# A METHOD FOR SOLVING ILL-POSED PROBLEM IN MULTICHANNEL CLOSED-LOOP FES CONTROL

Takashi Watanabe, Kan Iibuchi, Kenji Kurosawa, Ryoko Futami and Nozomu Hoshimiya
Dept. Electronic Eng., Graduate School of Engineering, Tohoku University

## Abstract

This study focused on multichannel closed-loop FES control of the redundant musculoskeletal system that involves ill-posed problem in stimulus intensity determination. We proposed a closed-loop controller consisting of multiple PID controllers that have mutual interference. The parameter tuning method proposed by Chien, Hrones and Reswick (CHR method) was modified for our controller. The transformation matrix, which was obtained by calculating a generalized inverse of the matrix that relates stimulus intensities with joint angles, was also used as parameters of the controller. The controller was examined with normal subjects in controlling the wrist joint that has 2-degrees of freedom of movement (dorsi/palmar- and radial/ulnar-flexions). Electrical stimulation was applied to four muscles (FCR, FCU, ECR, and ECU) through surface electrodes. Control tasks were to track a target on elliptical and rectangular trajectories defined on the joint angles. The controller could regulate stimulus currents and it could achieve the tracking tasks except for some cases.

## Introduction

The commercially available FES system in Japan uses EMG-based stimulus pulse amplitude data that are referred to when motions are restored [1]. Multichannel open-loop FES control of complicated redundant musculoskeletal system has become practical and effective clinically by this method. In addition to the open-loop control, however, closed-loop control is required for stability and safety of FES motions. Closed-loop control method for redundant system that involves the ill-posed problem in stimulus intensity determination has not been realized, although some closed-loop control methods were reported [2-4]. That is, multichannel closed-loop FES control for the joint that has some degrees of freedom of movement with multi-muscles to be stimulated are needed.

We propose a closed-loop controller consisting of multiple PID controllers that have mutual interference. The controller makes it possible to solve the ill-posed problem. Parameter tuning method is also proposed for the controller. The feedback controller is examined with normal subjects in controlling the wrist joint that has 2-degrees of freedom of movement with four muscles stimulated through surface electrodes.

## Methods

*A. Control Algorithm*

Output of the musculoskeletal system (joint angle vector $\boldsymbol{\Theta}$) can be described as functions of stimulus intensity vector $\boldsymbol{I}$ if gravitational effect is neglected:

$$\boldsymbol{\Theta} = \boldsymbol{F}(\boldsymbol{I}).$$

Here, small changes of angles about their current angles are obtained by using Jacobian matrix $\boldsymbol{M}(\boldsymbol{I})$ [5]:

$$d\boldsymbol{\Theta} = \boldsymbol{M}(\boldsymbol{I})\, d\boldsymbol{I}.$$

Because the Jacobian matrix can not be determined experimentally, we introduced the following assumption for the element of $\boldsymbol{M}(\boldsymbol{I})$: small change of joint angle in movement $i$, $\Delta\theta_i$, was approximated by

$$\Delta\theta_i = \frac{df_{i1}(I_1)}{dI_1}\Delta I_1 + \frac{df_{i2}(I_2)}{dI_2}\Delta I_2 + \ldots + \frac{df_{im}(I_m)}{dI_m}\Delta I_m .$$

The function, $f_{im}(I_m)$, shows joint angle of movement $i$ developed by stimulation to muscle $m$, $I_m$, when stimulus intensities to other muscles are zero. That is, the functions describe the input-output (stimulus intensity-joint angle) characteristics of musculoskeletal system when muscles are electrically stimulated separately. We used piece-wise linear approximation of the input-output characteristics to describe the function [6]. Therefore elements of the Jacobian matrix are obtained by

$$m_{ij} = (\theta_{i2} - \theta_{i1}) / (I_{j2} - I_{j1}),$$

where $I_{j1}$ and $I_{j2}$ are the minimum and the maximum stimulus currents, respectively. $\theta_{i1}$ and $\theta_{i2}$ are angles in movement $i$ at $I_{j1}$ and at $I_{j2}$, respectively.

If the inverse matrix of the Jacobian matrix can be calculated, small changes of stimulus currents are determined by small changes of joint angles. That is,

$$d\boldsymbol{I} = \boldsymbol{M}^{-1}\, d\boldsymbol{\Theta}$$

However, the inverse matrix of the Jacobian matrix does not exist in all cases because the musculoskeletal system has redundancy causing the ill-posed inverse problem. Therefore we used the generalized inverse matrix $\boldsymbol{M}^{-}$. The generalized inverse of the Jacobian matrix was calculated uniquely by the simplex method using Wolfe's algorithm including limitation in the sign of elements under the condition of minimizing the square sum of elements of the generalized inverse matrix [7].

The PID control algorithm used in the proposed controller is described by the following equation.

$$\boldsymbol{I}_n = \boldsymbol{I}_{th} + \boldsymbol{K}_{\mathrm{P}}\boldsymbol{e}_n + \boldsymbol{K}_{\mathrm{I}}\sum_{i=0}^{n}\boldsymbol{e}_i + \boldsymbol{K}_{\mathrm{D}}(\boldsymbol{e}_n - \boldsymbol{e}_{n-1})$$

$\boldsymbol{K}_P = \boldsymbol{a}_P \boldsymbol{M}^-$, $\boldsymbol{K}_I = \boldsymbol{a}_I \boldsymbol{M}^-$, $\boldsymbol{K}_D = \boldsymbol{a}_D \boldsymbol{M}^-$,

where $\boldsymbol{I}_{th}$ is the stimulation threshold. $\boldsymbol{a}_P$, $\boldsymbol{a}_I$ and $\boldsymbol{a}_D$ are fine tuning constant vectors. The error vector $\boldsymbol{e}_n$ is defined by $\boldsymbol{e}_n = \boldsymbol{\Theta}_n^{(T)} - \boldsymbol{\Theta}_n^{(M)}$, where $\boldsymbol{\Theta}_n^{(T)}$ and $\boldsymbol{\Theta}_n^{(M)}$ are the target and the measured angle vectors at time $n$, respectively.

In order to determine parameter values in fine tuning constant vectors, we modified the CHR (Chien, Hrones and Reswick) method that uses approximation of step response by the 1st-order delay with latency. Parameters of muscle $i$ about movement $j$ are described by

$K_{Pij} = m_{ij}^- 0.6 T_i / L_i$, $K_{Iij} = m_{ij}^- 0.6 \Delta t / L_i$, $K_{Dij} = m_{ij}^- 0.3 T_i / \Delta t$

Where, $m_{ij}^-$ shows the element of the generalized inverse matrix $\boldsymbol{M}^-$. $T_i$ and $L_i$ are the latency and the time constant of the step response of muscle $i$, respectively. If a muscle develops movements in different joint axes, $T_i$ and $L_i$ are calculated as averages of values obtained from those responses in every joint axis.

*B. Experiment*

Wrist joint angles in directions of the dorsi/palmar- and the radial/ulnar-flexions of five normal subjects were controlled by stimulating the flexor carpi radialis (FCR), the flexor carpi ulnaris (FCU), the extensor carpi radialis longus/brevis (ECR) and the extensor carpi ulnaris (ECU). The joint angles were measured with an electric goniometer (M110, Penny & Gills) and sampled at 20Hz. Stimulus pulse amplitudes (stimulus frequency: 20Hz, pulse width: 0.2ms) were regulated by the controller and stimulus currents were applied to the muscles through isolators (5384, NEC Medical Systems) and surface electrodes (F-150M, Nihon Koden).

Subjects were sat on a chair and the left arm was in the vertical direction to the ground. Gradually increasing stimulation was applied to each muscle to measure input-output characteristics about dorsi/palmar- and radial/ulnar-flexions. The characteristics were approximated to a straight line between the minimum and the maximum stimulus amplitudes by the least mean square method. The minimum and the maximum stimulus intensities were determined from the measured characteristics in order to get enough control range without pain. The Jacobian matrix of the stimulated musculoskeletal system was obtained from those results. Then step input of electrical stimulation was applied to each muscle to determine parameters of the PID controllers, $K_{Pij}$, $K_{Iij}$ and $K_{Dij}$.

The closed-loop controller was evaluated in tasks of tracking target joint angles varying with time on elliptical trajectories on the joint angle space. The angle space was defined by the axes of the dorsi/palmar- and the radial/ulnar-flexion angles on the rectangular coordinate system. Cycle periods were 10s, 5s, and 3s. The controller was also examined in tracking rectangular trajectory (1s tracking, 2s positioning). In those control tasks, the left arm was in 1) the vertical direction, and 2) the horizontal to the ground (90deg pronation). The first 5s control was for guiding to start position of the target.

We defined the following evaluation criteria using end point position of the hand calculated from wrist joint angles on the basis that the standard length between the wrist joint and the end point is about 18.2cm:

(1) mean error: $$err = \frac{1}{N}\sum_{i=0}^{N-1}\left\|\boldsymbol{P}_i^{(T)} - \boldsymbol{P}_i^{(M)}\right\| \quad \text{[cm]}$$

(2) standard deviation of movement velocity:

$$SD_v = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left\{\left\|\frac{\Delta \boldsymbol{P}_i^{(M)}}{\Delta t}\right\| - \frac{1}{N}\sum_{j=1}^{N}\left\|\frac{\Delta \boldsymbol{P}_j^{(M)}}{\Delta t}\right\|\right\}^2} \quad \text{[cm/s]}$$

Where, $\boldsymbol{P}_i^{(M)}$ and $\boldsymbol{P}_i^{(T)}$ are the measured and the target end point positions at time $i$. $N$ shows number of data without first 5s. $\Delta t$ shows sampling interval and $\Delta \boldsymbol{P}_i^{(M)} = \boldsymbol{P}_i^{(M)} - \boldsymbol{P}_{i-1}^{(M)}$.

## Results

Most of input-output relationships were approximated by a straight line as shown in Fig.1. Those of the ECU and the FCR, however, were not represented sufficiently by a straight line within the control range because of strong nonlinearity. Ulnarflexion, which was sometimes observed on the relationship of the FCR, was also a reason for insufficient approximation. The ulnarflexion was considered to be caused by the pronation developed by the FCR as stimulus intensity was increased. We used the linear approximation for all the characteristics in the experiments, however.

Experimental results of three trials obtained from three of five subjects were evaluated because the controller could not achieve the tasks with the other subjects. A typical result of tracking elliptical trajectory is shown in Fig.2. Evaluation results of one subject are shown in Table 1. Evaluation results of other subjects were quite similar. The joint angles were controlled with

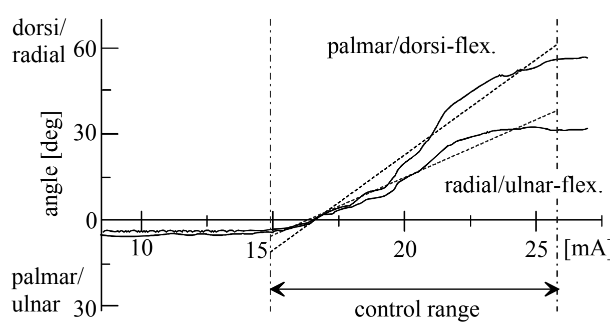


Fig.1 Measured input-output characteristics of the ECR. Broken lines show approximated lines. Control range was determined between the maximum and the minimum stimulus intensities.

good performance. Large difference in control results between different postures was not observed. $SD_v$ was large compared to the target velocity $v_T$ and was larger at horizontal position than at vertical position.

**Discussion**

Stimulus intensities to the muscles were determined by the proposed closed-loop controller which had parameters determined by piece-wise linear approximation of the input-output characteristics and the modified CHR method. Experimental results showed that the controller could control the wrist joint solving the ill-posed problem in stimulus intensity determination of the musculoskeletal system having nonlinearity.

The wrist joints of two subjects were not controlled by the controller. Possible reasons were small range of motion of electrically stimulated musculoskeletal system that was caused by pain, difficulty of selective muscle stimulation with surface electrodes and so on.

The results of this study show that the proposed control method can provide a solving method of the ill-posed problem in stimulus intensity determination of closed-loop FES control.

## References


[1]N.Hoshimiya et al.: Multichannel FES system for the restoration of motor functions in high spinal cord injury patients: A respiration-controlled system for multijoint upper extremity, IEEE Trans. Biomed. Eng., 36, 754/760, 1989.

[2]J.J.Abbas et al.: Feedback control of coronal plane hip angle in paraplegic subjects using functional neuromuscular stimulation, IEEE Trans. Biomed. Eng., 37, 687/698, 1991.

[3]N.Lan et al.: Control of end-point forces of a multijoint limb by functional neuromuscular stimulation, IEEE Trans. Biomed. Eng., 38, 953/965, 1991.

[4]J.J.Chen et al.: Applying fuzzy logic control cycling movement induced by functional electrical stimulation, IEEE Trans. Rehab. Eng., 5, 158/169, 1997.

[5]H.Asada and J.-J.E.Slotine: Roboto Analysis and Control, Jhon Wiley & Sons, 1986.

[6]T.Watanabe et al.: FES control using Jacobian matrix of the musculoskeletal system: Experiments on the wrist with four muscles of normal subjects, Proc. 4th IFESS, 295/298, 1999.

[7]K.Kurosawa et al.: A study on modification method of stimulation patterns for FES, Japanese J. Med. Electron. and Biolog. Eng., 34, 103/110, 1996. (in Japanese).



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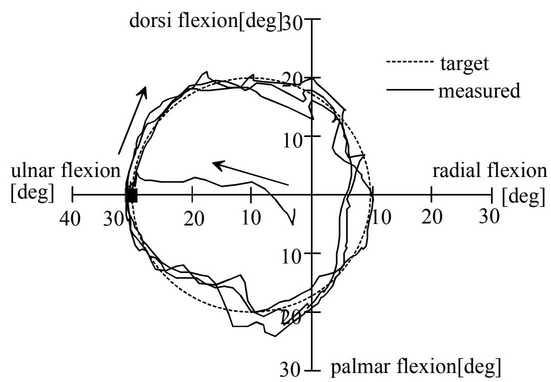
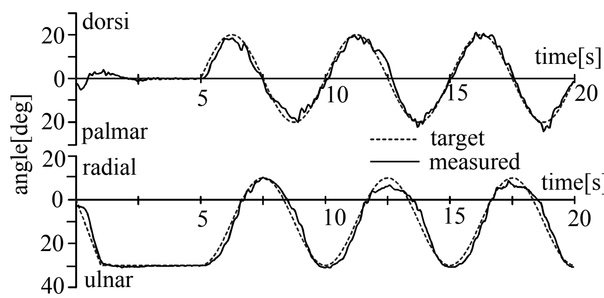



(a)




(b)

Fig.2 A typical result of tracking control. (a) Trajectories on joint angle space (the rectangular shows the target start position.), and (b) time cause. Cycle period was 5s.

Table 1 Evaluation results of tracking control (*err*: mean error, $v_T$: velocity of target movement, $SD_v$: standard deviation of movement velocity). Each value shows average of three trials.

| | target / arm direction | elliptical | | | rectangular |
|---|---|---|---|---|---|
| | | cycle period 10[s] $v_T$=3.90[cm/s] | cycle period 5[s] $v_T$=7.78[cm/s] | cycle period 3[s] $v_T$=12.9[cm/s] | |
| *err* [cm] | vertical | 0.55 | 0.99 | 1.64 | 0.58 |
| | horizontal | 0.59 | 0.95 | 1.69 | 0.62 |
| $SD_v$ [cm/s] | vertical | 2.48 | 4.34 | 5.89 | |
| | horizontal | 2.25 | 3.66 | 5.96 | |