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Force Detection Based on Internal Model Control and Its Application to an Assistive Device in Rehabilitation Medicine

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Abstract: This paper shows a controller scheme for force detection based on the internal model control method. The proposed method is applied for detecting force generated by humans. The results show the required robustness of the method, especially, disturbance estimation for parameter perturbations. The experimental results for an assistive device are also shown. By comparative experiments it is shown that the proposed controller scheme can detect forces of the disabled person without additional sensors.

Keywords: generalized internal model control, disturbance estimation, rehabilitation medicine

INTRODUCTION

Control applications in rehabilitation medicine are significant for the development for interaction between humans and machines. Assistive devices in rehabilitation technology are widely used by elderly or disabled people in order to support more life independence. For the interaction with humans, safety and reliability conditions have to be fulfilled and control design methods for appropriate assistive devices have to be robust. Moreover, in conventional situations, force sensors or pressure sensors are attached to assistive devices to detect ability of users. However, this complicates the mechanical structure and the controller scheme for such assistive devices.

To overcome these problems a control method based on internal model control (IMC) is applied for detecting force generated by humans. In this paper, a new controller scheme by using a structure of the generalized internal model control (GIMC) is introduced. The proposed method has the required robustness, especially, disturbance estimation for parameter perturbations. We apply the method to control an assistive device for standing up, and also confirm effectiveness of the disturbance estimation property of the proposed method.

In the work (Tani 2004), we discussed the effectiveness of the GIMC design control scheme based on LQ optimal control with servo compensation. Theoretically, we proved some properties of the GIMC design and showed on experimental result for speed control of a wheeled walking frame. However, comparative experiments to verify effectiveness of the disturbance estimation property are not enough, and an argument to confirm possibility of applications for rehabilitation technology is poor. By pointing out the input torque into the motor, we evaluate the disturbance estimation property of the GIMC scheme, and we show that this disturbance estimation property is effective in generating a suitable input to assistive devices.

The proposed research specifically emphasized that from theoretical and experimental findings the disturbance estimation property of the proposed GIMC is useful for detecting force without additional sensors, e.g. force sensors, pressure sensors, or electromyography (EMG). The results are a further step in rehabilitation technology to contribute towards the development of equipment interacting with humans.

ASSISTIVE DEVICE FOR STANDING UP

Phase of Standing Up

Standing up is an important for common daily activity. The ability to stand from the seated position is essential for independent living. However, many elderly or disabled people have problems with transition from sitting to standing. Inability to stand up does not limit only elderly or disabled people but affects also a burden to those who should care for them.

It is well known that standing motion can be more demanding than other activities of daily life, requiring more leg strength and greater joint ranges of motion than walking or climbing stairs (Hughes and Schenkman 1996, Schenkman 1990). There are four phases of standing up motion (see Table 1). Elderly persons with moderate functional impairments compensate for increased difficulty in standing by simultaneously attempting to increase both momentum generation and stability.

We design an assistive device which can support the persons in the phase II and III. Figure 1 shows the support function of the assistive device for standing. We also provide a function which can be displayed ability to stand up without additional sensors. Figure 2 shows the EMG data of an ordinary person. The data is measured from femoral muscles. We can see that ordinary persons need power in the moment transfer phase (Phase II). To support the first part of the lifting-off, we design an assistive device for standing up.

Table 1 – Phase of standing motion

Phase	Priority	Action
I. Flexion momentum	Balance	Sitting
II. Momentum transfer	Balance	Lift-off
III. Extension	Traction	Max dorsiflexion
IV. Stabilization	Balance	End hip extension

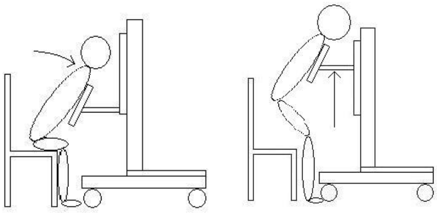

Figure 1 – Support function for standing up

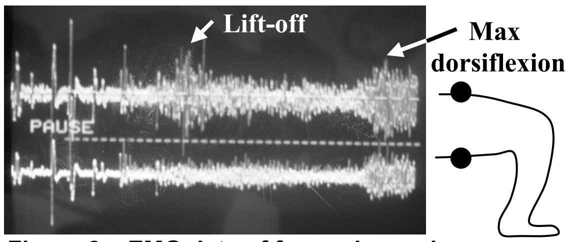

Figure 2 – EMG data of femoral muscles

System Overview

The structure of the assistive device for standing is shown in Fig. 3. The device is constructed by a battery, a DC motor, an electrical circuit for the DC motor, and a supporting part. The DC motor runs the supporting part by using a belt and a pulley. The controller unit is constructed by the 16bit H8S microcomputer. The microcomputer includes A/D converter, D/A converter and counting part. The controller is able to measure dependence of users to the assistive device by applying the disturbance estimation property of a controller scheme based on the IMC scheme.

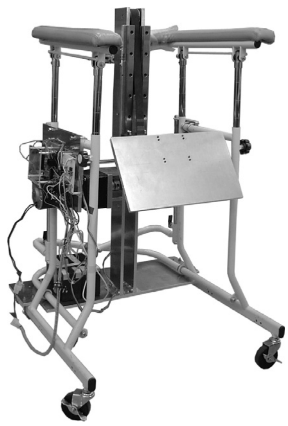

Figure 3 – Assistive device for standing up

GENERALIZED INTERNAL MODEL CONTROL DESIGN

Internal Model Control (IMC) Design Scheme

The IMC design is widely used in process control and mechanical systems control. Nevertheless the procedure of controller synthesis is very simple, some satisfactory properties, e.g., a disturbance rejection and a trajectory tracking were shown in the reference of Morari and Zafiriou (1989). By combining the IMC design with a feedback control, the scheme has good properties rather than previous results (see Suzuki 2002).

Figure 4 shows the IMC scheme with feedback control, where Σ_f is the transfer function of the control object, $\overline{\Sigma}_f$ is the mathematical model of the control object, and $\overline{\Sigma}_{f\rho}^{-1}$ is an approximate inverse system of $\overline{\Sigma}_f$ defined as

$$\overline{\Sigma}_{f\rho}^{-1}\overline{\Sigma}_f = \mathrm{diag}\left((\rho s+1)^{-d1},\ \cdots,\ (\rho s+1)^{-dm}\right).$$

ρ is very small value and d_i is the integral index to obtain a proper approximate inverse system. In the work of Suzuki (2002), the disturbance estimation property of the IMC structure based on LQ optimal control is also presented. We extend this structure to a general controller scheme.

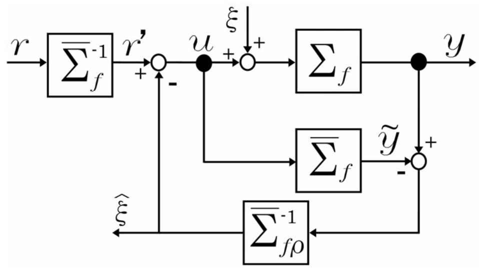

Figure 4 – IMC structure

Generalized Internal Model Control (GIMC) Scheme

The GIMC scheme has been firstly proposed by Zhou and Ren (2001). We discuss a new GIMC scheme from another point of views. Consider the linear time invariant system with disturbance as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu + D\xi \\ y &= Cx \end{aligned} \tag{1}$$

where $x \in R^n$ is the state vector, $u \in R^m$ is the input vector, $y \in R^m$ is the output vector and $\xi \in R^q$ is the disturbance vector. For this system we propose the GIMC scheme shown in Fig. 5. The proposed method is based on a two-degree-of-freedom servo system using an observer-based stabilizing controller. Let us consider the following observer Σ_{ob}

$$\begin{aligned} \dot{\hat{x}} &= (A + L_\rho C)\hat{x} - L_\rho y + Bu \\ L_\rho &= \lim_{\rho\to 0} - P_\rho C^T \\ AP_\rho + P_\rho A^T - P_\rho C^T C P_\rho + DD^T \frac{1}{\rho^2} &= 0. \end{aligned} \tag{2}$$

Suppose the system (1) satisfies $B = D$, because input channels of mechanical systems are mostly affected by disturbance, and F is a feedback gain obtained by limiting feedback gain (Suzuki 2000). In here, $Q(s)$ is a stabilizing controller parameterized an approximate inverse system of Σ_{ob}. The parameters $\hat{L}$, H and G are obtained by (3) where S is a Hurwitz matrix. The associated relations are

$$\begin{aligned} F = F_\varepsilon &= \lim_{\varepsilon\to 0} -B^T M_\varepsilon, \quad A^T M_\varepsilon + M_\varepsilon A - M_\varepsilon BB^T M_\varepsilon + \frac{1}{\varepsilon^2} C^T C = 0 \\ \hat{L} &= C(\ A + BF_\varepsilon\ )^{-1} \\ H &= -(\ \hat{L}B\ )^{-1} \\ G &= -HS = (\ \hat{L}B\ )^{-1} S \end{aligned} \tag{3}$$

The GIMC structure shown in Fig. 5 contains several controller schemes.

(1) The structure becomes an all stabilizing controller (Suzuki, et. al. 2001) if $G = 0$ holds. The all stabilizing controller has same disturbance decoupling property and trajectory tracking property as the IMC design structure by choosing an appropriate *Q(s)*.

(2) From another point of view, this structure becomes an observer based servo controller with the 2DOF (Nakamoto 2003) if Q(s) = 0 holds.

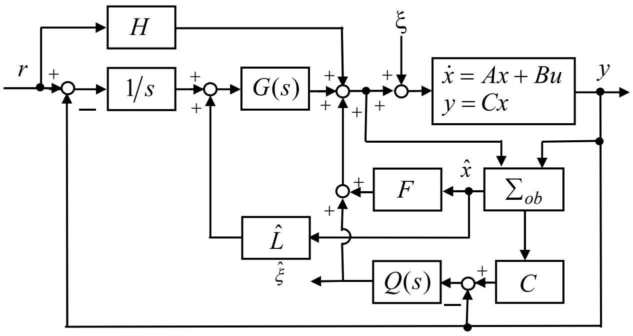

Figure 5 – GIMC structure with servo compensation

The error equation is obtained by

$$\Sigma_e(s):\begin{cases}\dot{e}=(A+L_\rho C)e-B\xi\\ \mu=Ce=y_m-y\end{cases} \tag{4}$$

and $Q(s)=\Sigma_{e\tau}^{-1}(s)$ is calculated by

$$\Sigma_{e\tau}^{-1}(s)\Sigma_e(s)=\mathrm{diag}((\tau s+1)^{-d1},\cdots,(\tau s+1)^{-dm})\;. \tag{5}$$

Let (A_Q,B_Q,C_Q,D_Q) be a minimal realization of the approximate inverse system of $\Sigma_{e\tau}^{-1}(s)$; τ is very small value and d_i is the integral index to obtain a proper approximate inverse system.

The augmented system is given by the following state equation

$$\dot{x}_e=\begin{pmatrix} A+BF_\varepsilon+BG\hat{L} & BG & B\;(\;F_\varepsilon+G\hat{L}+D_QC\;) & BC_Q \\ -C & 0 & 0 & 0 \\ 0 & 0 & A+L_\rho C & 0 \\ 0 & 0 & B_QC & A_Q \end{pmatrix} x_e+\begin{pmatrix} BH \\ I \\ 0 \\ 0 \end{pmatrix} r+\begin{pmatrix} B \\ 0 \\ -B \\ 0 \end{pmatrix}\xi \tag{6}$$

$$y=\begin{pmatrix} C & 0 & 0 & 0 \end{pmatrix}\;x_e$$

where $x_e^T=(x^T\quad w^T\quad e^T\quad \eta^T)^T$. By using the transformation matrix in the reference (Nakamoto 2003)

$$T=\begin{pmatrix} I & 0 & 0 \\ \hat{L} & I & 0 \\ 0 & 0 & I \end{pmatrix} \tag{7}$$

the augmented system (6) is represented as follows

$$\dot{\tilde{x}}_e=\begin{pmatrix} A+BF_\varepsilon & BG & B\;(\;F_\varepsilon+G\hat{L}+D_QC\;) & BC_Q \\ \hat{L}\;(\;A+BF_\varepsilon\;)-C & \hat{L}BG & \hat{L}B\;(\;F_\varepsilon+G\hat{L}+D_QC\;) & \hat{L}BC_Q \\ 0 & 0 & A+L_\rho C & 0 \\ 0 & 0 & B_QC & A_Q \end{pmatrix}\tilde{x}_e+\begin{pmatrix} BH \\ \hat{L}BH+I \\ 0 \\ 0 \end{pmatrix} r+\begin{pmatrix} B \\ \hat{L}B \\ -B \\ 0 \end{pmatrix}\xi \tag{8}$$

where $\widetilde{x}_e = Tx_e$. For the augmented system (8), we obtain the following properties. The signals r and ξ are not limited to step input or step disturbance. The proofs of the properties are shown in the reference (Tani 2004).

[Property 1]

Consider the augmented system (8), and suppose the system (A, B, C) is minimum phase. The closed loop system can immediately arrive at disturbance decoupled system by multiplicative effect of the disturbance rejection property of the IMC design structure and the disturbance rejection property of LQ control. That is, the following statement holds:

$$\lim_{\substack{\varepsilon \to 0 \\ \tau \to 0 \\ \rho \to 0}} H_{y\xi}(s) \to 0 \tag{9}$$

where $H_{y\xi}$ is the transfer function from disturbance to output described as

$$\begin{aligned} H_{y\xi}(s) = {} & C(sI - A - BF_\varepsilon)^{-1} B \ \{I + G(sI - \hat{L}BG)^{-1} \hat{L}B\} \{I - (D_Q + C_Q(sI - A_Q)^{-1} B_Q) \ C(sI - A - L_\rho C)^{-1} B\} \\ & + C(sI - A - BF_\varepsilon)^{-1} B \ \{I + G(sI - \hat{L}BG)^{-1} \hat{L}B\} G\hat{L}(sI - A - L_\rho C)^{-1} B. \end{aligned}$$

[Property 2]

Consider the augmented system (8), and suppose the system (A, B, C) is minimum phase. For the scheme shown in Fig. 5, if we parameterize $Q(s)$ as an approximate inverse system of $-\{C(sI - A - L_\rho C)^{-1} B\}$, then the output signal of $Q(s)$ can be estimated unknown disturbance ξ as $\tau \to 0$. For the transfer function from disturbance to the estimated disturbance holds

$$\begin{aligned} & \lim_{\tau \to 0} H_{\xi\hat{\xi}}(s) \to I, \\ & H_{\xi\hat{\xi}}(s) = \left\{ D_Q + C_Q(sI - A_Q)^{-1} B_Q \right\} C(sI - A - L_\rho C)^{-1}(-B). \end{aligned} \tag{10}$$

The approximate inverse system is obtained by (5). Moreover, the closed loop system maintains servo property.

EXPERIMENTAL RESULTS

Now we apply the proposed control scheme to the assistive device for standing. By comparative experiments, we show that the disturbance estimation property can be applied to measure user's ability to stand up. To measure such kind of ability, we need additional sensors, e.g., force sensor, pressure sensor, or electromyography (EMG). However, by using the proposed control scheme, we can estimate the user's ability to stand up.

The differential equation of the assistive device is obtained as follows

$$m\ddot{x} + c\dot{x} = u + \xi$$

where m is the mass 3.44[kg], c is the damping coefficient 40[Ns/m], u is the input torque, x is the displacement of a stay. In here, dependency of a user is added to the disturbance channels ξ. We design the controller scheme by tuning ε, ρ, τ.

The Fig. 7 and 8 show the experimental results for estimating the user's ability to stand up. The vertical axis stands for the estimate value of disturbance added to the equipment. The standing-up is positive direction and the sitting-down is negative direction. If the controller estimate large negative disturbance, then the equipment can be supported for standing with appropriate force. To evaluate the proposed method, the experimental data of weights (0kg, 15kg and 20kg) are also plotted in the Fig. 7 and 8. By using the proposed method and comparing the data of weights, we can estimate the ability to stand up.

Figure 9 shows the comparative date of Fig. 7 and Fig. 8. The bottom solid line shows the result of standing with high dependence, and the middle solid line shows the result with low dependence. From this figure the user and helper can easily know ability for standing without additional sensors. Moreover, we can know whether users depend on the assistive device for standing or not. Note that the estimated value includes the data of human ability, weight of the experiment, influence of friction, and so on. However, we can extract the user's data easily by comparing the data of weights.

From the experimental result, we can see the effectiveness of disturbance estimation property of the proposed method. By using the proposed scheme we estimate whether a user depends on the assistive devices. In addition, we can obtain instructing data for rehabilitation or training. The application is able to extend another assistive device which needs estimating ability for elderly or disabled persons.

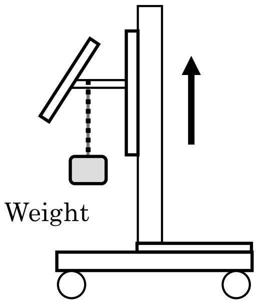

Figure 6 – Experimental setup to evaluate force detection property (load: 0kg, 15kg and 20kg)

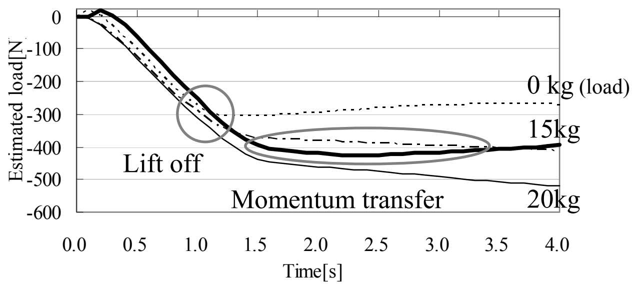

Figure 7 – Estimated ability to stand up: low dependence (Bold solid line shows user's data)

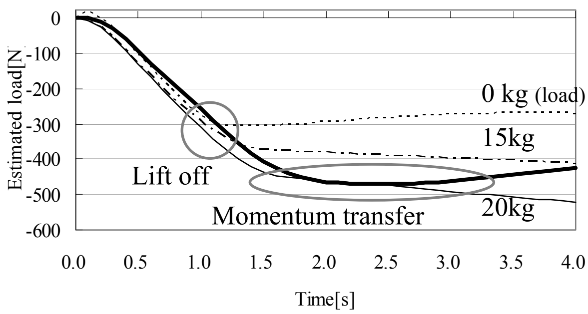

Figure 8 – Estimated ability to stand up: high dependence (Bold solid line shows user's data)

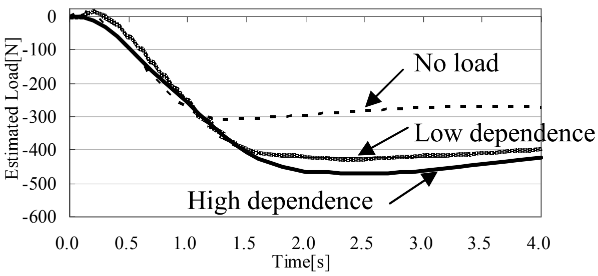

Figure 9 – Experimental result for estimating ability

CONCLUSIONS

This paper showed a controller scheme for force detection based on the internal model control method in rehabilitation medicine. The proposed method was applied for detecting force generated by humans. The proposed controller scheme based on the internal model control has the required robustness, especially, disturbance estimation for parameter perturbations. The experimental results for an assistive device were also shown. By comparative experiments it was shown that the proposed controller scheme could detect forces of the disabled person without additional sensors. From the experimental result, we can see the effectiveness of the proposed disturbance estimation property. In addition, we can obtain instructing data as “bio-feedback” for rehabilitation or training. The controller scheme is able to extend another assistive device which needs estimating ability for humans.

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REFERENCES

M. A. Hughes and M. L. Schenkman, 1996, Chair rise strategy in the functionally impaired elderly, *Journal of Rehabilitation Research and Development*, Vol. 33, No. 4, pp. 409-412.

M. Morari and E. Zafiriou, 1989, *Robust Process Control*, Prentice Hall.

M. Nakamoto, 2003, Two Degree of Freedom Servo Controller Incorporated with Reference and Disturbance Feedforward and an Application to a Steam Pressure and Flow Control System (in Japanese), *The Institute of Systems Control and Information Engineers*, Vol. 16, No. 3, pp. 111-117.

M. L. Schenkman, R. Berger, P. O. Riley, R. W. Mann and W. A. Hodge, 1990, Whole body movements during rising to standing from sitting, *Physical Therapy*, Vol. 70, No. 10, pp. 638-648.

R. Suzuki, N. Kobayashi and M. Fujita, 2000, Decoupling Control with a Limiting Form of Linear Optimal Regulator for a Non-minimum Phase System, *Electrical Engineering in Japan*, Vol. 32, No. 2, pp. 49-57.

R. Suzuki, T. Miyazaki and N. Kobayashi, 2001, Decoupling Control via All Stabilizing Controller with Limiting Properties of LQ Control and Its Application to A Mechanical System, *Proc. IEEE Conference on Control Applications*, pp. 412-417.

R. Suzuki, M. Tani and N. Kobayashi, 2002, Design and development of single side driven wheelchairs by using internal model control, *Proc. IEEE Conference on Control Applications*, pp. 355-360.

M. Tani, et. al., 2004, Internal Model Control for Assisting Unit of Wheeled Walking Frames, *Proc. IEEE Conference on Control Applications*, pp. 928-933.

K. Zhou and Z. Ren, 2001, A New Controller Architecture for High Performance, Robust, and Fault-Tolerant Control, *IEEE Transactions on Automatic Control*, Vol.46, No.10, pp. 1316-1618.

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