A PERCEPTUAL MOTOR CONTROL MODEL BASED ON OUTPUT FEEDBACK ADAPTIVE CONTROL THEORY

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Abstract: In this paper, a Perceptual Motor Control Model(PMCM) based on output feedback adaptive control theory is considered from the viewpoint of voluntary movement such as hand-tracking control. We give an account of the PMCM structure using together with both of the output feedback controller designed by using an almost strict positive real characteristics for the controlled plant and the Smith predictor for plant with pure time delay. In the proposed method, the attractive structural similarity exists between the cerebrum-cerebellum neuro-motor signal feedback loop and the adaptive controller - compensators local minor feedback loop. The proposed perceptual motor control model is evaluated through the comparison of between the experiment and the simulation of for handling 1-link mechanism in order to track an indicator.

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). 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 modeled 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

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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 the comparison between 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. Let us consider the following SISO plant:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + bu(t) \\ y(t) &= c^T x(t) \end{aligned} \tag{1}$$

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

$$\begin{aligned} G(s) &= c^T(sI-A)^{-1}b + d = \tfrac{N(s)}{D(s)} \\ N(s) &= b_m s^m + b_{m-1}s^{m-1} + \cdots + b_1 s + b_0 \\ D(s) &= s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0. \end{aligned} \tag{2}$$

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

$$G_c(s) = (1 + k_p G(s))^{-1} G(s) \tag{3}$$

is SPR(Strictly Positive Real). 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). Under the Assumption 1, the following adaptive algorithm:

$$u(t) = k(t)e(t) \tag{4}$$

$$\dot{k}(t) = ge(t)^2 \tag{5}$$

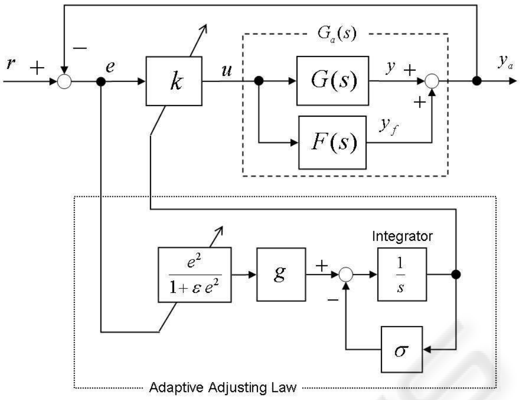

Figure 1: Adaptive Control System with PFC.

generates the control of the plant Eq.(1), where $e(t) = r(t) - y(t)$ and g is positive constant. And, it can achieve the output error $e(t)$ convergence to zero. Furthermore, against to the input disturbance and to the un-modeled dynamics of the plant, the following modified adaptive adjusting law

$$\dot{k}(t) = -\sigma k(t) + g\frac{e(t)^2}{1+\varepsilon e(t)^2}, \tag{6}$$

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 $\gamma > 1$. To overcome this problem, as shown in Fig.1, dynamic compensator $F(s)$ is introduced to construct the augmented ASPR plant $G_a(s) = G(s) + F(s)$ satisfying the above-stated sufficient condition. Thus, the output feedback adaptive control law can be applied to the augmented plant $G_a(s)$ and maintain the stability of closed loop system. So, $F(s)$, located in parallel path for the plant, is called as parallel feedforward compensator (PFC) (Kaufman et al., 1998).

3 PERCEPTUAL MOTOR CONTROL MODEL

In the brain science research area, 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 (Miall et al., 1993; Ito, 1970; Wolpert et al., 1998; Kleinman et al., 1970). Specially, based on data from the control of the primate arm in visually guided tracking tasks (Fig.2), Miall et al. have

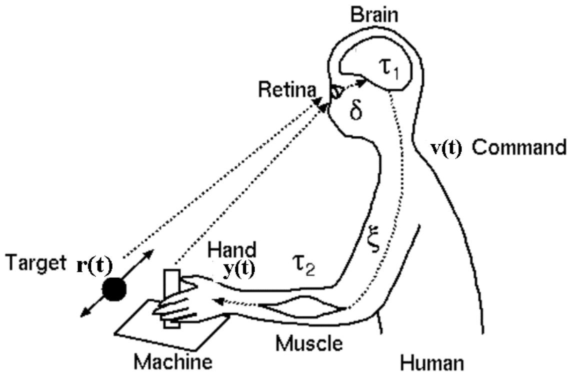

Figure 2: Human Body Dynamics.

Table 1: Parameters and Variables.

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

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. 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 (Ito, 1970). There are two varieties of internal model, *i.e.*, forward model and inverse model (Wolpert et al., 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 the problem of pure time delay can be overcome by 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, the adaptive control methods, based on the ability of animal to adapt itself to changes in its surroundings, have been developed.

Taking into account of both the concept of adaptive control method and the brain science researchers' suggestions, let us construct a new perceptual motor control model as shown in Fig.4 for the control problem as shown in Fig.2, in which a human operator controls the machine to follow the target. Here, the time delay of nervous system transmission is successfully compensated by Smith predictor:

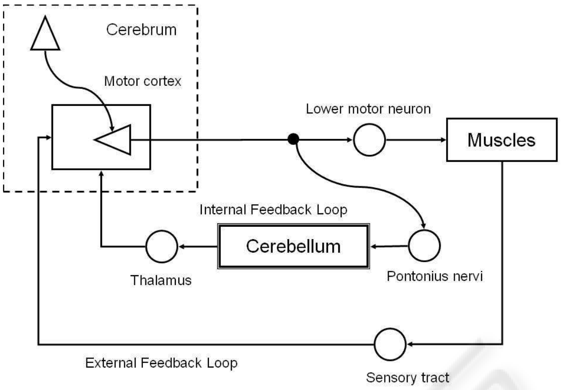

Figure 3: Cerebrum & Cerebellum (Ito, 1970).

$$G_1(s) - G_1(s)e^{-(\delta+\zeta)s} \tag{7}$$

where $G_1(s) = G_P(s)/(\tau_2 s + 1)$.

Then, the controlled system from a side of the output feedback adaptive controller becomes a series of three elements. Namely, it consists a first lag element with time constant τ_1 which is involved in brain dynamics, a first lag element with time constant τ_2 which is involved in muscle dynamics, and a controlled machine dynamics $G_P(s)$. In order to construct a stable output feedback adaptive control system, the ASPR compensation must be implemented for $G(s) = G_1(s)/(\tau_1 s + 1)$. So, suppose that the following assumption holds.

Assumption 2. $G(s)$ satisfies that

(1) $G(s)$ is minimum phase system.
(2) the relative degree γ is larger than 2.
(3) the nominal value of the leading coefficient b_m of $G(s)$ is known.

Then, according to one of practical PFC design method (Iwai et al., 1994), PFC:$F(s)$ as shown in Fig.5 can construct the augmented plant $G(s) + F(s)$ which satisfies the above-mentioned sufficient condition for Assumption 1. Here, δ is sufficiently small positive constant, γ is a relative degree of $G(s)$, α_i are positive constants and β_i are coefficients of the Hurwitz polynomial:

$$R(s) = \beta_{\gamma-1}s^{\gamma-1} + \cdots + \beta_1 s + \beta_0, \tag{8}$$

where β_0 is a leading coefficient of $G(s)$. Both the Smith predictor and PFC can be located into the mi-

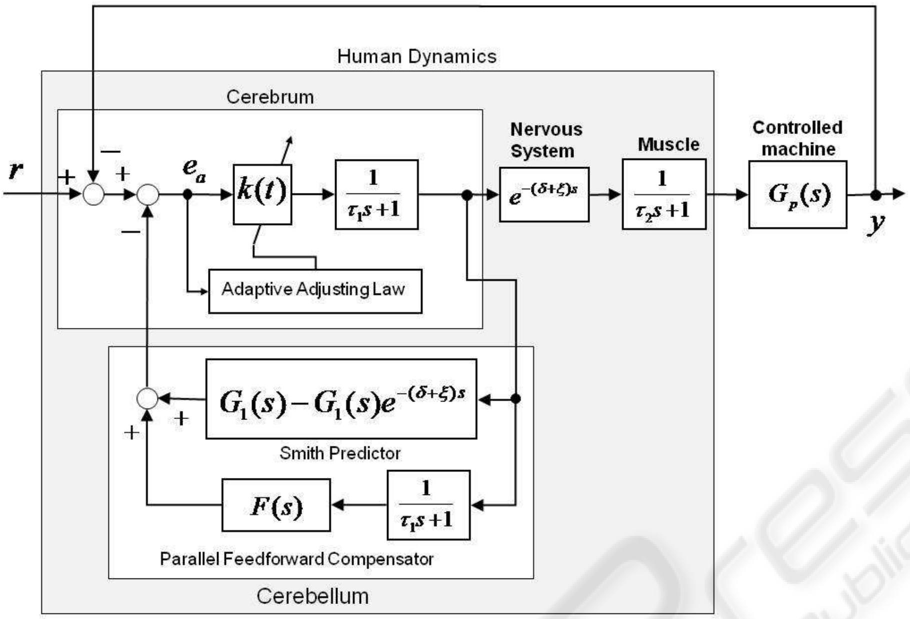

Figure 4: Perceptual Motor Control Model.

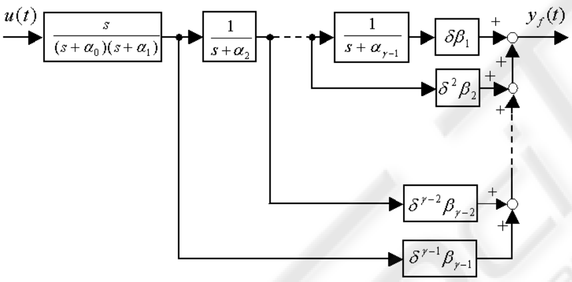

Figure 5: Ladder Network Type PFC (Iwai et al., 1994)

nor feedback loop for the output feedback gain k adjusted by the adaptive algorithm Eq.(6) using $e_a(t)$ instead of $e(t)$. So, it ease to recognize that such minor feedback structure is very similar to the cerebrum-cerebellum neuro-motor signal feedback loop model in Fig.3. Thus, we can imagine that the Smith predictor and PFC perform the role of cerebellum.

4 EVALUATION OF PMCM

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

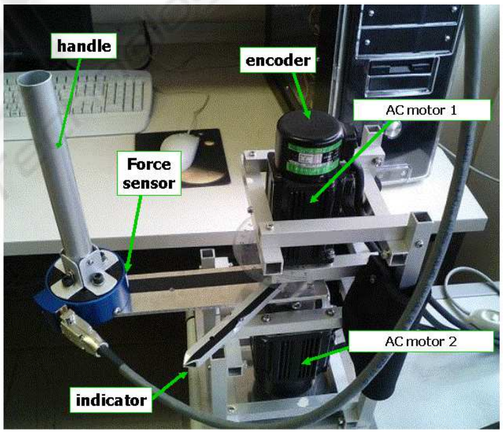

Figure 6: Experimental Equipment.

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

$$G_P(s) = \frac{4213}{s(s+1)} \qquad (9)$$

Human Dynamics Model. Through the experimental results, the parameters of human dynamics model are estimated such that $\delta+\zeta = 0.13$[s], $\tau_1 = \tau_2 = 0.03$[s],

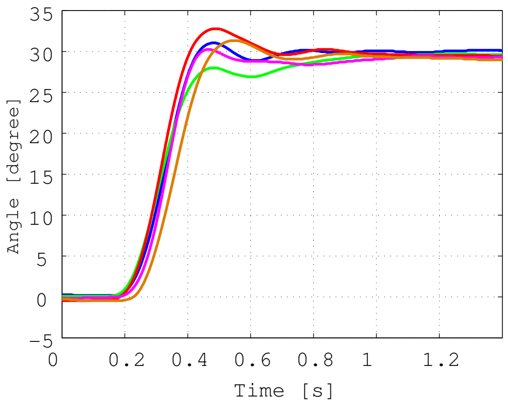

Figure 7: Experimental Results.

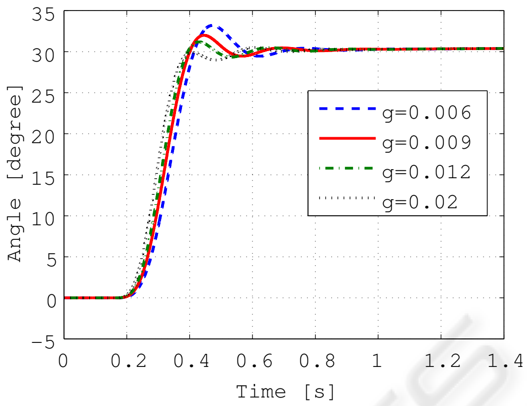

Figure 9: Simulation Results.

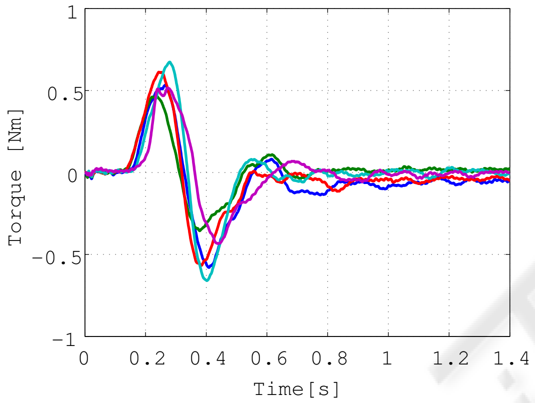

Figure 8: Input Torque (Experiment).

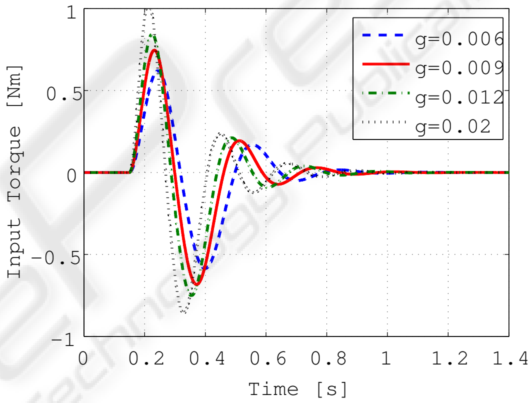

Figure 10: Input Torque (Simulation).

respectively (Saito and Nagasaki, 2002). In this case, the controlled system from a side of the output feedback controller, which is the above-mentioned series of three elements is given as follow.

$$G(s) = \frac{4213}{s(s+1)(0.03s+1)^2} \tag{10}$$

PFC. Because $G_1(s)$ has a relative order as 3 and minimum phase characteristics, for the simulation, PFC is constructed as follows:

$$F(s) = \frac{f_1 s}{(\tau_1 s+1)(s+\alpha)^2} + \frac{f_2 s}{(\tau_1 s+1)(s+\alpha)}, \tag{11}$$

where design parameters are given as $f_1 = 350$, $f_2 = 6$, $\alpha = 0.5$.

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.(6). In the simulation, the other parameters in Eq.(6) are given as $k(0) = 0$, $\sigma = 0.1$ and $\varepsilon = 0.01$. Although there exists some fluctuation in the experimental results obtained for three testors, we can recognize that the both responses are very similar. Because, by comparing between Fig.7 and Fig.9, the overshoots are almost same level and the damping ratio and the values of peak time are close resemblance. Furthermore, by comparison of Fig.8 and Fig.10, both signal wave forms also show a close 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 occurring every experiment can be interpreted as the fluctuation of PMCM parameters.

5 CONCLUSIONS

From the point aimed at the minor feedback loop in the brain, *i.e.*, 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 has been discussed. The proposed method is based on output feed back type adaptive control using 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.

From the viewpoint of the mutual connection between the cerebrum and the cerebellum, we showed that the PFC and Smith predictor perform as cerebellum generating a forward model for the controlled machine and human's motor apparatus, and the adaptive controller performs as cerebrum adjusting the visual feedback control signal. The effectiveness of the proposed model was examined through the comparison between of experimental results and simulation results for one-link arm positioning control problem. And, it was confirmed that the proposed model can represent the manual control response with sufficient accuracy.

REFERENCES

Furuta, K., Iwase, M., and Hatakeyama, S. (2004). Analysing saturating actuator in human-machine system from view of human adaptive mechatronics. In *Proceedings of REDISCOVER 2004, Vol.1, (3-1)–(3-9)*.

Ishida, F. and Sawada, Y. (2003). Quantitative studies of phase lead phenomena in human perceptro-motor control system. In *Trans. of SICE, Vol.39, No.1, 59-66*.

Ito, M. (1970). Neurophysiological aspects of the cerebellar motor control system. In *International Journal of Neurology, Vol. 7, 162-176*.

Iwai, Z., Mizumoto, I., and Deng, M. (1994). A parallel feedforward compensator virtually realizing almost strictly positive real plant. In *Proc. of* 33^{rd} *IEEE CDC, 2827-2832*.

Iwai, Z., Mizumoto, I., and Ohtsuka, H. (1993). Robust and simple adaptive control system design. In *International Journal of Adaptive Control and Signal Processing, Vol.7, 163-181*.

Kaufman, H., Bar-Kana, I., and Sobel, K. (1998). *Direct Adaptive Control Algorithms Theory and Application*. Springer-Verlag, New York, 2nd edition.

Kleinman, D. L., Baron, S., and Levison, W. H. (1970). An optimal control model of human response part i: Theory and validation. In *Automatica, Vol.6, 357-369*.

Miall, R. C. ., Weier, D. J., Wolpert, D. M., and Stein, J. F. (1993). Is the cerebellum a smith predictor ? In *Journal of Motor Behavior, Vol.25, No.3, 203-216*.

Ohtsuka, H., Shibasato, K., and Kawaji, S. (2007). Collaborative control of human-machine system by collaborater. In *Trans. of The Japan Society of Mechanical Engineers, Series C, Vol.73, No.733, 2576-2582*.

Saito, H. and Nagasaki, H. (2002). *Clinical Kinesiology*. Ishiyaku Publishers, Inc., 3rd edition.

Takahashi, T. and Ikeura, R. (2006). Development of human support system. In *Journal of the Society of Instrument and Control Engineers,Vol.45, No.5, 387-388*.

Wolpert, D. M., Miall, R. C., and Kawato, M. (1998). Internal models in the cerebellum. In *Trends in Cognitive Sciences, Vol.2, No.9, 338-347*.

Yamada, Y. and Utsugi, A. (2006). Human intention inference techniques in human machine systems and their robotic applications. In *Journal of the Society of Instrument and Control Engineering, Vol.45, No.6, 407-412*.