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Short communication

A charge-balanced pulse generator for nerve stimulation applications

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Abstract

Nerve stimulation typically employs charge-balanced current injection with a delay between the cathodal and anodal phases. Typically these waveforms are produced using a microprocessor. However, once appropriate stimulus parameters are chosen, they tend to remain fixed within an application, making computational power unnecessary. In such cases, it would be advantageous to replace the microprocessor with integrated circuitry and hardware controls for maintaining fixed pulse parameters. We describe here an architecture that generates controllable charge-balanced pulses but requires no computer processing components. The circuitry has been engineered such that minimum size and power consumption can be achieved when fabricated into an IC chip, making it ideal for many long term, portable nerve stimulation devices and applications.

Keywords: Nerve stimulator; Nerve stimulation; Charge-balanced pulse generator; Nervous system

1. Introduction

To stimulate peripheral (and central) nerve fibers, one typically applies a charge-balanced, biphasic stimulus through implanted electrodes. The first (cathodal) phase of the stimulus depolarizes the cell membrane, thus initiating an action potential. The second (anodal) pulse brings the net charge balance in the electrode to zero. Charge balance is necessary to avoid any adverse long-term effects such as pH shift, ionic charges near the implanted electrodes, and erosion of the electrode material. However, there must be a separation between the cathodal and anodal pulses. If the anodal pulse occurs too quickly after the cathodal pulse, the nerve membrane is re-polarized before threshold is reached, thereby preventing the firing of an action potential. This necessary time in between the biphasic stimulus pulses is referred to as the interphase interval. The magnitude of charge is determined by the product of the amplitude and width of the pulse. Creating a charge-balanced stimulus requires that this product for the anodal pulse be equal to that for the cathodal pulse.

Most nerve stimulation applications are specific in their design requirements and stimulating waveform parameters. As such, many stimulators include a programmable microprocessor for generation of the stimulus waveform (Arabi and Sawan, 1999; Ilic et al., 2004). Examples of applications using microprocessors in the stimulator design include functional activation of denervated muscles (Hofer et al., 2002), control of gastrointestinal motility (Jalilian et al., 2007) and the bladder (Balken et al., 2004), and stimulation of the vagus (Jandial et al., 2004) and common peroneal (Hart et al., 2006) nerves. However, not all stimulating applications require microprocessors to continuously control pulse parameters. In applications where stimulating pulse parameters are fixed (Dhillon and Horch, 2005), or determined for a particular location, such computer processing power is not necessary to re-compute pulse width and amplitude for each stimulus. Instead, a pulse generator constructed entirely from low-powered hardware components, which could consistently generate a user-selected charge-balanced pulse waveform, would eliminate the need for processing components to control pulse parameters. This would increase device portability and minimize power requirements, thus making it valuable in many functional electrical stimulation applications. The creation of such a device was the subject of this work.

2. Methods

Edge-triggered monostable multivibrators (SN74121, Texas Instruments) were used to generate digital pulses. An advantage of edge-triggered technology is that the duration of the trigger

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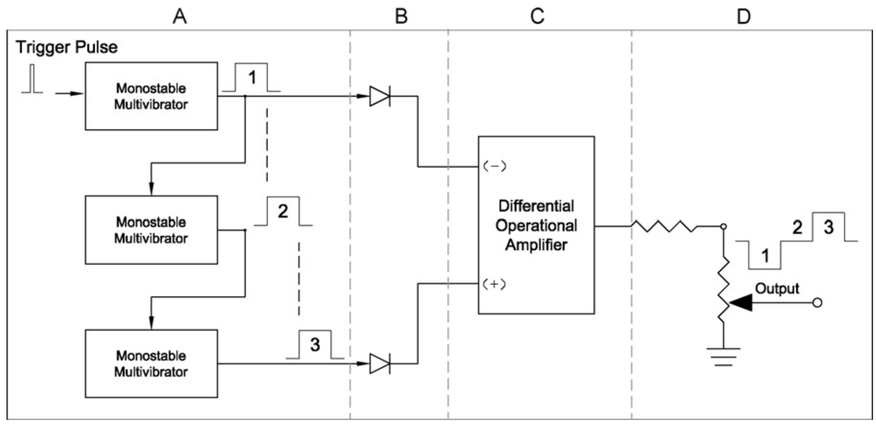

Fig. 1. After being initiated by a trigger pulse, three edge-triggered timing chips placed in series generate timed, digital output pulses (A) to provide controllable pulse widths and an interphase delay. Diodes placed at the output of the first and third multivibrator timing chips (B) remove unwanted low-level voltages, while still conducting the high-level cathodal and anodal pulses. The resulting cathodal and anodal pulses are amplified to saturation, with the cathodal pulse inverted (C). Final output pulse amplitudes are controlled by a voltage divider (D).

stimulus (pulse) is unimportant, so long as it remains shorter than the period between successive trigger stimuli.

Since there are three intervals/durations in the stimulus, three monostable multivibrators were used in series (Fig. 1A) to produce timed, digital output pulses. The input trigger pulse produces an output from the first multivibrator, which serves as the source for the cathodal phase of the stimulus and as the trigger for the second multivibrator. The latter provides the interphase interval and a trigger for the third multivibrator, which provides the anodal phase of the stimulus. The cathodal pulse is fired from the rising edge of the trigger pulse. The interphase interval and anodal pulse are both fired from the falling edges of their input pulses. By using edge-triggered timing chips, the outputs are independent of further transitions of the inputs and are a function only of the timing components used. The timing components, consisting of a resistor and capacitor combination, define the duration (width) for any output pulse. By selecting a constant capacitance value, alterable resistance values achieve the required various output pulse durations. Pulse widths for the cathodal and anodal stimulus phase were varied stepwise and identically by utilizing a two-level ganged rotary switch. Interphase interval duration was controlled using a rotary switch with incremental resistance values.

Specifications for the multivibrators indicated that low-level output voltages could be as high as 0.4 V, instead of the nominal 0 V. This would be problematic for amplification of the signal in later stages of the circuitry, as any non-zero signal, no matter how small, would induce a residual current flow. Therefore, low-level voltages emitted from the multivibrators needed to be blocked, without blocking the intended output pulses. Placing standard forward-biased silicon diodes at the output of the first and third multivibrator timing chips (Fig. 1B) blocked residual voltages when the multivibrators were in their low state, while still conducting the high-level voltages.

The output pulses from multivibrators 1 and 3 were amplified to saturation by a differential amplifier (NTE858M. NTE Electronics) (Fig. 1C), resulting in inversion of the cathodal pulse. One might assume that a simple comparator could more easily be utilized in place of the differential amplifier. However, when the two inputs are at a nominal 0 V, the output of the comparator is unstable and will tend to rail at one extreme or the other. For this reason, a differential amplifier was used and the gain was set high enough to saturate the output during high-level pulses, but low enough to produce 0 V output when the two inputs were zero. Amplifying the pulses to saturation ensures constant output and equal final output pulse amplitudes. The resulting output was fed through a voltage divider (Fig. 1D), ensuring that at maximum and minimum potentiometer position, amplitudes of 10 and 0 V were achieved, respectively. A voltage follower connected to the wiper of the potentiometer (not shown) was used to buffer the output. The schematic for the charge-balanced pulse generator is shown in Fig. 2.

Using diodes to remove low-voltage output creates asymmetrical gain between the cathodal and anodal pulses. This occurs because the basic op amp equations require that the point between D_2 and R_G2 looks like ground for any signal coming from the output, so the R_G1/R_G2 divider can work properly (Fig. 2). Insertion of diode D_2 prevents the intended voltage division between R_G1 and R_G2 from occurring when the diode is reverse biased, limiting the amplifier gain to 1.

Since the desire was to drive the op amp to saturation, and linear gain was not required, the problem was addressed by adding a resistor R_X in between D_2 and R_G2 so that feedback signals from the op amp output to the inverting input always had a path to ground. R_X was selected to be small enough to allow saturation of both cathodal and anodal pulses, but not so small as to draw excess current through diode 2 (D_2). Trial and error showed that 10.0 kΩ was the largest resistor value that resulted in symmetrical output between the anodal and cathodal pulses.

Standard 120 V ac line power was used to power the stimulator. The circuitry components required ±15 V dc for the NT858M dual op amp and +5 V dc for the SN74121 monostable multivibrator timing chips. A dc power block was used to obtain the ±15 V, and a 7805 voltage regulator (KA7805, Fairchild Semiconductor) was used to derive the +5 V. A 0.2 A fuse was used to protect circuit components. Capacitors were placed in between the +5 V and ground leads of the 7805 voltage regulator to help stabilize the +5 V rail during active signaling.

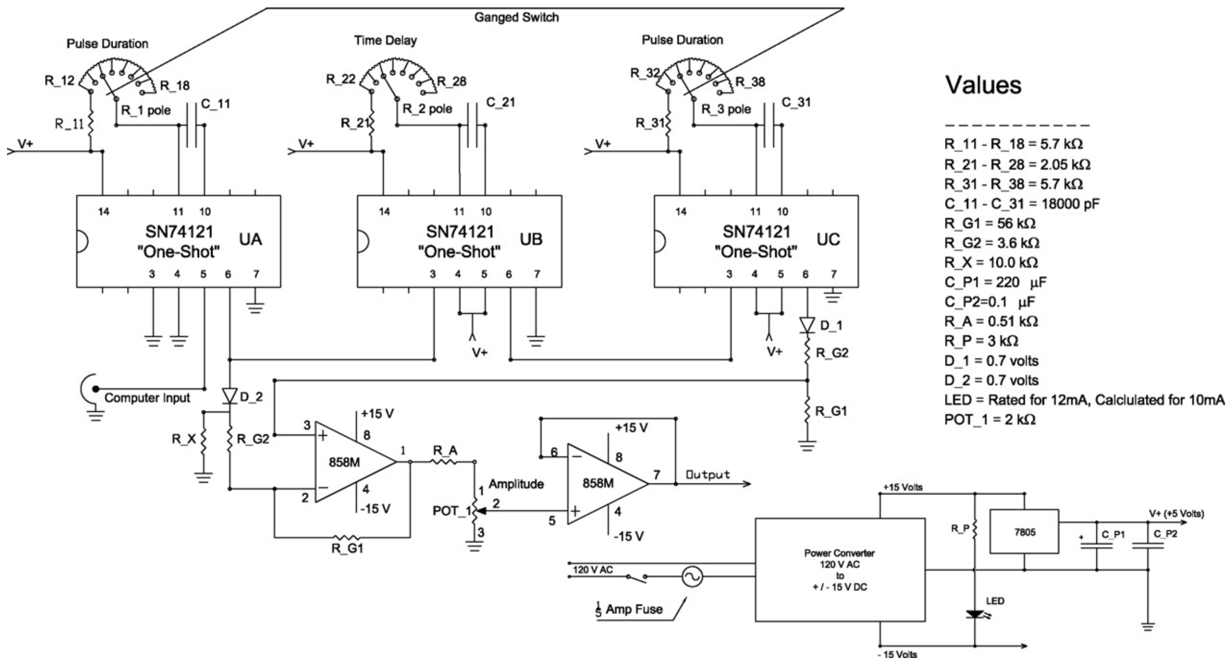

Fig. 2. Final circuit schematic. The schematic represents a single channel in the pulse-generator. R_X appears in the lower left hand portion of the schematic.

Table 1
Pulse durations and associated resistance values at each switch position for both cathodal and anodal pulses, and the interphase interval

Switch position	Capacitance (pF)	Resistance (kΩ)		Output pulse width (µs)	
		Cathodal/anodal	Interphase interval	Cathodal/anodal	Interphase interval
1	18,000	5.7	2.1	71.8	25.8
2	18,000	11.4	4.1	143.6	51.7
3	18,000	17.1	6.2	215.5	77.5
4	18,000	22.8	8.2	287.3	103.3
5	18,000	28.5	10.3	359.1	129.2
6	18,000	34.2	12.3	430.9	155.0
7	18,000	39.9	14.4	502.7	180.8
8	18,000	45.6	16.4	574.6	206.6

3. Results

Resistor and capacitor component values used in this design and the corresponding pulse and interval durations are shown in Table 1.

By applying a trigger pulse to the trigger input of the first multivibrator, the circuit produces a charge-balanced pulse stimulus, with separate and coupled control over cathodal and anodal pulse widths and amplitudes, and separate interphase interval control (Fig. 3).

Note that in this particular instantiation of the basic circuit design, fixed values for the timing resistors were used. Continuous, coupled control of pulse duration could be achieved by substituting ganged potentiometers for the ganged switches, and continuous control of interphase interval could be derived by using a potentiometer in place of a resistor bank.

Using the charge-balanced pulse generator in conjunction with a stimulus isolation unit (WPI), responses were recorded from an intact, anesthetized earthworm (*Lumbricus terrestris*) to stimuli of two different sets of pulse widths and interphase interval durations (Fig. 4). Band pass settings on the amplifier were 3 Hz and 3 kHz for low pass and high pass, respectively.

4. Discussion

The characteristics of this pulse generator circuitry make it ideal for applications in which stimulation pulse parameters are fixed and it is necessary that the stimulating equipment draw minimum power. Microprocessors such as the PIC16F87X (Microchip Technology Inc.) and the 80C517 (Siemens), used in other stimulation applications, report maximum power dissipation values of 1 and 2 W, respectively (Hofer et al., 2002; Lanmuller et al., 2005). On the other hand, CMOS components like that used in this design require only milliwatts of power when active and have quiescent power drains less that a milliwatt. The two referenced microprocessors have current drains during active signaling that require approximately four and seven times, respectively, the amount of current that is drawn during active signaling by the equivalent CMOS components described in this architecture. Since battery life is proportional

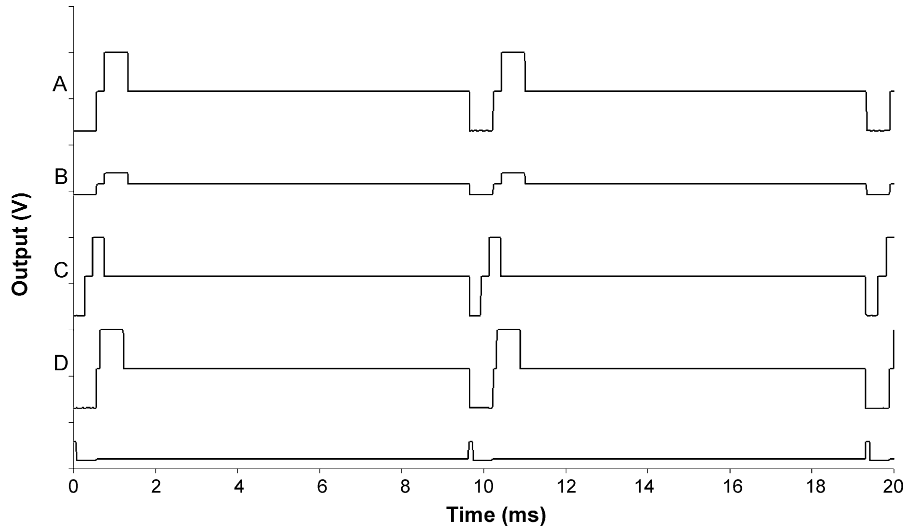

Fig. 3. Output waveforms showing a particular pulse duration–interphase interval–amplitude combination (A), with independent control of amplitude (B), pulse duration (C) and interphase interval (D). The bottom trace shows the input trigger used to initiate the output waveform. The tic mark interval on the vertical axis represents 10 V.

to current drain, this difference becomes significant in a battery-powered application.

The driving end of the device is very simple in that the only requirement to produce charge-balanced stimuli is a trigger pulse of 1.3 V amplitude and 40 ns minimum duration. The adjustable interphase interval between the cathodal and anodal pulses allows the user to specify when the anodal, charge balance event occurs. This is important in many applications to insure proper activation of the desired neural elements.

One feature of this specific design that is helpful in ensuring charge-balance is that when the user sets the cathodal pulse width, the anodal pulse width is automatically set to exactly equal it. However, in some applications, it is desirable to use lower amplitude, longer duration anodal pulses. This can easily be achieved by changing the values of the resistors for the third monostable multivibrator and clamping the input to the corresponding channel of the op amp with a diode.

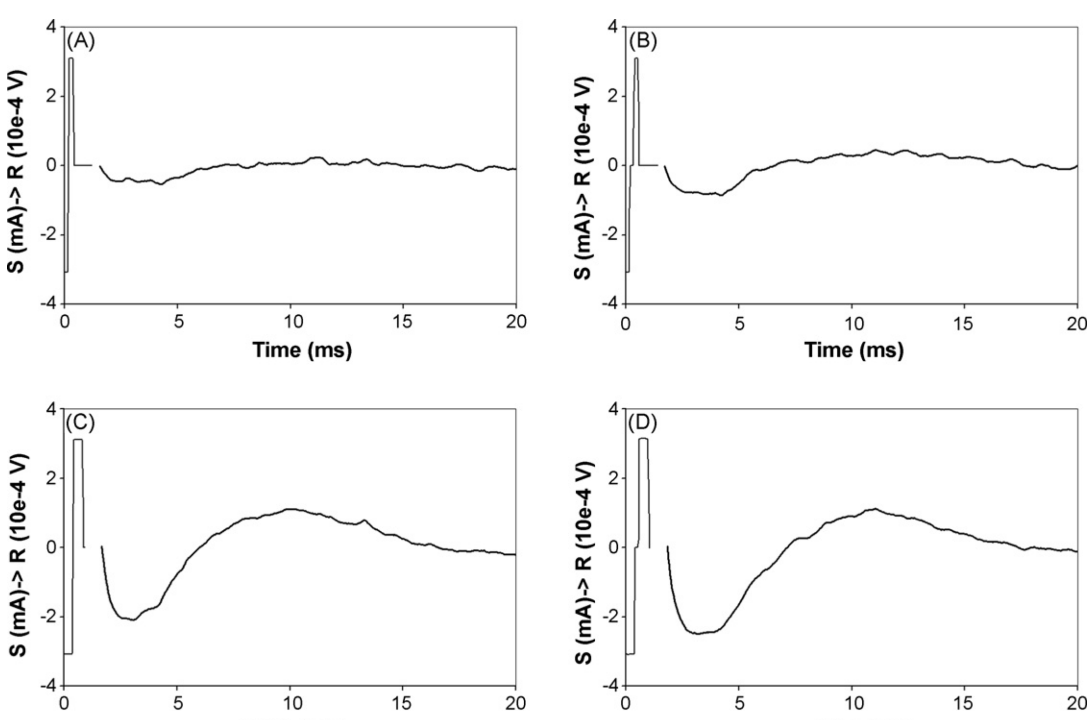

FIG. 4. Responses of an anesthetized, intact earthworm (*Lumbricus terrestris*) preparation to stimuli of different durations (A and B vs. C and D) and different interphase intervals (A and C vs. B and D). The initial component of the response containing the stimulus artifact and early giant fiber response has been deleted for clarity.

In neuroprosthetic applications, pulse parameters are established initially, and need not change throughout the stimulation process. Only the frequency of stimulation is changed to elicit different responses. Rather than have a microcontroller consume costly power by generating and re-computing unchanging pulse parameters continuously for each stimulus, the microcontroller could instead be replaced with the circuitry described here. Consisting completely of standard hardware components, this pulse generator circuitry could be fabricated on a low-powered CMOS chip, which would simultaneously provide small size and require low operating power. Additionally, since pulse duration and phase separation are generally fixed in a given neuroprosthetic application, a resistor–capacitor combination could be fixed on the chip to achieve the desired pulse width and interphase interval. The amplitude would be the only externally controlled parameter. What is left, then, is a small, low-powered charge-balanced pulse generator, whose amplitude and frequency of stimulation can be altered with ease.

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