A Transcutaneous Computer-based Closed-loop Motor Neuroprosthesis for Real-Time Movement Control

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Abstract

In this work, we developed a transcutaneous computer-based closed-loop functional neuromuscular stimulation (FNS) with eight channels for real-time control of electrically stimulated muscle. Up to 16 channels feedback information can be recorded and processed on-line. The system can operate in two mode of operation: open-loop and closed-loop. During the open-loop mode of operation, the system stimulates the paralyzed muscle according to a predefined patterns. During the closed-loop, this system both processes the feedback information and coordinates the multichannel stimulation to provide the desired movement in paralyzed limb. The system has the ability to modulate the stimulated muscle force either by PWM or PAM, or both of them.

1 Introduction

Motor neuroprostheses has been demonstrated to be effective in restoring hand function in quadriplegia and locomotion in paraplegia and hemiplegia [1]. Improved performance of these neuroprostheses can, in principle, be obtained through feedback control [2], [3]. For closed-loop control, it is needed to have on-line feedback information about the status of the limb. The feedback information has been used to regulate the muscle activation. For developing and evaluating different feedback controller schemes, a versatile closed-loop FNS system for use in research laboratory is essential. The system needs to be easy to use, reliable, and easy to implement any controller scheme.

In this work, we developed an eight-channel general purpose computer-based FNS system for real-time muscle model identification and on-line closed-loop control. The system is used to acquire feedback control information and to supply stimulation patterns for activation of paralyzed muscles. The system developed in this work comprises a personal computer (PC), 8-channel stimulator, and a data acquisition board. The system was programmed by using Matlab, Simulink, Real-Time Workshop, and Real-Time Windows Target [4]. The system was tested in real-time knee-joint angle control.

![Figure 1: Block Diagram of eight-channel Computer-Based Closed-loop FNS.](image)

2 System Description

2.1 Hardware

Figure 1 shows a functional block representation of the system. The entire system consists of a personal computer (PC), ISA interface circuit, 12-bit digital-to-analogue converter (DAC), voltage-to-current converter (VIC), high voltage DC-to-DC converter, waveshaping circuit, timers, and a high performance data acquisition card (PCL-818HG, Advantech).

ISA interface circuit decodes incoming information from the computer and executes the encoded function. It provides command signals for all the support circuitry used. Individual commands are used for activating the stimulation channel, programming and triggering the timers integrated circuits, and controlling the state of the amplitude latch register.

The amplitude of the stimulation pulses is loaded from ISA interface circuit and latched into the amplitude register. DAC converts the digital value of the pulse amplitude into an analogue signal which controls the analogue value of the pulse amplitude.
Each channel has a programmable timer integrated circuit which performs all of the timing functions in generating the stimulation waveforms. Each timer IC has three independently-controllable counters. These counters are used for controlling the positive and negative width and interphase interval of stimulus pulses.

![Matlab Simulink block diagram of the system software](image)

**Table 1: Computer-Based Closed-loop FNS Specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stimulation Channels</td>
<td>8</td>
</tr>
<tr>
<td>Pulse Waveform</td>
<td>monophasic/biphasic, monopolar/bipolar</td>
</tr>
<tr>
<td>Pulse width Duration</td>
<td>0-700µs</td>
</tr>
<tr>
<td>Pulse width resolution</td>
<td>1 µs</td>
</tr>
<tr>
<td>Interphase Duration</td>
<td>0-100 µs</td>
</tr>
<tr>
<td>Interphase Resolution</td>
<td>1 µs</td>
</tr>
<tr>
<td>Pulse Amplitude Range</td>
<td>0-100 mA</td>
</tr>
<tr>
<td>Pulse Amplitude Resolution</td>
<td>1 mA</td>
</tr>
<tr>
<td>Pulse Frequency Range</td>
<td>0-50 Hz</td>
</tr>
<tr>
<td>Modulation Technique</td>
<td>PWM or/and PAM</td>
</tr>
<tr>
<td>Number of Data Acquisition Channels</td>
<td>16</td>
</tr>
</tbody>
</table>

High-voltage DC to DC converter uses 12 volts DC from ISA computer bus and provides a regulated 120 volts DC. Constant positive voltage is converted to a constant positive current whose level is specified by the output of DAC. Finally, constant-current biphasic or monophasic pulses are generated by the waveform switching circuit. Table 1 summarizes the specification of the stimulator.

**2.2 Software**

For implementing such a close-loop FNS system, appropriate computer software is required. The software must handle online data acquisition and real-time processing and send the stimulus parameters to one or more FNS channel. In our case, we used Matlab Simulink [30], Real-Time Workshop [31], and Real-Time Windows Target under Windows 98. Simulink provides an interactive environment for modeling, simulating, controlling, and processing as a block diagram by using predefined blocks. Real-time Workshop provides the utilities for converting Simulink models into C code, and then compiling the code into a real-time executable by using a C compiler. The executable code is loaded into memory and the Real-Time Windows target kernel runs the code in real time.

The system can operate in two modes of operation: open-loop and closed-loop. Fig. 2 shows the Matlab Simulink block diagram for PID control of the knee joint angle. The user can activate the specified stimulator channel through CHANNEL blocks. The SENDING block is a C-MEX block that sends all stimulus parameters and control information to the ISA computer bus. The stimulation pattern is read and transmitted to SENDING block by READPATTERN block. The control strategy is implemented by the C-MEX S-function (PROCESSING block).

**2.3 Experiments**

Experiments were conducted on a complete level T7 spinal cord injury paraplegic. The subject was active participant in a rehabilitation research program involving daily electrically stimulated exercise of their lower limbs (either seated or
during standing and walking). The quadriceps muscle was stimulated using adhesive surface electrodes.

Knee Joint Position Control

Figure 3 shows the results of the knee joint position control based on the PID controller for two knee angles. The parameters of the PID controller were tuned using the Ziegler-Nichols’ method based on the step response of the open-loop system. The step response was obtained by stimulating the muscle at a constant frequency (20 Hz), constant amplitude (60 mA), and constant pulsewidth (300 µs).

![Figure 3](image)

**Figure 3**: PID position control of knee joint angle for two different knee joint angles.

Muscle Fatigue Compensation

Figure 4 (a) shows the variation of the measured knee joint angle during sustained constant electrical stimulation of quadriceps muscle. Figure 4 (b) shows the control of knee joint position during sustained electrical stimulation using closed-loop control. In this case, the controller adjusts the parameter of stimulation signals according to the following simple rule:

\[
\begin{align*}
\text{if } \Phi_m > \Phi_d & \text{, then } w(t) = w(t-1) - 1 \\
\text{if } \Phi_m < \Phi_d & \text{, then } w(t) = w(t-1) + 1 \\
\text{if } \Phi_m = \Phi_d & \text{, then } w(t) = w(t-1)
\end{align*}
\]

Here, \(w(n)\) is pulsewidth at time \(t\), \(\Phi_m\) and \(\Phi_d\) are measured and desired joint angle, respectively.

3 Results

In this work, we developed a versatile computer-based closed-loop FNS for FES control of paralyzed limb muscles. The system is easy to use, reliable, and easy to implement any controller scheme. The system modulates the stimulated muscle force either by PWM or PAM, or both of them. Figure 5 shows the standing of a T7 complete paraplegic subject using the system.

![Figure 5](image)

**Figure 5**: Standing of a T7 complete paraplegic subject using the FNS system

References


