A Versatile Multichannel Direct-Synthesized Electrical Stimulator for FES Applications

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Abstract

Functional electrical stimulation has been applied to restore or maintain the muscle activity of paralyzed patients who suffer spinal cord injuries and related neural impairments. In this paper, a direct-synthesized arbitrary waveform stimulator for multichannel stimulation is developed in this paper. A novel "element-envelope" method is proposed and implemented by a digital signal processor to synthesize required stimulating patterns with high resolution. This method not only generates arbitrary waveforms but also reduces the memory requirements. It preserves the ability to adjust stimulation parameters dynamically. We also design an output stage that can provide bi-phasic, voltage-controlled constant-current patterns while remain high compliance and wide bandwidth. This system can be considered as a full-featured stimulator for various FES applications with its flexibility in pattern generation and feedback processing capabilities.

1. Introduction

Electrical stimulation is employed to cause excitation of nerve cells or muscle fibers. Since the primitive experiment of frog legs in 1791 by Galvani, it has been applied in various clinical treatments and physiological researches, such as pain relieving, muscle strengthening, cardiac pacing, iontophoretic drug delivery, and functional electrical stimulation (FES) [1-2].

An electrical stimulator is the essential apparatus to elicit electrical stimulation patterns. Over the previous two decades, numerous electrical stimulators have been developed for various kinds of applications [3-8]. When designing electrical stimulators, several specific features are considered. 1) Multichannel stimulation: Compared with single-channel stimulation, coordinated multichannel output provides more precise control, and thus complicated functions could be achieved. 2) Bi-phasic stimulation: Electrical stimulation could induce electronic charge accumulation, which is harmful to tissues. Bi-phasic stimulation not only neutralizes the charge but also produces more efficient stimulation. 3) Constant-current output: Owing to the inevitable variation of tissue impedance, constant-current stimulation provides more stable and predictable responses. 4) Flexible and programmable patterns: Different waveforms would cause different results, therefore, if users could design their own patterns without limitations from instruments, more complex patterns could be produced for advanced researches. 5) Electrical isolation: In addition to safety considerations, isolated stimulation generates smaller artifact. 6) High compliance: The capability of enduring large current stimulation even in high impedance tissues is called the compliance. A high-compliance output stage could expand the dynamic range of electrical stimulation. 7) Feedback capabilities: Closed-loop control of electrical stimulation has been approved to contribute better performance in FES. 8) Friendly user-interface: When more flexible functions are provided, the interface that is easy to use is important.

The structure of electrical stimulators could be functionally divided into two parts. The first section is the pattern-generating circuit. A typical stimulation pattern is composed of a series of voltage or current pulse-like signals. Microcontrollers were widely used to generate patterns according to stimulation parameters, such as duration, frequency, amplitude and inter-pulse duration of the pulses. Conventionally, microcontrollers produced desired patterns by generating triggering signals to pulse-signal generators, or sending commands to timing

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peripherals (ex. Intel 8254). The amplitude of pulses, however, was TTL-leveled and therefore could be just altered by resisters or controlled by another augmented circuitry [7]. This kind of architecture complicated the hardware design and limited the potential applications of electrical stimulation due to its low flexibility in changing output amplitude. Flexible patterns can be achieved by selecting digital-to-analog converters (DACs) to synthesize desired patterns, however; the memory requirements for pattern storage could be extremely high. This makes the stimulator unfeasible. Stieglitz et al. [9] proposed the multi-resolution method to reduce memory usage. This method made use of fine samples when patterns alternating while using coarse samples elsewhere, but the method did not take the advantage of the pseudo-periodic characteristics of stimulation patterns and the memory requirements still remains high. Moreover, the method should be executed before sending the required patterns, that is, stimulation patterns can not be changed in real-time processing. This restricts the usage in closed-loop controlled applications, which required the stimulating parameters to be modified on-line.

The second section is the output-stage circuit. Constant-current or constant-voltage sources are served as output stages of electrical stimulators. Due to inevitable variations of tissue impedance and electrodes, constant-current sources are more prevalent than constant-voltage sources [10-11]. However, when the constant-current source is applied to the tissue with large impedance (> 20Kohms), a high voltage (100~300V) might be induced from the tissue load. The situation will cause the source to be dysfunction. Therefore, a constant-current source must provide enough operating range, namely, to have high voltage compliance. Bi-phasic output is also necessary for the constant-current source. It is important to balance the accumulated charges that might cause damage to stimulated subjects. Recently, complex waveforms are more concerned for selective stimulation of nerve fibers [12]. A constant-current source should also be flexible to provide complex waveforms for different applications of electrical stimulation. Conventional constant-current sources are realized by the operational amplifiers (OP-amps). The Holland architecture and its enhanced version are most adopted because of their linear and bi-phasic voltage-to-current conversion [13]. However, it needs high-precision and large resistors. Large resistors may cause self-oscillation from its feedback path. High-voltage and high-power OP-amps are also necessary in the Holland architecture for high voltage compliance [8]. High voltage transistors are the alternative selection to implement constant-current sources [14-15]. Nevertheless, the transistors suffer from their inherent variations of device parameters that make the output unreliable and unstable.

Because of the restrictions of the existing electrical stimulators, a direct-synthesized multichannel arbitrary waveform stimulator is developed. A novel "element-envelope" method is proposed to synthesize the stimulating patterns. The method can reduce the memory requirements as well as preserve the ability to control stimulation parameters on-line. Because the "element-envelope" method required huge computation load especially in multichannel applications, we chose a digital signal processor (DSP) to generate the patterns. In addition, a high-compliance constant-current source is designed. The architecture of the constant-current source is simple, flexible, and reliable. No high-voltage OP-amps and precision resistors are required. We also integrate feedback-control capabilities, such as PID and neural fuzzy, in the stimulator. These feedback algorithms are also implemented in the DSP. In our system, the feedback algorithms and the "element-envelope" method were synchronized by a real-time operating system. Analog or digital feedback signals could be acquired by the DSP and thus simplifies the system design. We also developed a windows-environment user interface to facilitate the usage of the proposed electrical stimulator for FES applications.

2. System Design

2.1 System description

The block diagram of the electrical stimulator is illustrated in figure 1. A DSP (TMS320C32, Texas Instruments) was selected to generate patterns and implement feedback-control functions. In addition to the high performance in computation of the DSP (50 MFLOPS in our system), there are many peripherals embedded inside the same DSP chip, including 2 timers, 1 serial port and 2 direct memory access (DMA) coprocessors. The DSP has also built-in 4096 bytes of random-access memory (RAM). 1024 Kilobytes of external RAM and 128 Kilobytes of flash read-only memory (ROM) were designed to execute programs and store data. A 16-bit dual-channel 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 connected to the DSP to sample analog feedback signals. The DAC and ADCs could be expanded to 8 channels respectively by two 8-to-1 multiplexers (CMOS 4051). The DSP communicated with the host computer via a universal asynchronized receiver/transmitter (UART) by 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.

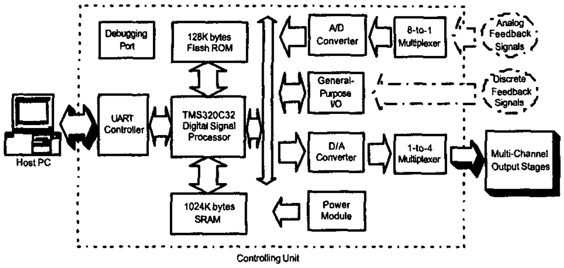

Figure 1. System block diagram.

2.2 Output stage

An elementary uni-phasic constant-current stage is illustrated in figure 2a and 2b. It is composed of an OP-amp, a transistor, and a resistor. It is impossible to realize a bi-phasic current source by the uni-phasic stages because the output of the stages sinks current from positive power or supplies current to negative power. Therefore, we use two current mirrors to change current directions. The schematic of the proposed constant-current source is illustrated in figure 3. This architecture is vertically symmetric. The upper circuitry supplies current to load (RL1), while the lower circuitry sinks current from load. When the input simulation voltage (V_s) is positive, U1 and Q3 sink current (i_1) from Q1. A Wilson current mirror (Q1, Q2, and Q4) then generates equivalent current to load. The required current is simply determined by R1:

$$i_1 = V_s / R1 \qquad (1)$$

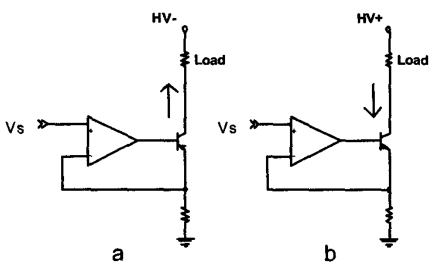

Figure 2. The elementary voltage-to-current uni-phasic stage.
(a) the "supply" stage
(b) the "sink" stage

The current mirror is very sensitive to unmatched V_{BE} of the transistors. We modified the Wilson current mirror by adding two resistors (R2 and R3). The modification will make the output insensitive to V_{BE} and temperature. Moreover, stability to load variation is achieved due to the larger output resistance of the Wilson current mirror. If the transistors have the same current gain β, then the output current of the current mirror i_{out} is:

$$i_{out} = \frac{1}{1 + 2 / (\beta^2 + 2\beta)} \qquad (2)$$

In order to endure high voltage, all transistors are chosen with high breakdown voltage. However, we don't need to use high-voltage OP-amps because the collect-emitter junction of Q3 endures most of the induced high voltage.

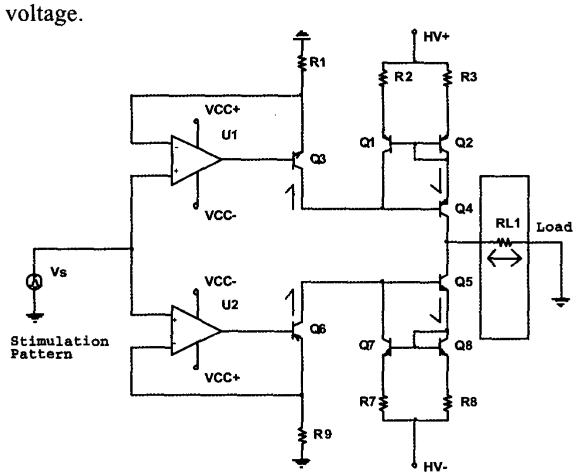

Figure 3. Schematic of the output stage.

2.3 Pattern Synthesizing

The "element-envelope" method is proposed to synthesize stimulation patterns more efficiently in storage while maintain the flexibility of generating stimulation patterns. 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 and samples of the profile of the patterns respectively. As illustrated in figure 4, an element and some envelope points are combined to build required patterns. One element is split into time slices, and the resolution of a time slice is 50uS, 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. The amplitude of each time slice in one element is stored in relative value (in percentage). After multiplied by an envelope sample, absolute amplitude of the element is determined. 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.

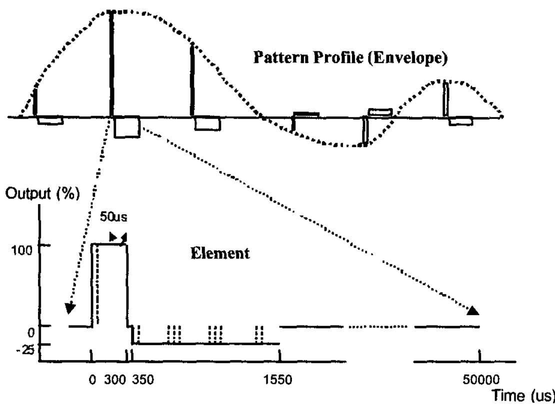

Figure 4. The element-envelope method.

The operation of synthesizing patterns is described as follows. The goal of the proposed system was to increase the flexibility so that various applications could be realized without designing specific stimulators. We modularized the firmware into three layers: application layer, data-manipulating layer, and device driver layer, as illustrated in figure 5. The device driver layer handled all hardware interfaces including serial communication, DACs, ADCs, and discrete I/O pins. The data-manipulating layer comprised 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 function of the system. After designing required patterns in the host PC, the element, envelope samples, and a series of parameters were sent to the buffers in the data-manipulating layer. Then the user started the system by sending predefined commands. When the system timer interrupted every 10ms, an envelope sample, controlling parameters were fetched, and the element were fetched from the buffers to construct stimulation patterns and then outputted to the waveform buffers. The system timer also coordinated the tasks in the application layer. Another timer, interrupted every 50us, controlled the timing of outputting patterns and acquiring feedback signals. Some feedback-control algorithms, such as fuzzy or PID control, generated patterns parameters and then modified the parameter buffer. The signal-processing task dealt with the feedback signals to extract signal features used in the algorithms. The feedback algorithms could modify the stimulation pattern in a rate of 100Hz due to the system timer.

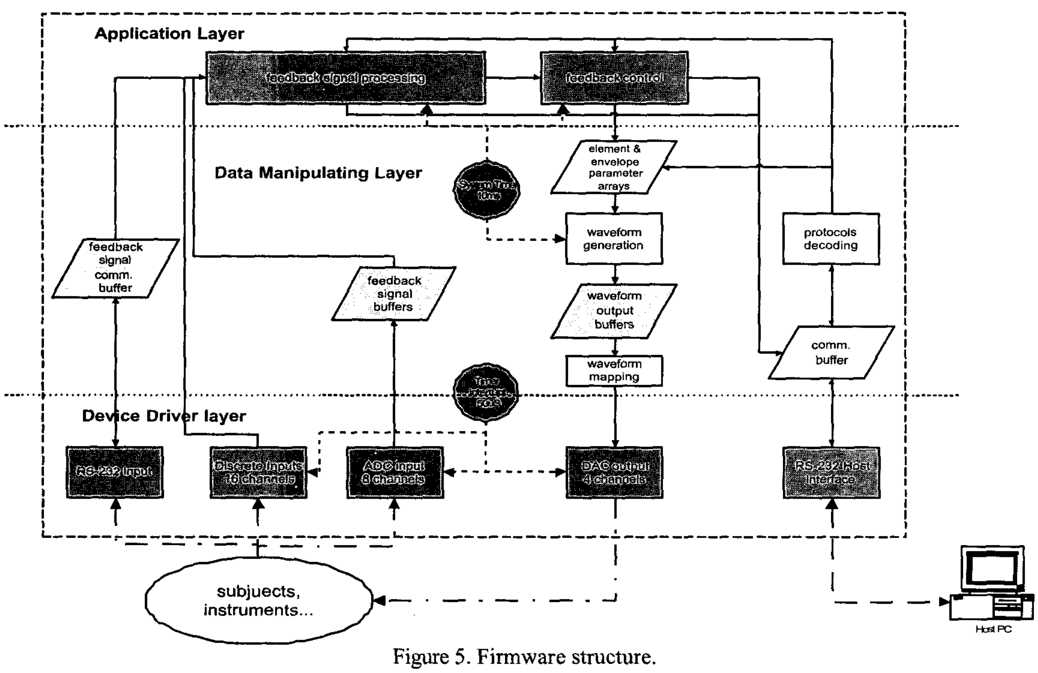

Figure 5. Firmware structure.

2.4 Host computer

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

3. Results

The specifications of the proposed electrical stimulator are summarized in table 1. All the specifications are determined by software control. Therefore, although the system is designed for FES applications, the stimulator can be easily altered for other researches, such as neural stimulation.

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

Table 1. System specifications.

We chose the TL062 OP-amps, the 2N6520 (PNP) and the 2N6517 (NPN) high-voltage transistors to implement the output stage in the prototype. Figure 6 shows an original quasitrapezoidal stimulation voltage and its associated current stimulus under 20mA maximum current output and 1kohm load. The measured rise time and fall time of the constant-current source are around 300ns, and they are much faster than other high-compliance current source. The output variation is less than 0.5%, which is also much smaller than that of the other referred transistor-based constant-current sources.

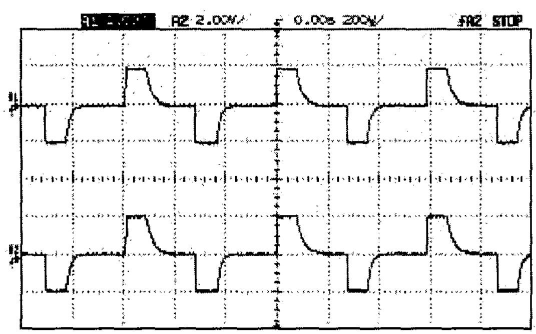

Figure 6. Measured current output from complex stimulus.
upper channel: original signal
lower channel: current output

This stimulator has 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 an element, including the parameters like pulse duration, period, and bi-phasic compensation, is illustrated in figure 7, and users could see the output waveform directly. The envelopes of different channels are determined separately in four windows (channel1~channel 4) as shown in figure 8.They could 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 could be saved in to files and then be loaded again. Users could generate complex patterns by other software, like MATLAB, and saved into files by using the same format. After The element and envelope are downloaded into the controlling unit, two buttons, START and STOP, are utilized to control the operation of stimulation. The four channels could be started simultaneously or individually.

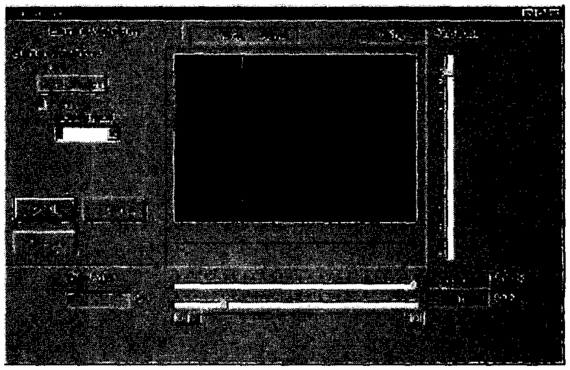

Figure 7. Element design interface..

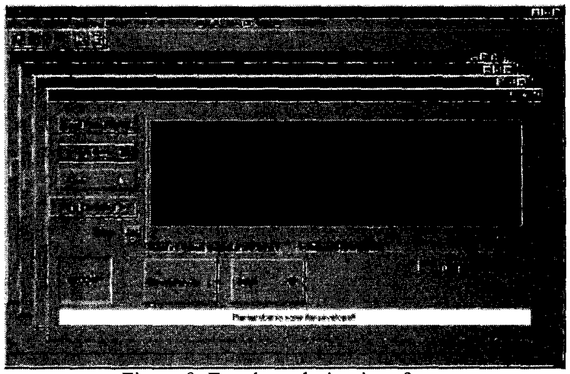

Figure 8. Envelope design interface..

4. Discussions and Conclusions

A versatile multichannel direct-synthesized electrical stimulator was successfully developed and evaluated. The stimulation patterns are digitally synthesized; therefore, they are much more easily synchronized with feedback control signals. A bi-phasic constant-current source for electrical stimulation is developed. It can 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, and no critical concerns are necessary when choosing components. The source not only facilitates the implementation of electrical stimulators, but also makes arbitrary current stimulus feasible. With the element-envelope method and output-stage circuit, all the parameters could be determined dynamically by the integrated feedback controller and it thus achieves extreme flexibility for various FES related applications. We also designed a friendly user interface installed on a host PC to communicate with the stimulator via RS-232 protocol. Users could simply input stimulating parameters or dragging the mouse to implement required patterns. Digital or analog feedback signals, such as EMG and foot switches, could be collected by the DSP as well. After manipulated by specific feedback controlled algorithms integrated in the DSP, stimulating parameters were changed and then the output patterns were modified. Because all the functions of the stimulator were implemented by the DSP, the system could be easily modified by replacing a new firmware and thus make this system more flexible and suitable for various FES applications.

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