Development and Application of a Versatile FES System

Shih-Ching Chen[1,7] Jer-Junn Luh[2] Yu-Luen Chen[3] Cheng-Liang Liu[4]
Chung-Huang Yu[5] Han-Chang Wu[6] Chun-Hao Chen[1] Yasunobu Handa[7]
Shuenn-Tsong Young[8] Te-Son Kuo[6] Jin-Shin Lai[*,9]

[1]*Department of Physical Medicine and Rehabilitation, Taipei Medical University and Hospital, Taipei, 110, Taiwan R.O.C.*
[2]*School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Taipei, 104, Taiwan R.O.C.*
[3]*Department of Electronic Engineering, Hwa-Hsia College of Technology and Commerce, Taipei, 235, Taiwan R.O.C.*
[4]*Department of Mechanical Engineering, National Taiwan University, Taipei, 104, Taiwan R.O.C.*
[5]*Institute of Rehabilitation Science and Technology, National Yang-Ming University, Taipei, 112, Taiwan R.O.C.*
[6]*Department of Electrical Engineering, National Taiwan University, Taipei, 104, Taiwan R.O.C.*
[7]*Department of Restorative Neuromuscular Surgery and Rehabilitation, Graduate School of Medicine, Tohoku University, Japan*
[8]*Institute of Biomedical Engineering, National Yang-Ming University, Taipei, 112, Taiwan R.O.C.*
[9]*Department of Physical Medicine and Rehabilitation, College of Medicine, National Taiwan University, Taipei, 104, Taiwan R.O.C.*

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Abstract

The purpose of this study was to develop a versatile Functional Electrical Stimulation (FES) system and to perform clinical applications to restore the functions of decentralized and paralyzed limbs. The development of the electrical stimulator, core of the FES system, is based on the element-envelope method. A direct-synthesized arbitrary waveform is generated by a digital signal processor, and bi-phasic, voltage-controlled, constant current stimuli are provided by an analog output circuit. The pattern generators receive the commands, coming from a patient-driven input device or a closed-loop feedback sensing device, to synthesize the required waveforms and elicit the required functions. In clinical application, a pedal cycling FES system, a patient-driven hand grasping FES system with a closed-loop feedback controller and an ankle motion FES system with a neural network and fuzzy controller were tested. The results showed that the proposed stimulator could be considered as a full-featured electrical stimulator for various FES applications with its flexibility in pattern generation and feedback processing capabilities. All of the clinical applications showed satisfactory results in the restoration and control of some specific functions.

Keywords: Functional electrical stimulation (FES), Constant current, Feedback control, Pedal cycling, Hand grasping, Ankle motion

Introduction

Functional electrical stimulation (FES) is a rehabilitation technology to restore functions by using a low level electrical current to the neuromuscular system [1,2]. For the past decades, FES has been used to regain the functions of spinal cord injured and stroke patients. An FES system is composed of the electrical stimulator, electrodes, patient-driven input devices, and/or closed-loop sensing feedback devices.

Although several systems have been developed [3-8] for laboratory or clinical applications, they are usually limited to a single application due to insufficient features. In this study, a versatile direct-synthesized multi-channel arbitrary waveform stimulator was proposed as a flexible instrument for various FES applications. A novel pattern-generation algorithm is presented to synthesize flexible and programmable patterns. The algorithm reduces the memory requirements and preserves the ability for feedback control. A new constant-current source was designed to overcome the operational limitations of the traditional driving stages. The constant-current source also provides high-voltage compliance with a linear current output. Analog and digital feedback interfaces were included in the proposed arbitrary waveform stimulator, and all the signals were directly handled or sent back to host a computer for the follow-up analysis. The feedback controller could be easily implemented using the digital signals processor (DSP). A Windows-environment host program was also developed to facilitate the usage of the proposed electrical stimulator.

To verify the efficacy of the system and to restore the functions of paralyzed limbs, clinical applications, including pedal cycling, patient-driven hand grasping with a closed-loop feedback control, and an ankle motion FES system with a neural network and fuzzy controller were performed.

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*Corresponding author: Jin-Shin Lai
Tel: +886-2-23123456 ext.2025; Fax: +886-623210037
E-mail: jslai@ccms.ntu.edu.tw

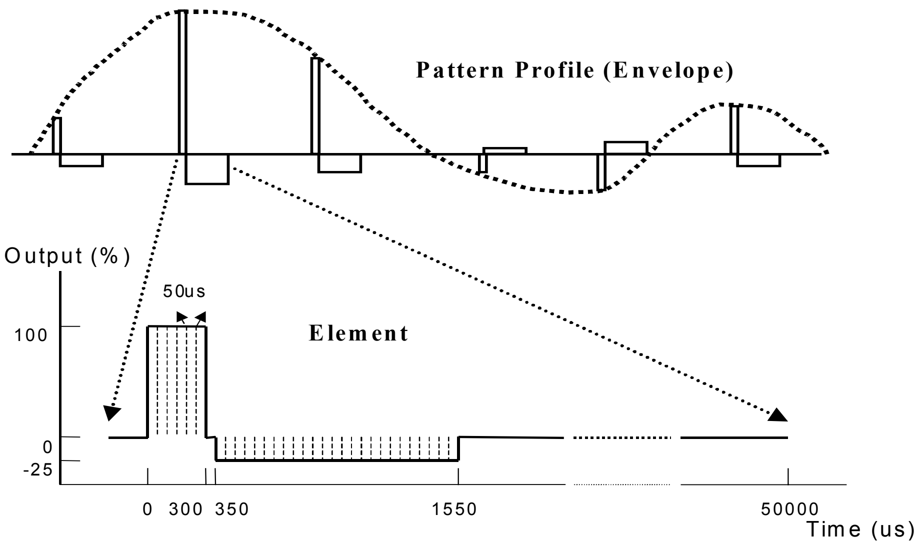

Figure1. The element-envelope method for stimulation patterns.

Methods

Design of a Versatile Electrical Stimulator

An electrical stimulator is functionally divided into four blocks: a command interpreter, a pattern generator, a driving stage and a feedback controller. For safety, electrical isolation circuits for power and signal were used to prevent serious electrical shock.

Command interpreter: The command interpreter receives instructions from patients or physicians, then translates the instructions into a series of parameters for pattern synthesis. The parameters include pulse-shape, activating duration, stimulating frequency, amplitude and inter-pulse duration.

Pattern generator: The pattern generator synthesizes pulse-like waveforms based on to the parameters received from the interpreter. This is the core of the electrical stimulator.

Driving stage: The driving stage acts as a constant-current or a constant-voltage source to pull up the electrical pulses so that the nerves and muscles can be excited. The constant-current sources are more prevalent than the constant-voltage sources in surface stimulation due to the inevitable variations in tissue impedance[9-10].

Feedback controller: The feedback controller is used to compensate for the loss of natural feedback in paralyzed patients. Suitable feedback should be provided for individual functional purposes. Mechanical and biological feedbacks, such as angles, positions, forces, and evoked electromyography (EMG) were the potential candidates. Several feedback controllers have been successfully proposed, such as PID controllers[11], artificial neural network controllers[12], and fuzzy controllers[13]. Based on the selected feedback and feedback controllers, some pattern parameters of stimulated waveforms were modified, and the pattern generators received the commands and synthesized the required waveforms.

The arbitrary waveform electrical stimulator was developed in our studies to emphasize flexible waveform design, simple operation, and compatibility with various applications. The stimulator offers four channels of arbitrary waveform regulated-current stimulation with maximum amplitudes of ±110 mA.

A. Waveform Generation

An "element-envelope" method was proposed to synthesize stimulation patterns. This method took advantage of the pseudo-period characteristic of stimulation patterns. A series of electrical pulses constructed a stimulation pattern, and the parameters of the pulse determined the stimulation modes, such as pulse-amplitude modulation (PAM), pulse-width modulation (PWM), and pulse-frequency modulation (PFM). The "element" represents a single pulse-like signal while the "envelope" stands for the samples of the pattern profile. As illustrated in figure 1, an element and some envelope points were combined to build required patterns. One element is composed of several samples, and the sampling interval is 50us, which is adequate for neuromuscular stimulation applications. The sample numbers with a positive value determine the duration of the stimulating pulse, and sample numbers of one element determine the stimulating frequency. The PWM and PFM can then be easily programmed. The amplitude of each sample in one element is stored in relative value (percentage to the maximum output). After being multiplied by an envelope sample, the absolute amplitude of the element is determined. In our system, the profiles of stimulation patterns were sampled at 100Hz, i.e., the amplitude of elements updated every 10ms. This proposed method only records the information of one element and the samples of the envelope, instead of sampling all the stimulation patterns, which wastes a lot of memory storage.

With the proposed element-envelope method, the waveforms can be generated in real-time. In a multi-channel stimulator, the computation is extremely high. Therefore, a DSP with its powerful computing capabilities (TMS320C32, Texas Instruments) was chosen to generate the patterns. The system block diagram of the proposed arbitrary waveform stimulator is illustrated in figure 2. A 16-bit dual-channel

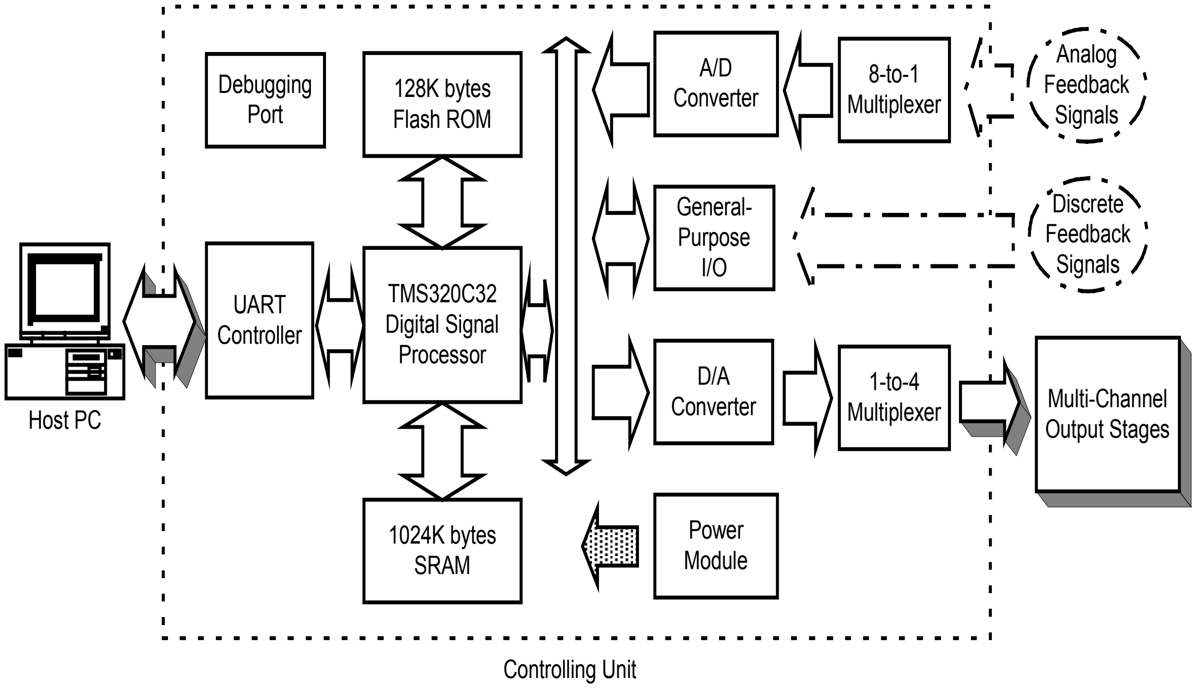

Figure 2. System block diagram of the multi-channel arbitrary waveform stimulator.

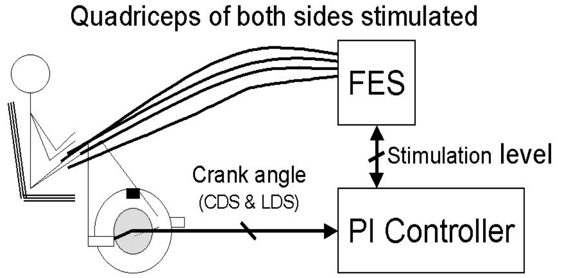

Figure 3. Stimulated pedaling experiment setting: a schematic diagram showing that two channels of stimulation were applied over both quadriceps and were synchronized with position sensors (CDS and LDS)

digital-to-analog converter (DAC725, Burr-Brown) was connected to the DSP to generate voltage patterns. Two 16-bit ADCs (ADS7815, Burr-Brown) were also used to acquire analog feedback signals. The DAC and ADCs channels were expanded to 4, each by two analog multiplexers (CMOS 4051). The DSP communicated with the host computer via a universal asynchronized receiver/transmitter (UART) (SCN2681, Philips) and a voltage level-shifting interface (MAX232, Maxim). To collect discrete feedback signals and to synchronize pattern outputs with other instruments, thirty-two general-purpose I/O pins were also designed.

B.Driving Stage Design

The proposed multichannel arbitrary waveform stimulator chose constant-current sources to be the driving stage. For flexible stimulation, we designed a new constant-current source that could provide linear voltage-to-current output with high voltage-compliance. It was basically a Holland architecture[14] with a Wilson current mirror. The output current can be simply adjusted and is linearly proportional to the input voltage.

C.User Interface

The proposed multi-channel arbitrary waveform stimulator was controlled by a host computer via the RS-232 interface at a 19200 baud rate with a proprietary protocol. For facilitating pattern design as well as stimulator control, a Windows-based software developed by Borland C++ Builder V1.0 was executed on the host computer to provide a user-friendly interface to generate required stimulation patterns. The software provided an intuitive design tool for implementing the waveforms and all the action buttons for each channel. The system configuration and the parameters could be saved or retrieved.

Clinical Application and Experiment Validation

A.Pedal cycling

The stationary pedal cycling device (Giant^{TM} SC-II) and the electrical stimulator were integrated to establish a FES pedal cycling system (Fig.3). A constant speed pedaling experiment with a target pedaling rate of 40 RPM FES program was conducted. Two subjects were involved in the experiment. Bilateral rectus femoris muscles were stimulated reciprocally to perform FES pedal cycling.

The proportion-integration (PI) controller [11] was built inside the stimulator to update the pedaling rate, measured by a position sensor, five times in each cycle, i.e. updated at each 72 angle degree. The target pedaling rate ω_r was set as part of the stimulator parameters before the protocol started, and its equivalent period T_r was calculated as the number of elapsed time interrupts between two checkpoints. The instantaneous pedaling rate ω_i was also represented with its equivalent period T_i by counting elapsed time interrupts. The PI controller computed the change for the next intensity by:

$$T_r = \frac{1}{5}\times\frac{60}{\omega_r}\times\frac{1}{50\cdot 10^{-6}} \quad \text{(interrupts)} \qquad (1)$$

Table 1. System specifications of the proposed versatile direct-synthesized multi-channel arbitrary waveform stimulator.

Number of channels	4
Output mode	Constant-current
Current output	0~110mA
Maximum output voltage	±88V
Time resolution	50us
Duration range	50~1000us
Frequency range	3~100Hz
Number of envelope points	Up to 10000 points
Stimulation time	60s
Data link with host PC	RS-232, 19200 bps
Software platform	Windows 95/98/NT

$$\Delta I = K_p \times \varepsilon_t + \frac{K_I}{5} \times \sum_{k=0}^{4} \varepsilon(t-k) \quad \text{(mA)} \qquad (2)$$

$$\varepsilon_k = T_r - T_I \quad \text{(interrupts)} \qquad (3)$$

Actually the structure didn't strictly follow the original definition of a PI controller. The error term was calculated from time difference instead of rate difference. The calculated output was current difference instead of current. The former modification was adopted in consideration of a computation load reduction. The second modification was adopted so that a converged stimulation level could be maintained when the target rate was reached. The adopted Kp value was –0.0005 and Ki was –0.002.

B.Patient-driven hand grasping FES system with a closed-loop feedback controller

1. The FES patterns for performing massive grasp, lateral pinch and precision grasp were established initially. All these stimulation patterns were established based on our knowledge of anatomy and motion, through a trial and error method. A joystick input device was implemented to drive the proportional control algorithm and to perform FES hand functions.

2. To prevent the grasped objects from slipping, a closed-loop feedback control system with a slip sensor was developed and tested. The slip sensor contains a contact roller and a counter. The counter detects the relative motion between the finger and the grasped object. Thus the feedback of the detected slip signal increases the grasping force through increasing electrical stimulation intensity.

3. To perform grasping with a proper force and to prevent rapid fatigue in the stimulated muscles, a closed-loop feedback control system with force sensors on the palmar surface of the fingers was developed and tested. The force sensor (force sensing resistor) detects changes in the grasping force in order to increase or to decrease the stimulating intensity.

C .Ankle motion FES system with a neural network and fuzzy controller

This application is aimed at establishing a neural network[12] and fuzzy feedback control[13] FES system for use in adjusting the optimum electrical stimulating current to control the motion of an ankle joint and to further improve the drop-foot problem in hemiplegic patients.

The proposed system includes both hardware and software. The hardware system determines the patient's ankle joint angle using a position sensor located in the patient's affected side. This sensor stimulates the tibialis anterior with an electrical stimulator that induces dorsiflexion action and achieves an ideal ankle joint trace motion. The software system estimates the stimulating current using a neural network. The fuzzy controller solves the nonlinear problem by compensating the motion trace errors between the neural network control and the actual system.

Three control methods were used to perform the ankle joint angle control experiment. The three methods were the neural network control experiment, the neural network control plus PID control experiment, and the neural network plus fuzzy control experiment. An ankle joint dorsi-flexion angle was chosen for this test because this is the biggest obstacle faced by hemiplegics during walking. When a patient is walking, that problem can be solved through applying the control method to control the ankle joint angle with electrical stimulation. In the angle feedback control experiment, we tested three hemiplegic patients.

Results

Electrical stimulator

The specifications of the proposed versatile direct-synthesized multichannel arbitrary waveform stimulator are summarized in Table I. Four independent stimulation channels can be programmed to generate arbitrary FES with a sampling interval of 50us. The driving stages were implemented with inexpensive components. The stability to human tissue variation was simulated and tested by load resistors ranging from 500 to 2000ohms with 100mA current output. The current output variation is less than 0.5%, which is much smaller than that of the other referred transistor-based constant-current sources. The driving stage also showed its linear voltage-to-current capability. Figure 4 shows the linearity of output current with different loads.

The envelopes can be designed using pre-defined profiles, such as exponential or triangular patterns, or by dragging the mouse to draw arbitrary profiles. The information from the element and the envelopes can be saved as files and loaded later. Users can also design complex patterns with mathematical software, such as MATLAB, and then save the results into files with a proprietary format. By transmitting the parameters of the element and the envelopes to the buffers, two buttons, START and STOP, can be utilized to control the stimulator's operation. The users can start the four channels simultaneously or individually.

Table 2 Comparison of three different control strategies in FES ankle motion

Time (sec)	0-13 sec		0-13 sec		0-13 sec	
Control strategy	Neural Network control		Neural Network + PID control		Neural Network + Fuzzy control	
	RMSE	ME	RMSE	ME	RMSE	ME
Subject A	8.11	2.32	5.76	1.98	4.07	1.62
Subject B	7.81	2.34	4.83	1.73	3.75	1.41
Subject C	5.59	1.93	5.05	1.80	4.19	1.55

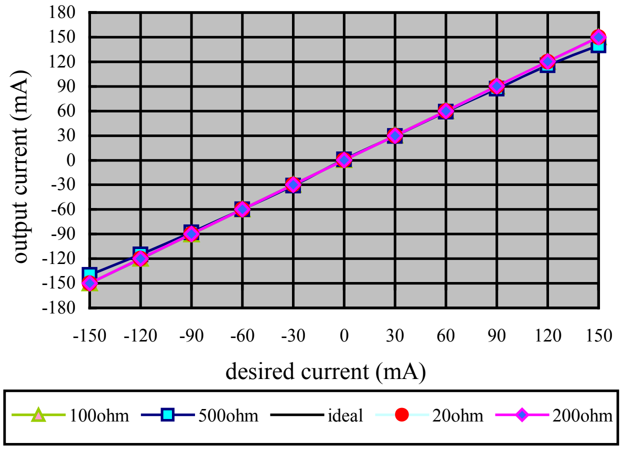

Figure 4. The linearity of output current with different loads

FES pedal cycling system

The results of the constant speed pedaling experiment showed that the desired speed of pedaling can be traced smoothly by using this FES system through a crank-angle sensing feedback controller.

Patient-driven FES hand system

Success rates for taking objects by massive grasp, lateral pinch, and precision grasp through the developed patient-driven FES system were 90 %, 70 %, and 90 %, respectively.

Slip sensor feedback control

As soon as the slip sensor was triggered, the contact roller activated the feedback mechanism. The result showed that a drop of the grasped object was successfully stopped by the triggered increase of FES grasp movement.

Force sensor feedback control

Four force sensing resistors were used to detect the feedback grasp force. The result showed that the reacting force can reach the trajectory of the preset grasping force through this feedback control system. Muscle fatigue was also postponed effectively.

Ankle motion FES system with feedback control

With the neural network plus fuzzy control, the root mean square error and mean error for the joint angles were minimal, as shown in Table 2, because the neural output current was being supplemented. Because the fuzzy control system outputs the feedback and amends the system error frequently, a suitable current volume change was output to make up for the lack of neural output current. This demonstrates that the neural network plus fuzzy control can solve some nonlinear and time-varied problems and can also enhance the ankle joint control FES system.

Discussions and Conclusions

A versatile direct-synthesized multi-channel arbitrary waveform stimulator was successfully developed and evaluated. The stimulator is suitable for various kinds of FES applications via surface stimulation, both for experimental and clinical studies. The system shows great flexibility because a powerful DSP was used to synthesize waveforms, using the proposed element-envelope method. The DSP generates waveforms dynamically based on the parameters sent from the host program or feedback controllers.

A constant-current source for electrical stimulation was also designed in the proposed stimulator. It provided linear voltage-to-current stimulation with high-voltage compliance[15,16]. Excellent linearity is essential for complex electrical stimulation. The constant-current source has many other additional features, including high bandwidth, reliability, and simple architecture. Furthermore, it is easy to implement because no special components are required.

To make the proposed stimulator more flexible and user-friendly, we designed a communication protocol and implemented a special command set. With the command set, a host computer can directly control the stimulator via a standard RS-232 interface. We also designed a user-friendly interface installed on the host PC, which allows users to enter stimulating parameters or drag the mouse to implement the required patterns. The communication protocol also demonstrated its compatibility with other software. For example, we successfully used the LABVIEW software to control our stimulator. Compatibility is very important, because it lets users design their own user interfaces in different software environments. A closed-loop FES system can also be implemented easily. The controller can be programmed in the DSP or in the host computer via feedback commands. After being manipulated by the integrated feedback controller, the parameters in the buffers are adjusted, then the stimulation patterns are modified. Because the pattern generator and the feedback controller are both programmed in the DSP, the proposed stimulator can be applied to various FES applications by modifying the firmware.

In this study, 3 clinical applications, including a pedal cycling FES system, a patient-driven hand grasping FES system with closed-loop feedback controller, and an ankle motion FES system with a neural network and fuzzy controller, were tested. The results showed that the parameters of the electrical stimulator can be adjusted arbitrarily to reach all of the specific functions.

The desired speed of pedaling can be traced smoothly by using this FES system through a crank-angle sensing feedback controller. Hand functions, including massive grasp, lateral pinch, and precision grasp, was well restored through the developed patient-driven FES system. The use of closed-loop feedback controllers with a slip sensor and a force sensor prevented the grasped object from slipping and successfully postponed muscle fatigue. The neural network plus fuzzy control can solve some nonlinear and time-varied problems to enhance the FES ankle joint control system.

In regards to the developed hand grasping FES system, future work is planned to expand elbow and shoulder motion through a hybrid FES system.

Some limitations were found in the ankle motion FES-assisted locomotion system. The limitations included the hardware and software devices and patient walking pace variations. Therefore, in future experiments, patient walking pace variations should be taken into full consideration. To get an ideal angle, the output current should be adjusted with the walking style cycle.

Acknowledgement

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