A Versatile Multichannel Electrical Stimulator for Functional Electrical Stimulation Applications

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Abstract

Functional electrical stimulation has been applied to restore the muscle activity of paralyzed patients who suffer from spinal cord injuries and related neural impairments for several decades. In this paper, a direct-synthesized arbitrary waveform stimulator for multichannel FES applications is described. A novel element-envelope method is proposed. A digital signal processor is chosen to synthesize required stimulating patterns with high time-resolution, and it preserves the ability to adjust stimulation parameters dynamically. Also, the system can provide bi-phasic, voltage-controlled constant-current patterns while remaining high-voltage compliance and wide bandwidth. The proposed stimulator can be considered as a full-featured stimulator for various FES applications with its flexibility in pattern generation and feedback processing capabilities.

Introduction

FES is a methodology to activate multiple muscles electrically in a coordinated sequence. For the past two decades, FES has been applied to restore or maintain the muscle activity of paralyzed patients who suffer from spinal cord injuries or related neural impairments. Numerous electrical stimulators have been developed for various kinds of applications to elicit electrical stimulation patterns [1-2]. Electrical stimulators could be functionally divided into four blocks（command interpreter, pattern generator, driving stage , and feedback controller）.

The command interpreter receives instructions from patients or physicians and translates it into a series of pattern parameters for different muscles. The pattern generator synthesizes pulse-like waveforms by the pattern parameters, such as pulse-shape, activating duration, stimulating frequency, amplitude and inter-pulse duration. Conventionally, microcontrollers are utilized to synthesize required waveforms by triggering pulse-signal generators or sending commands to timing peripherals (Intel 8254). However, the pulse amplitude is fixed and the shape of stimulating patterns is limited to square waves. Augmented circuitry is necessary to adjust pulse amplitude and to generate complicated waveforms [3].

The driving stage is served as a constant-current or constant-voltage source. Due to inevitable variations of tissue impedance of patients, constant-current sources are more prevalent than constant-voltage sources [4]. Constant-current stimulation can provide more predictable responses. However, when the constant-current source is applied to the tissue with large impedance (>2Kohms) and large stimulation current (>50mA), a high voltage (100~300V) might be induced from the tissue. The high voltage will cause the source dysfunction. Therefore, a constant-current source must provide enough operating range of voltage, namely, to have high-voltage compliance. Bi-phasic capability is also necessary for the constant-current source.

As discussed above, although several electrical stimulators have been developed, their functions are confined in specific applications. Those stimulators lack flexible pattern-generation capability. Moreover, their driving stage cannot provide high-voltage compliance and linear voltage-to-current conversion in the same time. In our designed stimulator, there are the following features: multichannel stimulation, flexible and programmable patterns, high-voltage compliance and constant-current driving stage, electrical isolation, feedback capabilities, and friendly user-interface. In this paper, a versatile direct-synthesized multichannel arbitrary waveform stimulator is proposed for FES applications.

Methods

The block diagram of our designed electrical stimulator is illustrated in figure 1. A DSP (TMS320C32, Texas Instruments) was used to generate patterns with its high-computation capabilities. There are additional peripherals embedded inside the same DSP chip, including two timers, one serial port and two direct memory access (DMA) coprocessors. The DSP has 4096 bytes of built-in random-access memory (RAM). 1024 Kilobytes of external RAM and 128 Kilobytes of flash read-only memory (ROM) are included for program and data storage. A 16-bit dual-channel digital-to-analog converter (DAC725, Burr-Brown) is connected to the DSP to generate voltage patterns. Two 16-bit ADCs (ADS7815, Burr-Brown) are also used to acquire analog feedback signals. The DAC and ADCs channels are expanded to 4 channels respectively by two multiplexers (CMOS 4051). The DSP communicates with the host computer via a universal asynchronized receiver/transmitter (UART) 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.

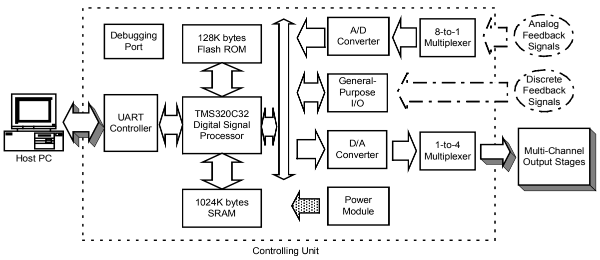

Figure 1.

A novel "element-envelope" method is proposed to generate stimulation patterns more efficiently in storage. It takes the advantage of the pseudo-period characteristic of stimulation patterns. A series of electrical pulses construct a stimulation pattern, and the parameters of a pulse determine the stimulation modes, such as pulse-amplitude modulation (PAM), pulse-width modulation (PWM), and pulse-frequency modulation (PFM). The terms "element" and "envelope" stand for a single pulse-like signal and samples of the profile of the patterns, respectively. As illustrated in figure 2, an element and some envelope points are combined to build required patterns.

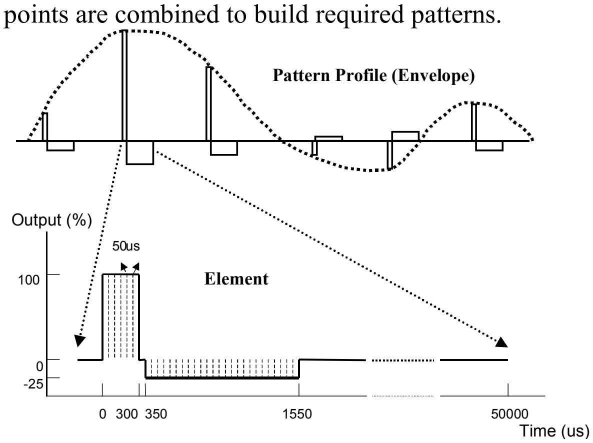

Figure 2.

One element is split into time slices, and the resolution of a time slice is 50 us, which is adequate for neuromuscular stimulation applications. Number of positive-value slices determines the duration of stimulating pulse, and number of slices in one element determines the stimulating frequency, thus the PWM and PFM can be easily generated. In our system, the profiles of stimulation patterns are sampled at 100Hz, i.e., the amplitude of elements updates every 10ms. This method only needs to record the information of one element and the samples of envelope instead of sampling all the stimulation patterns, which may wastes a lot of memory storage.

The goal of our electrical stimulator is to increase the flexibility so that various FES applications. Therefore, we modularized the firmware into three layers: an application layer, a data-manipulating layer, and a device driver layer. The device driver layer handles all hardware interfaces, including serial communication, DACs, ADCs, and discrete I/O pins. The data-manipulating layer comprises various buffers for the element and envelope samples, controlling parameters, synthesized patters, feedback signals, and communications messages. The application layer, including signal processing and feedback control tasks, determined the actual function of the system. The data-manipulating layer provides proprietary application interface (API) to the application layer. After designing required patterns in the host PC, the element, envelope samples, and a series of parameters are sent to the buffers in the data-manipulating layer. Then the user starts the system by sending the START commands. When the system timer interrupts every 10ms, an envelope sample and required parameters are fetched. The element information is also fetched from the buffers to construct stimulation patterns. The system timer coordinates all the tasks in the application layer. Another timer, interrupts every 50us, controls the time resolution of stimulation patterns and feedback signals. An embedded feedback controller generates patterns parameters and then modifies the parameter buffer.

A window-based software programmed by Borland C++ Builder V1.0 is executed on a host computer to provide friendly but friendly interface to design required stimulation patterns. The element and the envelope are designed individually. The host computer communicates with the electrical stimulator via the RS-232 interface in 19200bps with a proprietary protocol for exchanging both the pattern and feedback information.

Results

The specifications of our proposed electrical stimulator are summarized in table I. We chose the TL062 OP-amps, the 2N6520 (PNP) and the 2N6517 (NPN) high-voltage transistors to implement the output stage in the prototype. The output variation is less than

0.5%, which is much smaller than that of the other referred transistor-based constant-current sources.

Our stimulator had been evaluated in many groups for implanted or external FES applications, including shoulder joint control, pedaling wheelchair system, and gastric function restoration. A typical example of designing parameters of an element, such as pulse duration, period, and bi-phasic compensation, is illustrated in figure 3. The envelopes of multiple channels are determined separately in four windows. The envelopes can be designed by pre-defined profiles, such as exponential or triangular patterns, or by dragging mouse to draw arbitrary profiles. The information of both the element and envelope can be saved in to files and then be loaded again. Users can also design complex patterns by mathematical software, such as MATLAB, and then save into files by a proprietary format. After the element and envelope are transmitted to the buffers, two buttons, START and STOP, are utilized to control the operation of stimulation. The users can start the four channels simultaneously or individually.

Table 1.

Number of channels	4
Output mode	Constant current
Current output	0~110 mA
Time resolution	50 us
Duration range	50~1000 us
Frequency range	3~100 Hz
Envelope points	Up to 10000 points
Stimulation time	60 sec.
Data link with host PC	RS-232, 19200 bps
Software platform	Windows 95/98/Me/NT/2000

Discussions and Conclusions

A versatile multichannel direct-synthesized electrical stimulator was successfully developed and evaluated. By the element-envelope method, the patterns can be generated efficiently and easily synchronized with feedback control signals. A novel constant-current source for electrical stimulation is proposed to provide bi-phasic and linear voltage-to-current output with high-voltage compliance, which is essential for complex electrical stimulation. Additional features, including high bandwidth, reliability, and simple architecture, can also be achieved. We also designed a friendly user-interface installed on a host PC to communicate with the stimulator via RS-232 protocol. Users can simply enter stimulating parameters or dragging the mouse to implement required patterns. Analog or digital feedback signals, such as physiological information and foot switches, can be collected and processed by the DSP as well. Because the pattern generator and the feedback controller of the stimulator are implemented by the DSP, the system can be modified for various FES applications by replacing a new firmware. Our designed stimulator could be considered as a full-featured stimulator for various FES applications with its high flexibility in pattern generation and feedback processing capabilities.

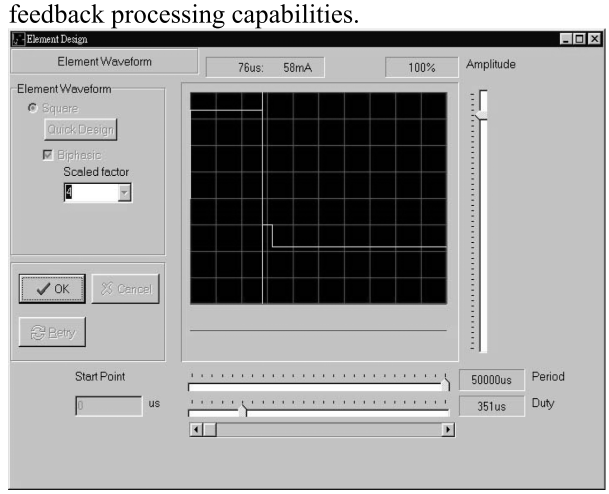

Figure 3.

References

[1] James R. Buckett, P. Hunter Peckham, Geoffrey B. Thrope, Steven D. Braswell, and Michael W. Keith, □ flexible, portable system for neuromuscular stimulation in the paralyzed upper extremity," *IEEE Trans. Biomedical Engineering*, vol. 35, no. 11, pp. 897-904, November 1988.

[2] Christophor J. Poletto and Clayton L. Van Doren, □ high voltage, constant current stimulator for electrocutaneous stimulation through small electrodes," *IEEE Trans. Biomedical Engineering*, vol. 46, no. 8, pp. 929-936, August 1999.

[3] Milan Ilic, Dragan Vasiljevic, and Dejan B. Popovic, "A programmable electronic stimulator for FES systems," *IEEE Trans. Rehabilitation Engineering*, vol. 2, no. 4, pp. 234-238, December, 1994.

[4] Yoshitake Yamamoto, Hiromi Isshiki, and Takao Nakamura, "Instantaneous measurement of electrical parameters in a palm during electrodermal activity," *IEEE Trans. Instrumentation and Measurement*, vol. 45, no. 2, pp. 483-487, April, 1996.

Acknowledgment

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