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Wearable, Battery-Powered, Wireless, Programmable 8-Channel Neural Stimulator

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***Abstract*— In this paper, a wearable, battery-powered, low-power, low-size, cost-efficient, fully programmable neural stimulator is presented. The system comprises a wearable stimulator module and an external controller. To receive the settings required for the operation of the system, the wearable module is programmed through wireless connection to the external controller. Implemented using off-the-shelf components, the wearable neural stimulator weighs 60g and measures 9cm×5cm×2cm. The system is capable of generating independent biphasic stimulations on 8 channels with programmable amplitudes and timings. The neural stimulator consumes about 1.5mW in the power-down mode and about 51.2mW in the active mode when all the 8 channels are active. For in-vivo experiments, the system was used to stimulate motor cortex of an anesthetized rat fixed in a stereotaxic instrument.**

I. Introduction

Nowadays, treatment of a variety of neurological disorders (e.g., Parkinson's disease, epilepsy, and depression) are one of the main reasons of research on the development of neuroprosthetic devices and neural stimulators [1, 3]. To be portable, worn by the subject, and operate for a long time, a neural stimulator needs to be compact in size, light weight, and consume small amount of power [4]. Most of the research efforts in neural stimulation have been recently focused on designing implantable and wearable stimulators. In implantable stimulators, a microsystem is typically implanted in body and wirelessly received the power and stimulation parameters from an external controller [5, 6]. Wearable stimulators are widely used in functional electrical stimulation (FES) research. Design of the stimulation front-end (SFE) in a typical wearable neural stimulator usually faces challenges such as power efficiency, small size, and complying with the voltage requirements of the system [7, 8].

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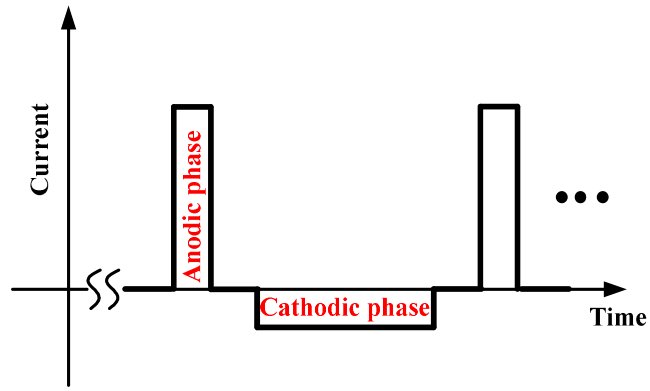


Figure 1. Typical biphasic current pulses

The most common current waveforms applied to the excitable tissue in neural stimulation are: monophasic pulses and biphasic pulses. Charge accumulation at the electrode-tissue interface is the main disadvantage of using monophasic stimulation. Biphasic stimulation is widely used in neural stimulators and is shown in Fig. 1 [5, 7, and 9].

In this paper, an 8-channel, low power, low size, wireless, battery-powered, programmable neural stimulator is presented. Off-the-shelf components are used to implement the proposed neural stimulator. The stimulator is capable of generating independent biphasic stimulus currents for all channels and is also wirelessly programmed by a portable external controller.

II. System Description

As shown in Fig. 2, the neural stimulator system reported in this paper consists of two main parts: the *wearable module*, which generates stimulation current pulses on 8 independent channels, and the *external controller*, in charge of programming the wearable module through wireless connection.

- *Digital Control Unit*

Operation of the wearable module is administered by a Digital Control Unit (DCU), which is indeed the ATMEL's commercial microcontroller, Xmega128a1. The DCU receives all the settings required for the operation of the system from the external controller via a telemetry link. As for the main function of the system, the controller generates biphasic stimulation current pulses with programmable

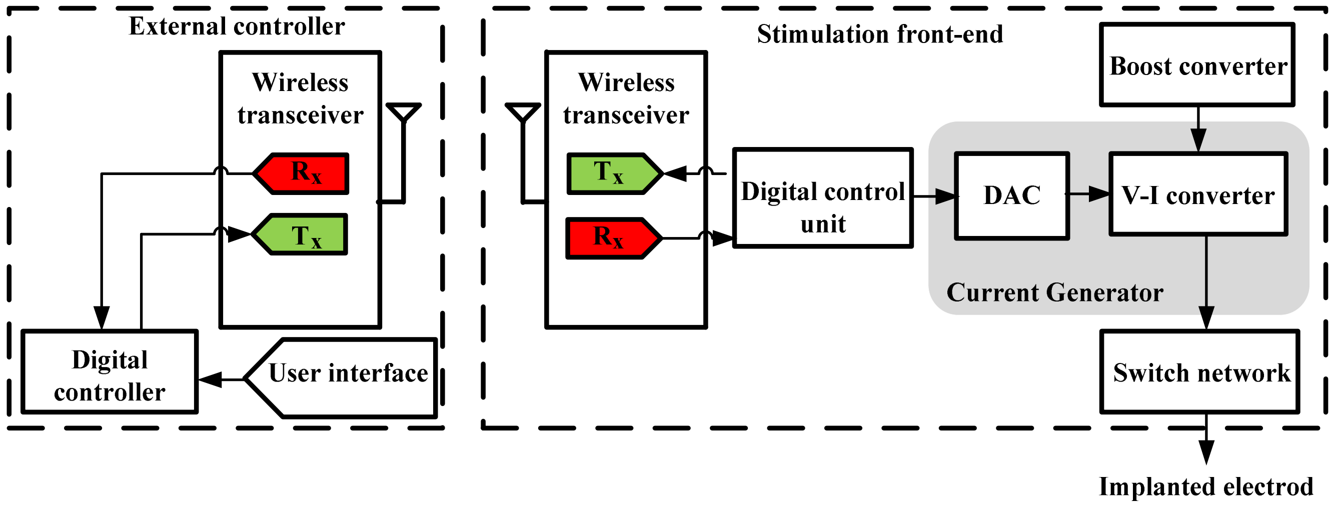


Figure 2. Block diagram of the proposed neural stimulator

amplitudes and pulse widths for both anodic and cathodic phases, as well as the inter-phase delay. There are two options for the generation of stimulations, which are 'single pulse' and 'pulse train'. It is worth noting that the settings on each channel can be performed completely from other channels. Moreover, the controller is capable of detecting the errors that are likely to happen when receiving data through wireless connection. In this case, the controller informs the external controller that an error has been occurred and asks for resending the missed data. When the system is in the *active mode*, the DCU runs at a master clock frequency of 2MHz, while it stops working when the system goes to the *power-down mode*.

- *Current Generator*

As shown in the block diagram of Fig. 2, the *current generator* comprises two main parts: a digital-to-analog converter (DAC) and a voltage-to-current (V-I) converter. Simplified circuit schematic of the current generator is shown in Fig. 3. Digital output codes of the digital control unit converted to the related analog voltage by a DAC which determined the voltage amplitude of the pulses. Two quad, parallel, 8-bit resolution, low-power, and voltage-output commercial DACs (AD5334, Analog Devices) are used to cover all the 8 stimulation channels. The reference voltage of the DAC is 2.5V and is created by a commercial reference voltage generator microchip (LM4040). Analog output voltage of the utilized DAC varies from 0 to 2.5V.The least significant bit (LSB) of the DAC is calculated to be 9.76mV. Setting the full-scale stimulus current of the neural stimulator to I_{FS} = 400μA, only 40 steps (out of a total of 256 steps) will be required to cover the entire output current range. Hence, the 6 most significant bits of the DAC input code are used to set the output current and the two LSBs are set to 0. Remembering that the AD5334 contains 4 DACs, the two address bits, A_1 and A_0, are used to address the DAC, into which the input data is to be loaded. To reduce

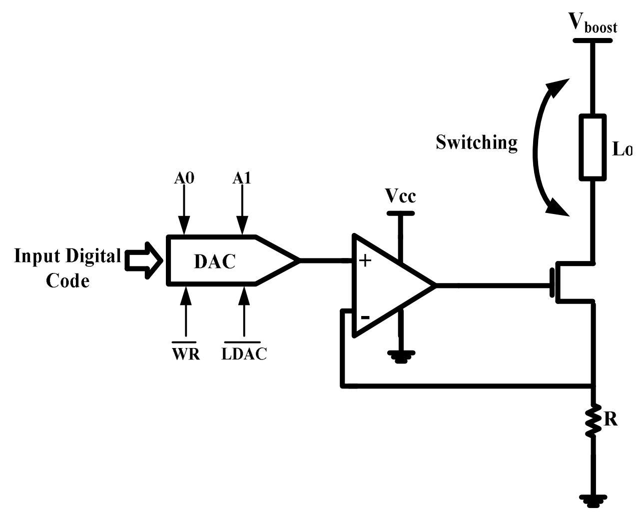


Figure 3. Circuit schematic of the current generator

the power consumption of the system in the power-down mode, all the DACs are turned off. The analog voltage at the output of the DAC is then converted to current using an op-amp-based precision source follower circuit. The result is a current sunk from the output node of the current generator, which is indeed the drain of the transistor in Fig. 3.

To be able to drive an equivalent resistor load up to 50kΩ, the 3.3V supply voltage globally used in wearable part of the neural stimulator is boosted up to 23V by a boost converter. The boost converter supplies a required headroom voltage of the current generator output stage.

- *Switch Network*

To convert the current provided at the output of the current generator, I_{stim}, to a biphasic current pulse, *the switch network* shown in Fig. 4 is employed. With the patterns dictated by the DCU, switches S_1-S_4, which are connected in a bridge-like configuration, are turned on and off in such a way that the constant I_{stim} current is shaped as a biphasic

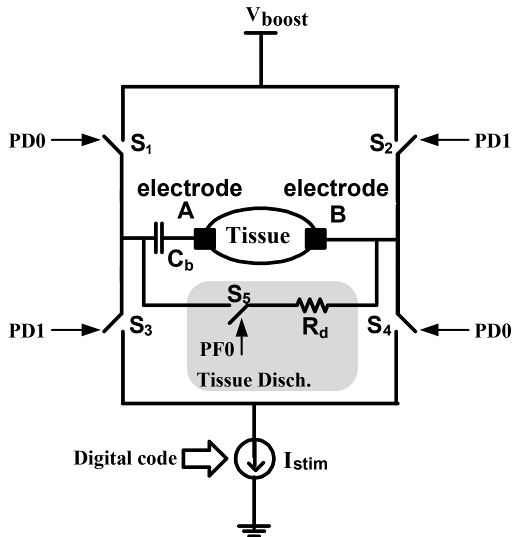


Figure 4. Simplified circuit schematic of the switch network

current pulse.

To protect the target tissue from damages caused by switch charge leakage, a DC blocking capacitor is considered in series with the tissue. Accumulation of charge in the tissue because of inevitable charge imbalance between anodic and cathodic phases is another concern. To prevent the tissue from damages caused by charge accumulation, the switch S_5 is envisioned. When closed, this switch provides a discharge path for the residual charges in the tissue being stimulated. Resistor R_d =1KΩ is used to suppress a current spike generated by the discharging phase.

- *Wireless Interfacing Module*

As mentioned before, stimulation parameters are wirelessly transferred from the external controller to the wearable module. For this purpose two identical commercial transceiver modules (RXQ2, Telecontrolli S.r.l), one on the external controller side and the other on the wearable module side, are used. This module provides reliable wireless communications for data transfer at data rates up to 100 kbps by Gaussian frequency shift keying (GFSK) and Manchester encoding. The data is sent from the external side to the wearable module in the form of serial packets. To enhance the reliability of the data transfer towards the wearable module, the transceiver on the wearable module returns an acknowledge message after the receipt of each data packet. This protocol, known as the 'stop-and-wait automatic repeat request (ARQ)' in computer networks [10], is briefly illustrated in Fig. 5.

- *The Stimuli*

The neural stimulator is capable of delivering biphasic stimulus current pulses, both single pulse and pulse trains, to the target tissue. Stimulation parameters and the associated ranges and incremental steps are listed in Table I.

In the neural stimulator reported in this paper, two twisted stainless steel insulated wires (125µm diameter, Advent Co., UK) except at the tip, separated along the vertical axis by 0.5 mm are used as bipolar electrodes.

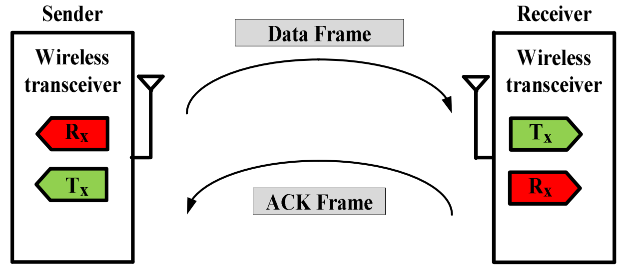


Figure 5. Conceptual illustration of the data communication protocol between the external controller and the wearable module

TABLE I: STIMULATION PARAMETERS

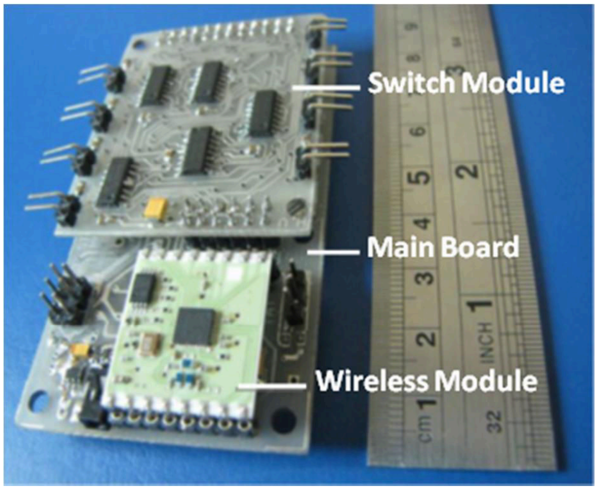
Parameter	Value	Incremental Step
Pulse width, Anodic	0-500µs	100µs
Inter-Phase Delay	0-500µs	100µs
Pulse width, Cathodic	0-500µs	100µs
Inter-Pulse Delay	0-500µs	100µs
Pulse Amplitude, Anodic	0-400µA	10µA
Pulse Amplitude, Cathodic	0-400µA	10µA
Frequency	0.1-400Hz	0.1Hz
# of pulses in a pulse train	1-60	1
# of pulse trains	1-60	1

III. EXPERIMENTAL RESULTS

Both the wearable and the external modules of the system were implemented using off-the-shelf components. Two key advantages of the system reported in this paper over the other wearable neural stimulator systems reported in the literature are its compact size and low power consumption. Fig. 6(a) shows a photograph of the wearable module, which is composed of three printed circuit boards (PCBs). The switch module and the wireless module are assembled on the main board to reduce the size of the system.

For in-vitro functional tests, the system was operated to generate both single pulses and pulse trains. For these tests, 15-kΩ resistive load, resembling sites and tissue impedances, was connected between two adjacent electrodes, and stimulation pulses with different parameters were successfully generated. Fig. 7 shows two oscilloscope screen shots exhibiting the resulting waveforms in a functional test, where all the 8 channels are active with different pulse specifications. The system consumes 51.2mW when all the channels are active, and around 1.5mW in the power-down mode.

After passing in-vitro functional tests, the system was tested on a rat in both anesthetized and freely-moving forms.



(a)

(b)

Figure 6. (a) The wearable module consisting of three PCBs (b) The subject carrying the wearable module during a freely-moving test

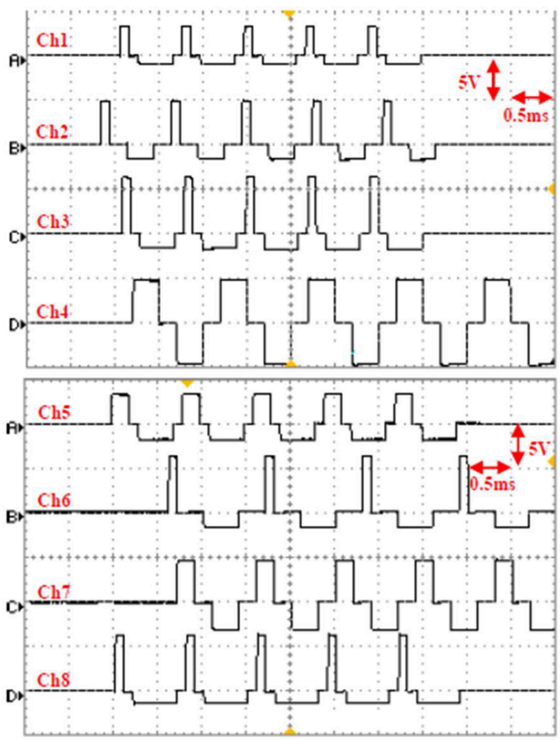


Figure 7. Oscilloscope screen shots showing stimulation waveforms on all the 8 channels during an in-vitro test

For this purpose, the electrodes were placed and fixed in the motor cortex of the subject. The wearable module was then tightened on the back of the subject and connected to the electrodes as shown in Fig. 6(b).

IV. Conclusions

In this paper, an 8-channel wearable neural stimulator was reported. The system is programmed through wireless connection, receiving details and parameters of the stimulations to be generated for all the channels. Compared to the systems with similar functionality, the wearable system reported in this paper is more compact in size, and consumes lower power.

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