52. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCCEDINGS | 10 - 13 September 2007

FACULTY OF COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

TECHNISCHE UNIVERSITÄT ILMENAU

Bibliografische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der deutschen Nationalbiografie; detaillierte bibliografische Daten sind im Internet über **http://dnb.ddb.de** abrufbar.

ISBN 978-3-939473-17-6

Impressum

Herausgeber:	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Peter Scharff
Redaktion:	Referat Marketing und Studentische Angelegenheiten Kongressorganisation Andrea Schneider Tel.: +49 3677 69-2520 Fax: +49 3677 69-1743 e-mail: kongressorganisation@tu-ilmenau.de
Redaktionsschluss:	Juli 2007
Verlag:	Technische Universität Ilmenau/Universitätsbibliothek Universitätsverlag Ilmenau Postfach 10 05 65 98684 Ilmenau www.tu-ilmenau.de/universitaetsverlag
Herstellung und Auslieferung:	Verlagshaus Monsenstein und Vannerdat OHG Am Hawerkamp 31 48155 Münster www.mv-verlag.de
Layout Cover:	www.cey-x.de
Bezugsmöglichkeiten:	Universitätsbibliothek der TU Ilmenau Tel.: +49 3677 69-4615 Fax: +49 3677 69-4602

Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.

- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.

- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.

- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.

- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.

- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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R. Suzuki / N. Fujiki / Y. Taru / N. Kobayashi / E. P. Hofer

Internal Model Control for Assistive Devices in Rehabilitation Technology

INTRODUCTION

Control applications in rehabilitation technology 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, a lot of sensors are attached to assistive devices to detect ability of users or to estimate unknown disturbance added to systems. However, this complicates the mechanical structure and the controller scheme for such assistive devices.
To overcome these problems a control method based on the generalized internal model control (GIMC) is applied to assistive devices for rehabilitation, e.g. wheelchairs, assistive devices for standing-up.

Generalized Internal Model Control (GIMC) 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 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.
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:

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

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. 1. 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. $Q(s)$ 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

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

The GIMC structure shown in Fig. 1 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.

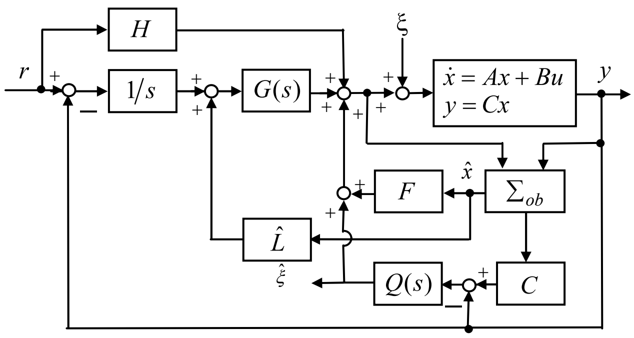

Figure 1 – GIMC structure with servo compensation

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

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

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 $\tilde{x}_e=Tx_e$. For the augmented system (8), we obtain the following properties. The signals r and ξ are not limited to step input or step disturbance.

[Property 1]

Consider the augmented system (8), and suppose the system (A,B,C) has no unstable zeros. 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:

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

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) has no unstable zeros. For the scheme shown in Fig. 1, 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

Firstly, the proposed controller scheme based on the GIMC is applied to the assistive device for standing-up. By comparative experiments it is shown that the controller scheme can detect forces of the disabled person without additional sensors (see Fig. 2). 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 controller scheme, we can estimate the user's ability to stand up.

Here dependency of a user to the assistive device is added to the disturbance channels. We design the controller scheme by tuning ε, ρ, τ. Figure 2 shows the experimental results of estimating human ability for standing up motion. 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 experimental data.

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.

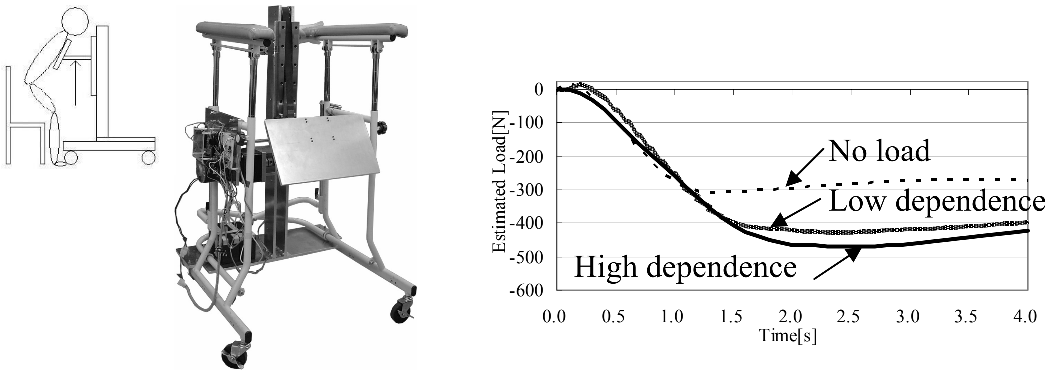

Fig. 2: Assistive device for standing and experimental result for detecting force

Secondly, the proposed scheme is applied to the single side driven wheelchairs. By using the proposed scheme the wheelchair is able to traverse on slant slopes without an inclinometer (see Fig. 3). As for wheelchairs, when it crosses on slant slopes, it is not possible to advance straight. Because center of gravity of wheelchairs changes on slopes, and then force given to two wheels would be changed. By using the estimation property of the GIMC, the controller scheme estimates this change as disturbance. As the result, the single side driven wheelchairs can traverse on slant slopes.

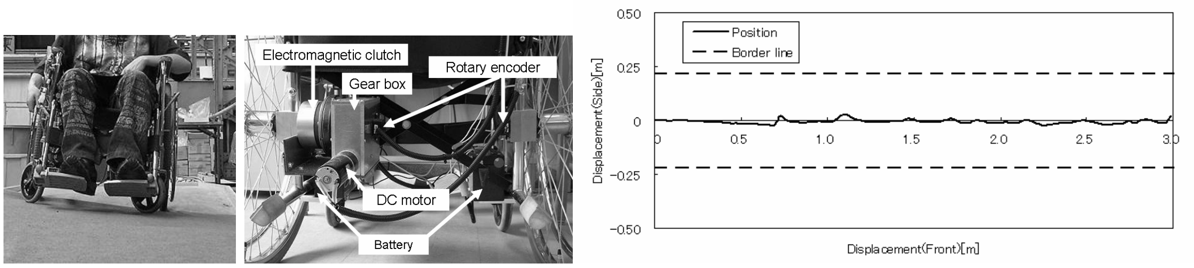

Fig. 3: Single side driven wheelchair and experimental result on slant slope

Conclusions

This paper showed a controller scheme for force detection based on the internal model control method in rehabilitation technology. 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. 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.

The proposed research specifically emphasizes that from theoretical and experimental findings the disturbance estimation property of the proposed GIMC is useful for detecting unknown disturbance without additional sensors, e.g. inclinometers, 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.

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