Force Control during Grasp using FES Techniques: Preliminary Results

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Abstract – *This work concerns the design and the implementation of feedback controllers to regulate the properties of electrically stimulated muscle. Two different closed-loop controllers (a PID and a fuzzy controller) have been developed to regulate the force produced during grasp by modulating the stimulation parameters in real-time.*

The controllers were implemented using a C++ program running on a PC. In each experiment, the recruitment characteristics of the different muscles were first obtained in order to provoke the flexion of the fingers and the thumb. Then, the stimulation parameters of one muscle (the Flexor Digitorum Superficialis) were closed-loop controlled to provoke the hand closing/opening in order to obtain the desired value of the force chosen by the subject. The results indicate that the fuzzy algorithm seems to be more able to deal with the complexity of the controlled system.

***Keywords**: Closed-loop control, FES, hand neuroprosthesis, fuzzy logic*

1. Introduction

Functional Electrical Stimulation (FES) is a rehabilitation technique used to restore function in neurological impaired individuals [1-2].

The systems based on FES provide appropriate electrical stimuli to provoke the contraction of paralyzed muscles to obtain functional movements. The highly nonlinear and time-dependent characteristics of the muscles when stimulated make the use of closed-loop control strategies mandatory. In fact, although an open-loop control system is capable of tracking a desired trajectory, it cannot compensate for changes in the stimulated system, due, for example, to fatigue [3-4]. Moreover, a closed-loop controlled FES system can be more easy to control because of the linearization effect of the dynamics of the system [5].

This work is part of a long-term effort which is going on in the framework of the European Project GRIP ("An inteGRated system for the neuroelectrIc control of grasP in disabled persons", ESPRIT LTR #26322). whose aim is the development of an implantable closed-loop FES system to restore hand function in tetraplegics using the sensory information recorded from a glove worn by the patient (see Figure 1). In this paper we illustrate the results of the implementation of closed-loop control algorithms in able-body subjects as a preliminary step towards the achievement of the final goal of the project. The aim of this study was to validate the experimental set-up and to prove the feasibility of our approach.

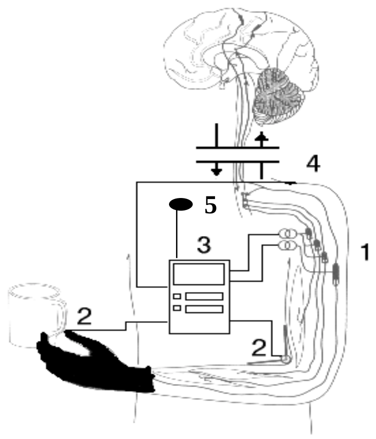

Figure 1: Schematic view of the final demonstrator of the GRIP Project: (1) Neural electrodes, implantable stimulator and telemetry system; (2) artificial sensors (position, contact); (3) control system; (4) signals for high level control; (5) system to provide cognitive feedback

2. Methods

2.1. Experimental set-up

The set-up of the experiment (shown in Figure 2) includes a stimulator, a PC, one force sensor (Flexiforce-Tekscan Inc. USA) mounted on the thumb of the subject [6] and an electronic acquisition board to record sensor information.

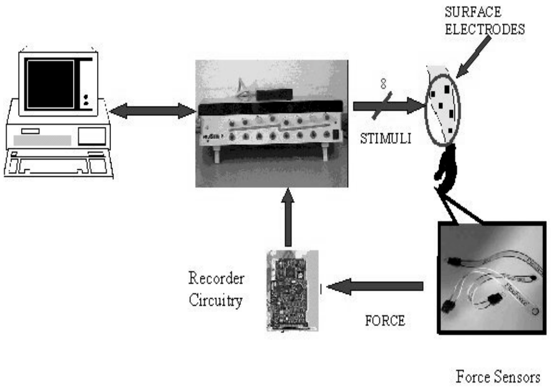

Figure 2: Set-up of the experiment

The stimulator used was the Prostim8 (Neuromedics, Montpellier, France). It is a portable, programmable, multichannel system for FES and biofeedback. The stimulator has 8 input channels to record sensory information, and 8 programmable output channels to deliver electrical stimuli to the muscles. The control of the channels was made by means of a PC. The stimulation impulse is biphasic (mean value zero), with a negative phase that follow the capacitor discharge to eliminate completely the residual charge in the subject tissue see Figure 3.

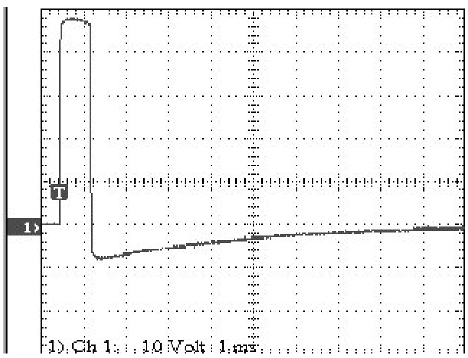

Figure 3: Biphasic Impulse with a negative phase that follows the capacitor discharged

The impulse parameters were:

- current amplitude: 0-170 mA
- Impulse duration 0-1400 µs
- Stimulation frequency 0-250 Hz

The main advantage of the system is the programmability:

- the amplitude, the frequency and the duration of the stimulus can be regulated independently
- the control can be manual (open-loop) or automatic (closed-loop).

The stimulator can be used to record sensory information making the A/D conversion on 10-bit of the analog input signals (0-5V).

The controllers were implemented using a C++ program running on the PC.

2.2. Controller implementation

Two different controllers were designed to implement a closed loop controlled hand neuroprosthesis: a PID and a fuzzy controller. The aim of these controllers was to regulate the force producted by the muscle by modulating the amplitude of a constant pulse-width electrical stimulation pulse train.

The PID control can be written as:

$$x\,(k)= K_I*[x(k-1)+e(k)]+K_D*[e(k)-e(k-1)]+K_P*e(k)$$

The controller output at each sampling time is a linear combination of the error (weighted by tunable parameter K_P), the difference between the current and the most recent error (weighted by K_D) and the sum of the past tracking errors. The parameters of the controller (K_P, K_I, and K_D) were empirically tuned.

The fuzzy logic controller developed had two input variables (error and the change of error) and one output. The universe of discourse of these variables was the range [-1 1] as in [7-8]. The scaling factor of the input variables was chosen to map them into the interval [-1,1] by means of a trial-and-error procedure. The linguistic values of the variables were defined by their respective membership function shown in Figure 4.

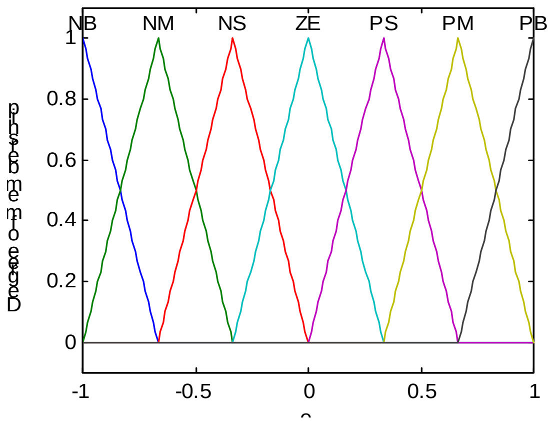

Figure 4: Membership function

The rule base implemented a PI controller.

2.3. Grasp synthesis

In this study the palmar grasp has been synthetised by stimulating the following muscles :

a) Finger flexors
   - Flexor Digitorum Superficialis (FDS)
b) Finger extensors
   - Extensor Sigitorum Superficialis (EDS)
c) Thumb flexor
   - Flexor Pollicis Longus (FPL)
d) Thumb Abductors
   - Abductor Pollicis Brevis (AbPB)
   - Opponens Pollicis (OP)

The typical templates for the palmar grasp are shown in Figure 5.

This grasp is used for picking up larger objects such as a cup or a book [9]. In this grasp the thumb position remained constantly in opposition. Finger position changed from full extension to full flexion.

The stimulus templates were set for each muscle. These were the initial settings, the controller and the user (by means of the keyboard) can change these settings in real-time.

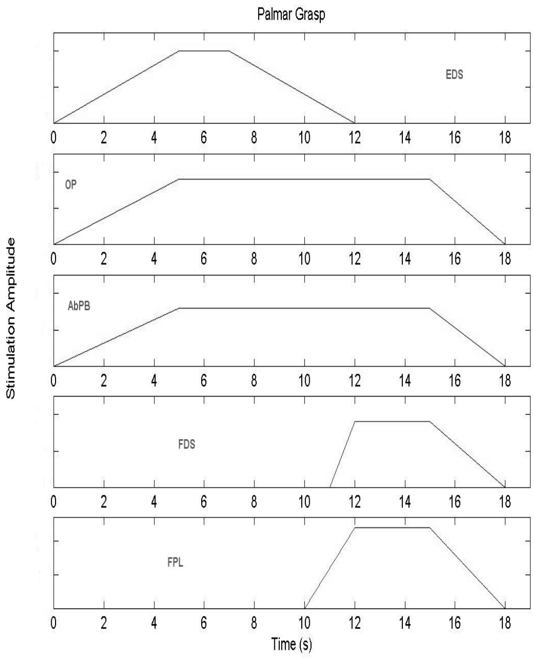

Figure 5: Palmar Grasp Template

The philosophy of the control strategy was the following: (1) the initial stimulation parameters were set in order to provoke the flexion of the fingers and thumb; (2) when the subject thought that the force was enough to avoid slippage, he gave the command "hold the grasp". In this work the subjects gave the commands (onset of the stimulation, hold the grasp, stop of the stimulation) by means of the keyboard keys; (3) after the command "hold the grasp" the system set the reference force to the value obtained by the average of the last five measures of the sensor. At this point the stimulation parameters of the FDS were closed-loop controlled to provoke the hand closing/opening in order to obtain the desired value of the force.

3. Results

Three subjects (mean age: 30 years) participated in this study. For all these subjects the palmar grasp was synthesised. The muscle used for the closed-loop control was the FDS. In all the subjects 5 electrodes were used to stimulate the following muscles: OP, AbPB, EDS, FDS, and FPL. The object grasped by the subjects was a cylindrically shaped object (diameter: 5 cm, and weight: 0.2 Kg).

The experiment typology was deducted from the works described in [10-14]. In these trials the wrist and the elbow were set in intermediate pronosupination position. We tested the performance of two controllers was tested during tracking of different force trajectories. The results of some tracking tasks are shown in Figure 6, Figure 7 and Figure 8.

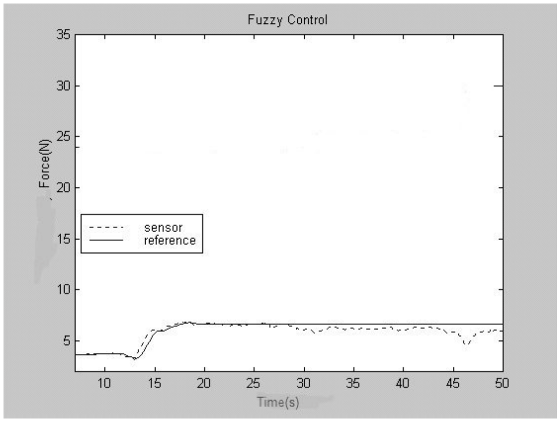

Figure 6: Result obtained from one tracking experiment using the Fuzzy Control

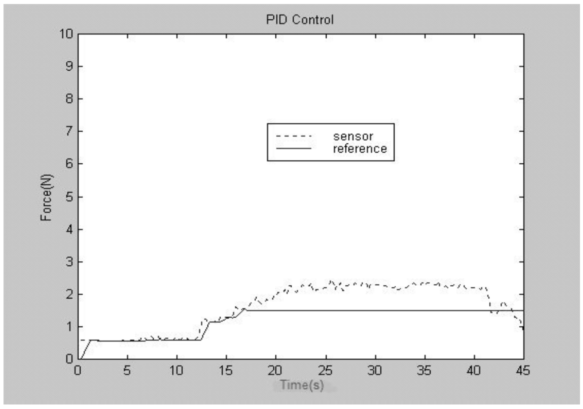

Figure 7: Result obtained from one tracking experiment using the PID Control

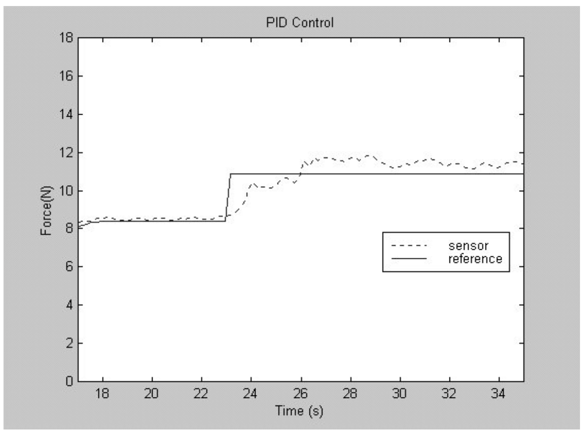

Figure 8: Result obtained from one experiment using the PID Control .

In Table 1 The mean error, the standard deviation and the integral of absolute error (IAE) during the tracking tasks for the two controllers are given.

Control	Duration (ms)	Mean error	Standard deviation	IAE
Subject 1				
PID Control	12	0.9	1.8	250
Fuzzy Control	12	0.24	0.33	70
PID Control	45	0.4	0.37	70
Fuzzy control	45	0.21	0.36	53
Subject 2				
Control	Duration (ms)	Mean error	Standard deviation	IAE
PID Control	12	0.3	0.4	55
Fuzzy Control	12	0.2	0.3	40
PID Control	45	0.4	0.4	89
Fuzzy control	45	0.21	0.36	52
Subject 3				
Control	Duration (ms)	Mean error	Standard deviation	IAE
PID Control	12	0.36	0.5	55
Fuzzy Control	12	0.15	0.5	25
PID Control	45	0.4	0.43	80
Fuzzy control	45	0.3	0.53	52

Table 1 Characteristics of the force responses: Mean Error, Standard deviation, IAE

4. Conclusions

The results of the experimental evaluation showed the feasibility of the approach proposed. Moreover, the fuzzy-logic-based algorithm seems to be more able to deal with the complexity of the controlled system because of its non-linear structure. We are currently working on the implementation of the control strategies presented in this paper with disabled subjects.

Acknowledgements

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