consideration through the experimental study.

In this paper, for the upper limb motion in the hand-tracking control, a new Perceptual Motor Control Model (PMCM) is considered. Namely, the visual feedback controller is represented as the output feedback type adaptive controller stabilizing the closed loop system based on an Almost Strict Positive Real (ASPR) characteristic of the controlled system. The Parallel Feed-forward Compensator (PFC) has been introduced in order to make an ASPR augmented system (Iwai et al., 1993). And, Miall et al. have proposed a human's brain model by introduction of Smith Predictor (as forward internal model) in order to predict the consequences of actions and to overcome pure time delays of neuro-motor signal transmission associated with feedback control (Miall et al., 1993). So, taking into account of those approaches, both PFC and Smith Predictor are located into the minor feedback loop for the output feedback adaptive controller. So, the PMCM has similar structure to the cerebrum-cerebellum neuro-motor signal feedback loop. The effectiveness of the proposed PMCM is discussed through a comparison of the experiment and simulation results.

2. Output Feedback type Adaptive Control System

In this section, as a preparation for discussion about the PMCM of human, we briefly outline an output feedback adaptive control method, where the controller is designed to realize the plant output converging to reference signal.

2.1 Configuration and Controlled Plant

Let us consider the following SISO plant:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + \mathbf{b}u(t) \\ y(t) &= \mathbf{c}^T\mathbf{x}(t) + du(t) \end{aligned} \tag{1}$$

, where $\mathbf{x}$ is the nth order state vector, u and y are scalar input and output, respectively. A, $\mathbf{b}$, $\mathbf{c}$ and d are unknown matrix, vectors with appropriate dimensions, and scalar. The transfer function form of the plant Eq.(1) is expressed by

$$G(s) = \mathbf{c}^T(sI - A)^{-1}\mathbf{b} + d = \frac{N(s)}{D(s)} \tag{2}$$

, where

$$\begin{cases} N(s) = b_m s^m + b_{m-1}s^{m-1} + \cdots b_1 s + b_0 \\ D(s) = s^n + a_{n-1}s^{n-1} + \cdots a_1 s + a_0 \end{cases} \tag{3}$$

Now, we make the following assumption.

Assumption 1 The Plant Eq.(1) or Eq.(2) is ASPR(Almost Strictly Positive real). From this assumption, there exists a constant gain k_p such that the transfer function

$$G_C(s) = (1 + k_p G(s))^{-1}G(s) \tag{4}$$

is SPR(Strictly Positive Real). $G_C(s)$ Eq.(4) can be expressed by the following state space representation:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= (A - k_p\overline{\mathbf{b}}\mathbf{c}^T)\mathbf{x}(t) + \overline{\mathbf{b}}v(t) \\ y(t) &= \overline{\mathbf{c}}^T\mathbf{x}(t) + \overline{d}v(t) \end{aligned} \tag{5}$$

where,

$$\overline{\mathbf{b}} = \frac{\mathbf{b}}{1 + dk_p},\ \overline{\mathbf{c}}^T = \frac{\mathbf{c}^T}{1 + dk_p},\ \overline{d} = \frac{d}{1 + dk_p} \tag{6}$$

by taking into account of that state space representation of $G(s)$ as Eq.(1).
Sufficient condition for Assumption 1 can obtained, such that (1) $N(s)$ is Hurwitz polynomial, (2) $\gamma = n - m \leq 1$, and (3) $b_m > 0$ (Kaufman et al., 1998).

In practice, it is necessary for the realization of the output feedback adaptive control system that the controlled plant must satisfy the ASPR condition in Assumption 1. Unfortunately, this condition is not satisfied by most real systems. Namely, many practical plant satisfies $d = 0$ and the relative degree of plant is larger than 1. To overcome this problem, several types of PFC (Parallel Feed-forward Compensator) have been proposed.(Z.Iwai and M.Deng, 1994; Z.Iwai and H.Ohtsuka, 1993; H.Kaufman and K.Sobel, 1998) For example, Iwai et.al. (Z.Iwai and M.Deng, 1994) have shown the following theorem giving the design procedure of PFC.

Theorem 1(Z.Iwai and M.Deng, 1994) Augmented plant $G_a(s)$:

$$G_a(s) = G(s) + G_f(s) \tag{7}$$

becomes ASPR system and the output of augmented plant $y_a(t)$ approximately equals to the plant output $y(t)$, if the transfer function of PFC $G_f(s)$ is given as

$$G_f(s) = \sum_{i=1}^{\gamma-1} \bar{\delta}^i G_i(s) \tag{8}$$

$$G_i(s) = \frac{\bar{\beta}_i n_i(s)}{d_i(s)} \tag{9}$$

where, $d_i(s)$ is n_{di} -th order monic stable polynomial, $n_i(s)$ is $m_{ni} = \{n_{di} - (\gamma - i)\}$-th order monic polynomial ($m_{ni} \geq 0$), $\bar{\delta}$ is sufficiently small positive constant, and $\bar{\beta}_i$ are coefficients of the Hurwitz polynomial:

$$R(s) = \bar{\beta}_{\gamma-1} s^{\gamma-1} + \cdots \bar{\beta}_1 s + \bar{\beta}_0 \tag{10}$$

(Proof) See the reference. (Z.Iwai and M.Deng, 1994)

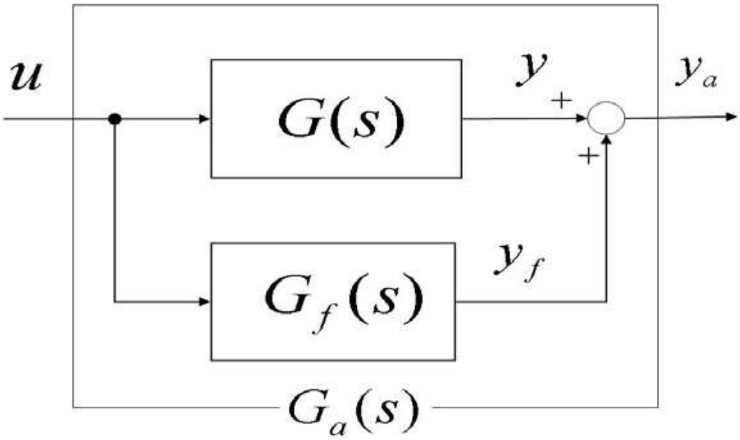

Fig. 1. Augmented Plant with PFC

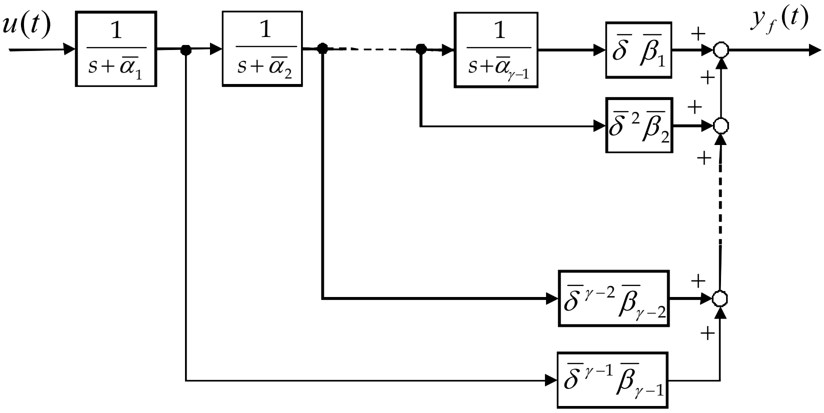

Fig. 2. Ladder Network type PFC

While Theorem 1 gives a general structure of PFC, the practical realization of PFC with simple structure is shown in Fig.1 and can be described as follows.

$$\begin{cases} n_i(s) = s^\rho \\ d_{\gamma-i}(s) = (s+\bar{\alpha}_0)^\rho \bar{d}_{\gamma-i}(s) \\ \bar{d}_{\gamma-i}(s) = (s+\bar{\alpha}_i)\bar{d}_{\gamma-i+1}(s) \\ \bar{d}_\gamma(s) = 1 \\ \bar{\alpha}_i > 1 \end{cases} \tag{11}$$

where $i = 1,2,\cdots,\gamma-1$. In Theorem 1, $n_i(s) = s^\rho$ is introduced in order to remove an offset (steady state error on plant output) caused by the addition of PFC. In the case of the step type reference signal, *r* is given as 1. Fig.2 shows the one of practical realization of PFC based on the Theorem 1.

2.2 Basic Adaptive Control Algorithm

Under the Assumption 1, the following adaptive algorithm:

$$u(t) = k(t)e(t) \tag{12}$$

$$\dot{k}(t) = g\, e(t)^2 \tag{13}$$

generates the control input of the plant Eq.(1), where $e(t)=r(t)-y(t)$ and *g* is positive constant.

2.3 Stability

The following theorem can be obtained under the Assumption 1.

Theorem 2 Suppose that the Assumption 1 is satisfied. Then, the adaptive control law Eqs.(12),(13) can achieve the output error convergence to zero, namely

$$\lim_{t\to\infty} e(t) = 0 \tag{14}$$

(Proof) Under the assumption 1, let us consider an ideal plant state vector $\mathbf{x}^*(t)$ which can satisfies $e(t)=0$, $(t \geq 0)$, then the following relationship:

$$\begin{aligned} \dot{\mathbf{x}}^*(t) &= A\mathbf{x}^*(t) \\ y^*(t) &= \mathbf{c}^T\mathbf{x}^*(t) \end{aligned} \tag{15}$$

is held by using the output feedback control:

$$u^*(t) = k^* e(t) \tag{16}$$

from Eqs.(1)and(12). Eq.(15) is called as an ideal plant. Now, suppose that the state error vector is defined as

$$\mathbf{e}_x(t) = \mathbf{x}(t) - \mathbf{x}^*(t) \tag{17}$$

from Eqs.(1) and (15), we have

$$\begin{aligned} \dot{\mathbf{e}}_x(t) &= A\mathbf{e}_x(t) + \mathbf{b}u(t) \\ e(t) &= \mathbf{c}^T\mathbf{e}_x(t) + du(t) \end{aligned} \tag{18}$$

So, rewriting the control law as

$$u(t) = \bar{k}(t)e(t) + k^*e(t) = \bar{u}(t) + k^*e(t) \tag{19}$$

$$\bar{k}(t) = k(t) - k^* \tag{20}$$

$$\bar{u}(t) = \bar{k}(t)e(t) \tag{21}$$

gives next equation from Eqs.(18) and (19).

$$e(t) = \bar{\mathbf{c}}^T\mathbf{e}_x(t) + \bar{d}\bar{u}(t) \tag{22}$$

Substitution of the above equation into Eq.(18) gives

$$\begin{aligned} \dot{\mathbf{e}}_x(t) &= A\mathbf{e}_x(t) + \mathbf{b}(\bar{u}(t) + k^*e(t)) \\ &= (A + k^*\bar{\mathbf{b}}\mathbf{c}^T)\mathbf{e}_x(t) + \mathbf{b}\frac{1}{1+dk^*}\bar{u}(t) \\ &= (A + k^*\bar{\mathbf{b}}\mathbf{c}^T)\mathbf{e}_x(t) + \bar{\mathbf{b}}\bar{u}(t) \end{aligned} \tag{23}$$

Thus, we have the following error system representation.

$$\begin{aligned} \dot{\mathbf{e}}_x(t) &= (A + k^*\bar{\mathbf{b}}\mathbf{c}^T)\mathbf{e}_x(t) + \bar{\mathbf{b}}\bar{u}(t) \\ e(t) &= \bar{\mathbf{c}}^T\mathbf{e}_x(t) + \bar{d}\bar{u}(t) \end{aligned} \tag{24}$$

Then, it follows from assumption 1 and the Kalman-Yakubovich lemma (H.Kaufman and K.Sobel, 1998) that there exist $n \times n$ positive symmetric matrices P and Q and vector l and scalar w satisfying the following equations:

$$\begin{aligned} &(A + k^*\bar{\mathbf{b}}\mathbf{c}^T)^T P + P(A + k^*\bar{\mathbf{b}}\mathbf{c}^T) = -Q - ll^T \\ &P\bar{\mathbf{b}} = \bar{\mathbf{c}} - wl \\ &2\bar{d} = w^2 \end{aligned} \tag{25}$$

Take the positive function:

$$V(t) = \mathbf{e}_x(t)^T P \mathbf{e}_x(t) + \frac{\bar{k}(t)^2}{g} \tag{26}$$

Then, because the following relationship holds

$$\dot{\bar{k}}(t) = g\, e(t)^2 \tag{27}$$

from Eqs.(13) and (20), the following equation is obtained.

$$\begin{aligned}\dot{V}(t) = {} & \mathbf{e}_x(t)^T \left\{(A - k^* \overline{\mathbf{b}}\mathbf{c}^T)^T P + P(A - k^* \overline{\mathbf{b}}\mathbf{c}^T)\right\} \mathbf{e}_x(t) + 2\mathbf{b}^T P \mathbf{e}_x(t)\bar{k}(t)e(t) + 2\bar{k}(t)e(t)^2 \\ = {} & -\mathbf{e}_x(t)^T \mathrm{Q}\, \mathbf{e}_x(t) - \mathbf{e}_x(t)^T l l^T \mathbf{e}_x(t) + 2\mathbf{c}^T \mathbf{e}_x(t)^T \bar{k}(t)e(t) \\ & - 2wl^T \mathbf{e}_x(t)\bar{k}(t)e(t)^2 + 2\bar{k}(t)e(t)^2 \\ = {} & -\mathbf{e}_x(t)^T \mathrm{Q}\, \mathbf{e}_x(t) - \mathbf{e}_x(t)^T l l^T \mathbf{e}_x(t) - w^2(\bar{k}(t)e(t))^2 - 2wl^T \mathbf{e}_x(t)\bar{k}(t)e(t) \\ = {} & -\mathbf{e}_x(t)^T \mathrm{Q}\, \mathbf{e}_x(t) - \left\{\mathbf{e}_x(t)^T l + w\bar{k}(t)e(t)\right\}^2 \le 0\end{aligned} \tag{28}$$

From the above relationships, we can see that $V(t)$ is the Lyapnov function and both $\mathbf{e}_x(t)$ and $\bar{k}(t)$ asymptotically converge to zeros. Namely, from (28), we obtain Eq.(14).

(End of Proof)

2.4 Modified Adaptive Adjusting Law

Furthermore, against to the input disturbance and to the un-modeled dynamics of the plant, the following modified adaptive adjusting law

$$\dot{k}(t) = -\sigma\, k(t) + g \frac{e(t)^2}{1 + \varepsilon\, e(t)^2} \tag{29}$$

can be utilized in order to maintain that the all signals in the closed loop system become uniformly ultimate bounded (UUB), where σ and ε are given as sufficiently small positive constants (Iwai et al., 1993).

However, Assumption 1 is not satisfied by most practical systems with large relative degree $\gamma > 1$. In this case, the stability of closed loop system can also be maintained while the all signals in the closed loop system are uniformly ultimately bounded (UUB). (Z.Iwai and H.Ohtsuka, 1993)

3. Neuro-motor Apparatus Model

In the brain science, the cerebellum has attracted the attention of theorists and modelers and the need for a unifying theory for the role of the cerebellum in motor control has been recognized for many years (R.C.Miall and J.F.Stein, 1993; M.Ito, 1970; D.M.Wolpert and M.Kawato, 1998; D.L.Kleinman and W.H.Levison, 1970). Specially, based on data from the control of the primate arm in visually guided tracking tasks, Miall et.al. suggested that the cerebellum acts as a Smith Predictor, which is based on internal representation of controlled object suffering with long and unavoidable feedback delays. Ito et.al. (M.Ito, 1970) also suggested that there exists the cerebrum-cerebellum neuro-motor signal feedback loop (Fig.3) and the cerebellum may form the internal model, based on physiological and clinical evidence. There are two variety of internal model, forward and inverse models (D.M.Wolpert and M.Kawato, 1998). Forward models capture the forward or causal relationship between inputs to the system, such as the arm, and the outputs. The Smith predictor can be regarded as a kind of forward model. While we can overcome the issue for the pure time delay by using a Smith predictor, the performance of visual feedback control is mainly affected by the setting of output feedback gain.

However, conventional most of neuro motor models have fixed the feedback gain as constant. On the other hand, many control engineering researcher study about the adaptive control method based on the ability of animal to adapt itself to changes in its surroundings.

Taking into account the above-mentioned brain science researchers' suggestions, and based on the output feedback type adaptive control strategy described in above section, let us construct a new perceptual motor control model as shown in Fig.5 for the control problem as shown in Fig. 4 in which a human operator controls the machine to follow the target. In later the time delay of nervous system transmission is successfully compensated, the controlled system from a side of the output feedback controller becomes a series of three elements consisted of a first lag model with time constant τ_1 which is a model of brain dynamics, a first lag model with time constant τ_2 which is one of muscle dynamics, and a controlled machine dynamics $G_P(s)$. To construct a stable output feedback adaptive control system, the ASPR compensation must be implemented for such a series of three elements. Here, suppose that such ASPR compensator forms as PFC whose transfer function described as $F(s)$. Then, both the Smith predictor and PFC can located into the minor feedback loop for the adaptively adjusted output feedback gain k, as shown in Fig.5. Here, it eases to recognize that the structure of proposed perceptual motor control model is very similar to the cerebrum-cerebellum neuro-motor signal feedback loop model (Fig.3). Namely, we can imagine that the Smith predictor and PFC perform the role of cerebellum, which generates the forward model of controlled object.

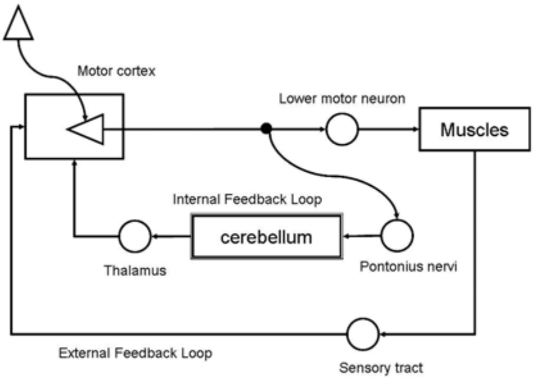

Fig. 3. Cerebrum & cerebellum (M.Ito, 1970)

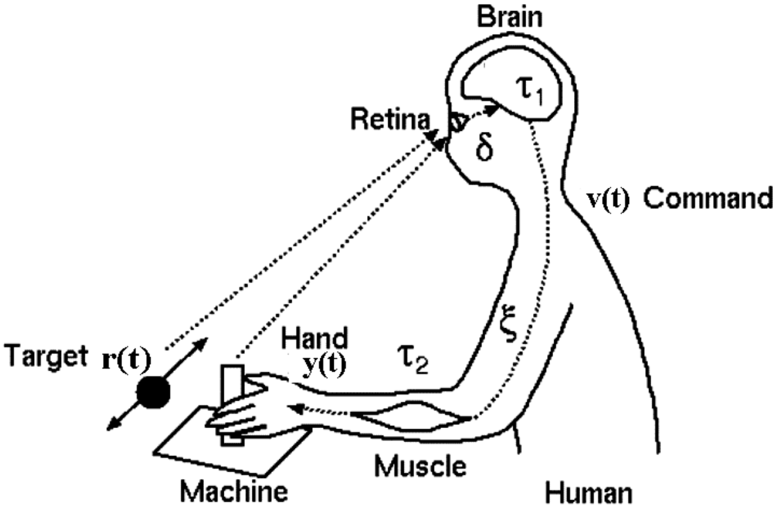

Fig. 4. Human Body Dynamics

Notation	Parameters and Variables
$r(t)$	position of the target
$y(t)$	position of the hand
$v(t)$	command signal from the brain
δ	dead time in the nervous system from the retina to the brain
ξ	dead time in the nervous system from the brain to the muscle
τ_1	time constant of the brain
τ_2	time constant of the muscle dynamics

Table 1. Parameters and variables

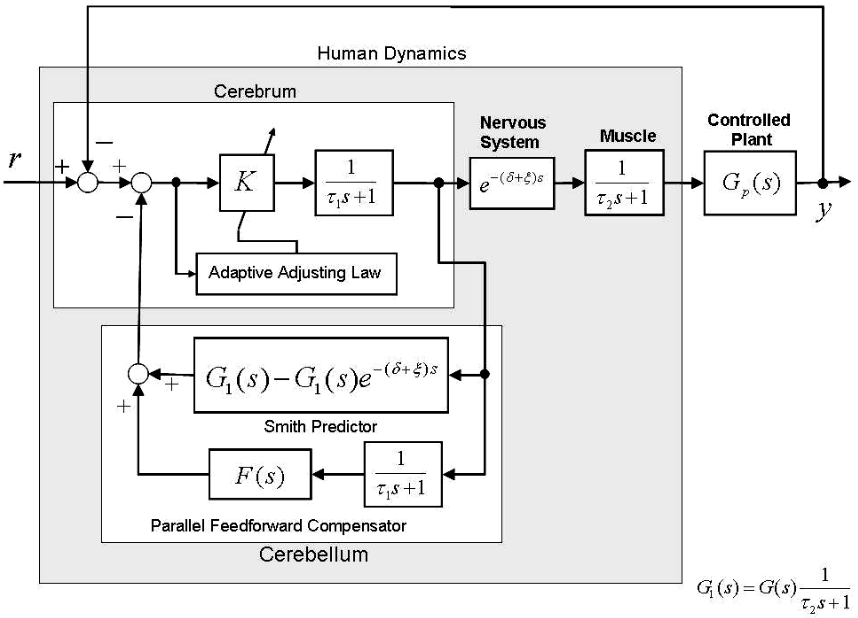

Fig. 5. Perceptual Motor Control Model

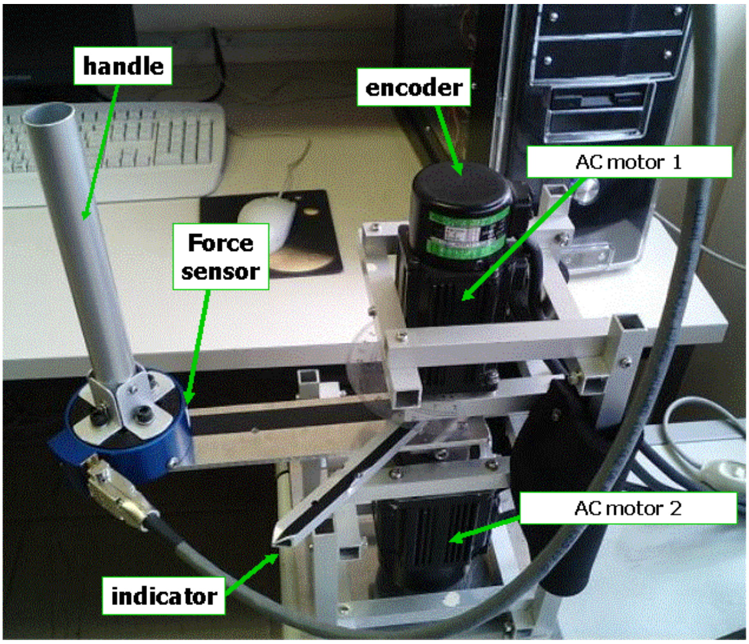

Fig. 6. Experimental Equipment

4. Experiments

Fig.6 shows the experimental equipment. An indicator shows the target position, which is driven by AC motor 1, and an operator controls a handle to follow the indicator. AC motor 2 is assembled in order to generate the assisting torque for human, while it performs as load inertia for human in this stage.

Mechanical System: From the experimental results of automatic positioning control, the transfer function of the one-link arm mechanism involving AC motor 2: $G_P(s)$ was estimated as follows.

$$G_P(s) = \frac{4213}{s(s+1)} \tag{30}$$

Human Dynamics model: Through the experimental results, the parameters of human dynamics model are estimated such that $\delta + \varsigma = 0.13$ [s], $\tau_1 = \tau_2 = 0.03$ [s], respectively (Saito and Nagasaki, 2002).

Perceptual Motor Control Model: In this case, the controlled system from a side of the output feedback controller, which is the above-mentioned series of three elements are given as follow.

$$G_1(s) = \frac{4213}{s(s+1)(0.03s+1)^2} \tag{31}$$

Because it has a relative order as 4 and minimum phase characteristics, PFC: $F(s)$ in Fig.5 is constructed based on Theorem 1 as follows:

$$\begin{aligned} F(s) &= \frac{f_1 s}{(\tau_1 s+1)(s+\alpha)^2} + \frac{f_2 s}{(\tau_1 s+1)(s+\alpha)} \\ &= \frac{350\,s}{(0.03\,s+1)(s+0.5)^2} + \frac{6\,s}{(0.03\,s+1)(s+0.5)} \end{aligned} \tag{32}$$

Results of Experiment and simulation: Experimental results for the target position r(t)=30 [degree] are shown as Fig.7 and Fig.8. And, Fig.9 and Fig.10 also shows the simulation results for the variance of design parameter g in Eq.(13). For the variance of design parameter of PFC, we can obtain the simulation results shown in Figs.11 and 12. In the simulation, the other parameters in Eq.(6) are given as $k(0) = 0$, $\sigma = 0.1$, $g = 0.009$, $\varepsilon = 0.01$.

Although there exists some fluctuation in the experimental results obtained for 3 testers, we can recognize that the both responses are very similar. Because, by comparing between Fig.7 and Fig.9/Fig.11, the overshoots are almost same level and the damping ratio and the values of peak time are close resemblance.

Furthermore, comparing between Fig.8 and Fig.10/Fig.12, these signals also show a close

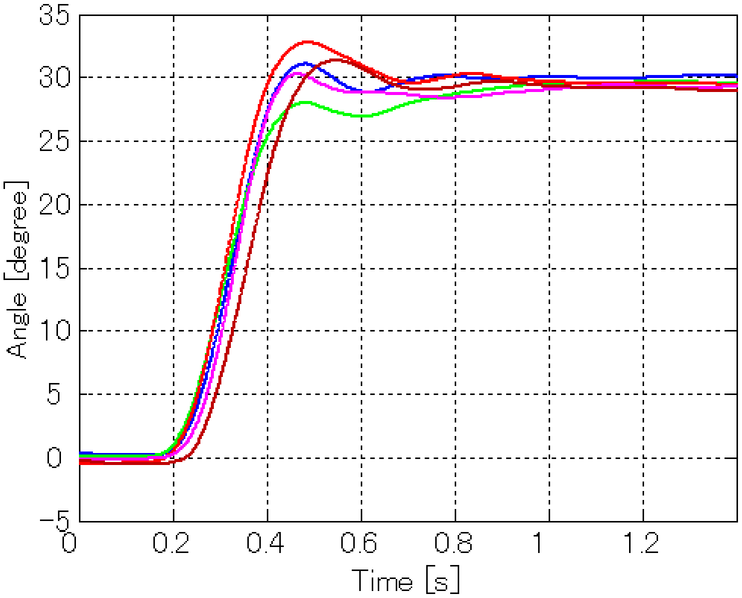

Fig. 7. Experimental Result (Output: Angle)

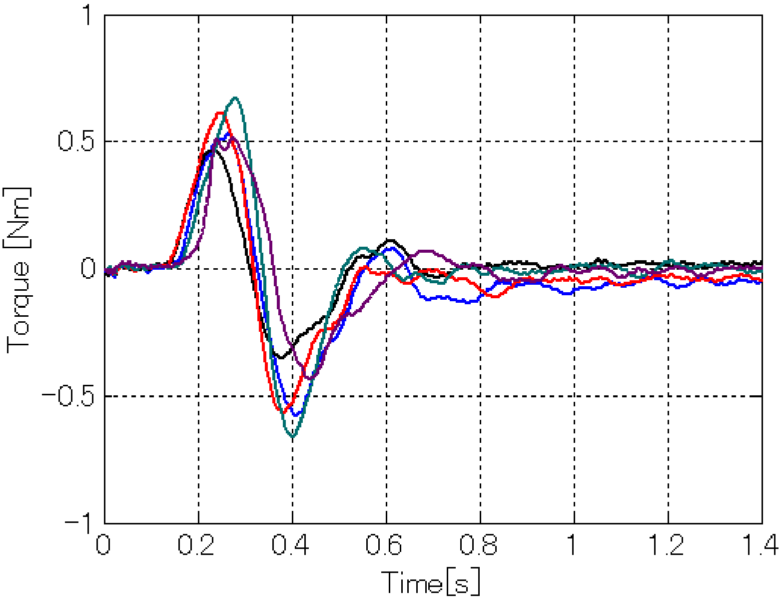

Fig. 8. Experimental Result (Input: Torque)

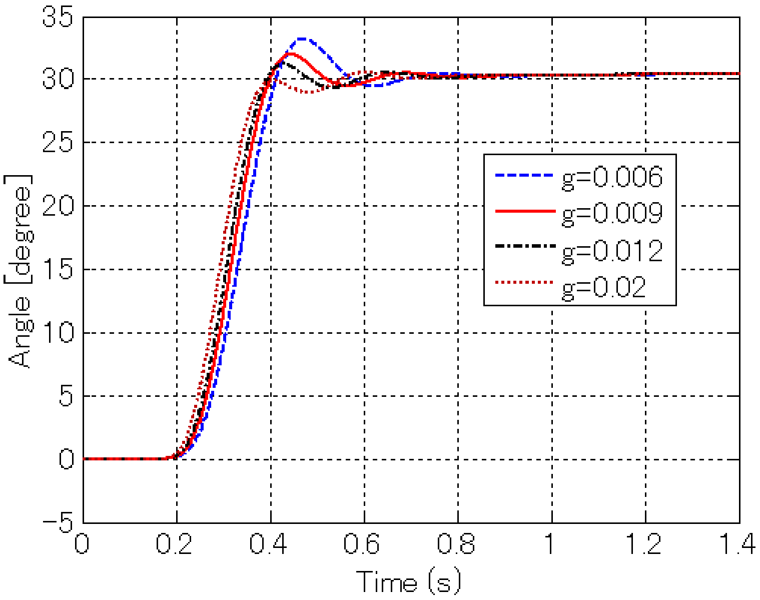

Fig. 9. Simulation Result (Output: Angle)

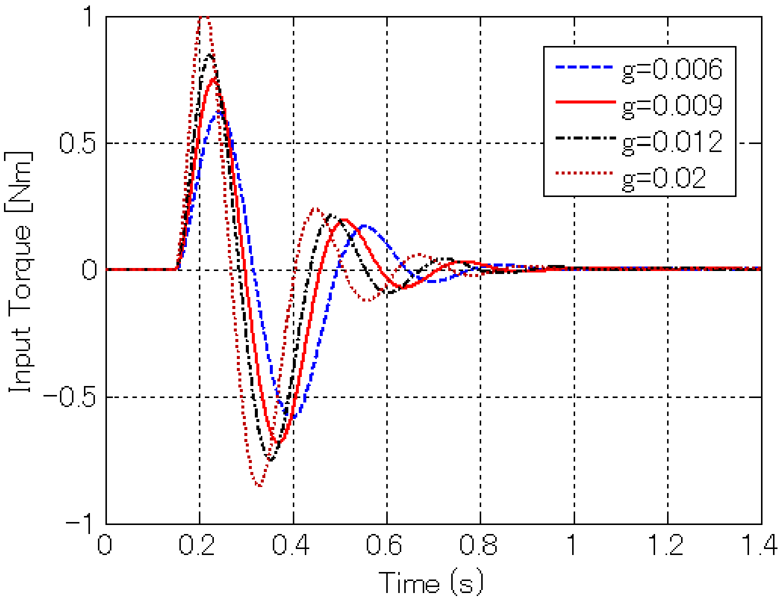

Fig. 10. Simulation Result (Input: Torque)

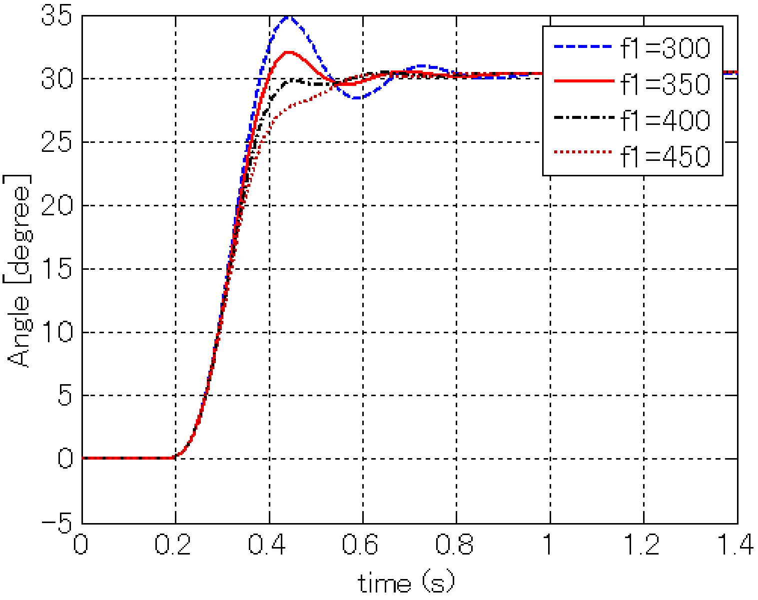

Fig. 11. Simulation Result (Output: Angle)

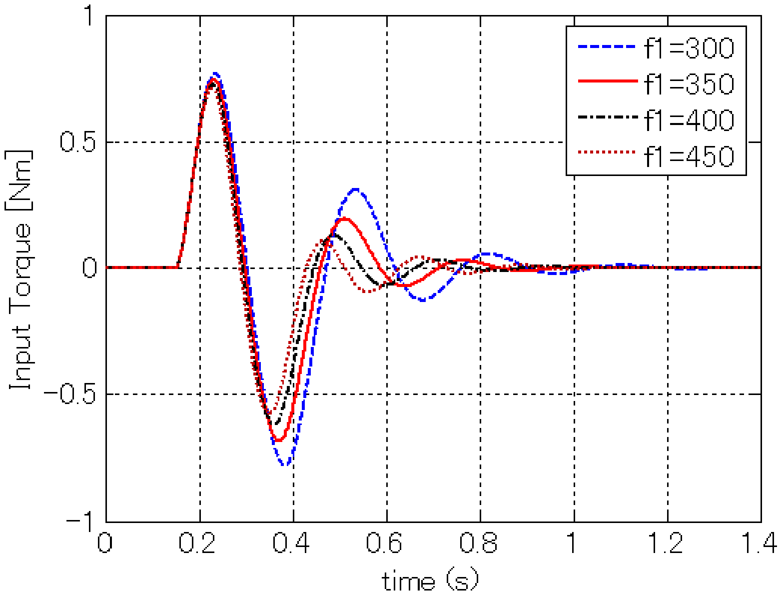

Fig. 12. Simulation Result (Input: Torque)

similarity. So, we can note that the proposed model can maintain its good performance.

Furthermore, we can set up a hypothesis such that the fluctuation in the response can be interpreted as the fluctuation of PFC parameters and/or parameter of adaptive adjusting law g.

5. Conclusions

From the point aimed at the minor feedback loop in the brain, that is, the nervous network between the cerebrum and the cerebellum performing minor feedback loop element, and a hypothesis for cerebellum generating a forward model of motor apparatus dynamics, a perceptual motor control model is discussed. The proposed method is based on output feedback type adaptive control using a ASPR characteristics of the controlled plant, which accompany with PFC. In the nervous network, there necessarily exists dead time (pure time delay) of signal transmission between cortex and lower apparatus. To overcome the influence of the feedback of the sensed signal involving time delay, the Smith predictor method is introduced. The effectiveness of proposed model are examined through the comparison between of experimental results and simulation results for one-link arm positioning control problem. And, it is confirmed that the proposed model can represent the manual control response with sufficient accuracy. Furthermore, we suggest that the fluctuation in the response can be interpreted as the fluctuation of PFC and/or adaptive adjusting law parameters. The proposed model will be utilized to design and realize an assisting system for human-machine system, that is, “Collaborater”.

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This book book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of contemporary robotics and autonomous systems. The volume is organized in four thematic parts according to the main subjects, regarding the recent advances in the contemporary robotics. The first thematic topics of the book are devoted to the theoretical issues. This includes development of algorithms for automatic trajectory generation using redudancy resolution scheme, intelligent algorithms for robotic grasping, modelling approach for reactive mode handling of flexible manufacturing and design of an advanced controller for robot manipulators. The second part of the book deals with different aspects of robot calibration and sensing. This includes a geometric and treshold calibration of a multiple robotic line-vision system, robot-based inline 2D/3D quality monitoring using picture-giving and laser triangulation, and a study on prospective polymer composite materials for flexible tactile sensors. The third part addresses issues of mobile robots and multi-agent systems, including SLAM of mobile robots based on fusion of odometry and visual data, configuration of a localization system by a team of mobile robots, development of generic real-time motion controller for differential mobile robots, control of fuel cells of mobile robots, modelling of omni-directional wheeled-based robots, building of hunter- hybrid tracking environment, as well as design of a cooperative control in distributed population-based multi-agent approach. The fourth part presents recent approaches and results in humanoid and bioinspirative robotics. It deals with design of adaptive control of anthropomorphic biped gait, building of dynamic-based simulation for humanoid robot walking, building controller for perceptual motor control dynamics of humans and biomimetic approach to control mechatronic structure using smart materials.

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