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A Wireless Neurostimulator System with an Embedded ARM™ Microprocessor

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Abstract

In this study, a novel multi-layer printed circuit board (PCB)-based neurostimulator system with an embedded microprocessor is presented for applications in neuroprosthesis. The system integrates rechargeable batteries, a power management block, adjustable constant-current waveforms, voltage transient monitoring, and evoked neural response recording. The system can be configured to select channels among the 16 stimulation channels via Bluetooth communication wirelessly. Bench top measurements demonstrated that the system generated biphasic current waveforms with various stimulation parameters with approximately 407 mW of power consumption. Additional testing and validation with microelectrodes are underway.

I. Introduction

Neurostimulator systems can be used to excite and sense neuronal activity wirelessly. Multichannel electrodes driven by neurostimulator circuits have been utilized in neuroprosthetics and neurotherapeutics applications, such as vagus nerve stimulation for reduction of epileptic seizures [1] and deep brain stimulation for treatment of movement disorders such as Parkinson's disease [2].

Generally, neurostimulator and recording circuits can be designed as commercial-grade off-the-shelf integrated circuits (COTS ICs) or as application specific integrated circuits (ASICs). ASICs have advantages of small dimensions and customized design, but have drawbacks in terms of development time and cost. On the other hand, COTS IC systems can be developed and prototyped faster and be fabricated at a lower cost. For instance, PennBMBI, a general-purpose brain-computer interface system, was designed with COTS IC [3]. This system implemented a 32-bit microprocessor with a four printed circuit boards (PCBs). Other COTS IC designs include Neurochip-2 [4] and Bidirectional Telemetry Controller [5]. Neurochip-2 was constructed with an 8-bit Programmable System-on-Chip (PSoC) microprocessor and three PCBs, which were capable of neural recording and stimulation in free roaming animals. The Bidirectional Telemetry Controller was designed with two 8-bit microcontrollers and with three PCBs to operate as a neurostimulator capable

of monitoring voltage transients and recording evoked neural responses. However, PennBMBI, Neurochip-2, and Bidirectional Telemetry Controller were constructed with multiple PCBs. In behavioral animal experiments, there may be a lack of stability in terms of physical connections, signal transmission between multiple circuit boards via connectors, power consumption, and overall dimensions.

To address this problem, we have developed an embedded system with a 32-bit microprocessor-controlled using a 6-layer PCB. The key features of the system include neurostimulation, voltage monitoring, and evoked neural response recording. A compact and single board design reduces possible antenna effects due to wiring or connection between the circuit boards, any electronic noise artifacts in the circuit boards communication, and unpredicted power loss. We employed the high speed (216MHz) and energy-efficient ARM[™] M7 Cortex microprocessor (STM32F767, ST Microelectronics, Switzerland), which consumes less power and has a higher core speed than the 32-bit AVR microprocessor used in the PennBMBI design. For example, in stand-by mode, the 32-bit AVR consumes approximately 40 μ A current whereas the STM32F767 consumes approximately 4 μ A. This paper presents key specifications of the system, hardware architecture, the user interface, and preliminary test results.

II. Methods

A. System Overview

As illustrated in Fig. 1, the circuit was designed with a modular approach and was assembled on the 6-layer PCB. Its main components and functions are listed in the Table I. The circuit is composed of a Bluetooth module, a stimulation pattern generator, Howland current pumps, IC switches, voltage waveforms monitoring circuit, and evoked neural response recording circuit. Two 3.7V Li-ion rechargeable batteries are connected in series to power this board and recharged via an in-circuit charge-control design. A main aim with an embedded microprocessor is to generate and autonomously transmit constant-current pulses to an array of microelectrodes.

B. Hardware Architecture and Implementation

This design integrated 16-channel current stimulation and voltage monitors, two-channel neural recording, communication via Bluetooth 4.0, a power management unit, battery monitoring, and other passive components. The microprocessor has been programmed to generate the stimulation waveforms based on user inputs. For a biphasic voltage signal generation, the microprocessor creates digital codes for uni-phasic signals, then the digital signals are converted to analog biphasic signals using an 8-bit rail-to-rail output DAC (Digital-to-Analog Converter) with a non-overlapping two phase signal generation circuits. With a serial peripheral interface (SPI), the data transmission is established between the microprocessor and DAC. The voltage waveform of the signal is then converted into current form with the dual-rail powered (± 5 V) Howland current pump circuit. The main reason for using the current pump is to eliminate possible distortions that may occur during phase changes between positive and negative and for transconduction mismatches [7]. The biphasic current signals are then directed to the stimulating electrodes via a 20-pin connector

(Omnetics Connector Corp. Minneapolis, MN) soldered on to the board by IC switches. Voltage transients are fed to the user interface, wirelessly through the Bluetooth connection, to monitor electrode polarization, and thus, to ensure safety of electrical stimulation.

Two channels were allocated for differential-recordings of evoked neural responses. In the first stage, two passive high-pass filters attenuated low-frequency signals with 9.65Hz cutoff frequency. In the second stage, the analog signals were differentiated and amplified. In the third stage, the microcontroller on-chip analog-to-digital conversion (ADC) was used. Finally, evoked neural responses are fed back to the user interface through the Bluetooth connection.

We used a multi-layer PCB which is known to be reliable, have less electronic noise, and have a more compact design. Packaging with surface-mountable devices (SMDs) allowed a smaller overall dimension. In addition, with enclosed assembly of individual SMD components, the lead length can be short, which yields faster signal transmission among the peripherals. Our circuit was designed using the Altium Designer 18 (Altium, Ltd., San Diego, CA) and was manufactured by Sunstone Circuits (Mulino, OR).

The microprocessor utilizes two different programs: STM32CubeMX toolchain and uVision Keil MDK Version 5 IDE. The former is used to assign each pin a specific function, such as for USART (Universal Synchronous/ Asynchronous Receiver/ Transmitter) communication, digital to analog converters (DAC), and analog to digital converters (ADC). Once the necessary pins are configured in the STM32CubeMX toolchain, the code can be generated in the uVision Keil MDK Version 5 IDE. The instances of the selected pins in the CubeMX toolchain are declared in the main form of the IDE to allow for coding specific functions to various pins in the language of ANSI (American National Standards Institute) C.

C. User Interface

A computer interface, as illustrated in Fig. 2, has been encoded and designed in a the Microsoft Visual Studio IDE (Integrated Development Environment), and has been programmed in VB.NET (Visual Basic .NET platform). Major parts of the interface include: 1) Bluetooth communication panel, in which Communication Port (COM Port) and baud rate can be adjusted, 2) a stimulation parameters panel, where the stimulation signal amplitude, pulse width, frequency, and bias voltage can be set, 3) stimulation electrode selection and electrode monitoring panel, 4) a stimulation polarity panel, where the biphasic current signal will be cathodic or anodic first can be selected, 5) battery monitor panel, where the rechargeable battery level can be monitored with percentage rate, and 6) an amplitude modulation panel, where modulation percentage of the signal can be set. The interface sends commands to the microprocessor wirelessly, which then communicates with its peripherals.

III. Results

Fig. 3 shows the fabricated and assembled PCB board with a dimensions of 52.56 mm × 64.13 mm. An Omnetics™ connector was mounted for stimulation and recording channels as well as reference and ground connections. The whole system consumed approximately

407 mW and 666 mW, in active mode and during Bluetooth communication, respectively. In addition, the linear regulator output ripple voltages were 10 mVPP, 11 mVPP, and 13.5 mVPP for 5V, 3.3V, and -5V voltage regulators, respectively. Fig 4 shows these output ripple voltages oscillations. The user interface, utilizing COM port and baudrate (9600) configurations and Bluetooth communication, successfully sent the stimulation parameters with amplitude, pulse width, and frequency to the microprocessor.

The biphasic currents generated by the Howland current pumps were measured across an 11k Ω load. Fig. 5 shows voltage transient across the load with the cathodic-first biphasic current signal. The evoked neural response recording feature of the circuit was tested with a Plexon™ sound test board. The test board is input with sound waveforms which emulate neural spikes riding on a sinewave. Fig. 6 shows high-pass filtered, differentiated, and amplified analog signals.

IV. Discussions

We developed a wireless neurostimulator system consisting of rechargeable batteries, a neurostimulator circuit board that generates biphasic current pulses, and a computer interface. Our multi-layer PCB circuit with an ARM™ microprocessor consumed slightly less power (407 mW) compared to Neurochip-2's 412 mW [4] and that of the bidirectional telemetry controller's at 418 mW [5], in active modes.

Considering these systems and PennBMBI designs were structured with multiple PCB boards, our single-board multi-layer design system showed high power efficiency and low voltage regulator ripples. We have so far validated biphasic current waveform generation, communication via Bluetooth, voltage transient monitoring, and neural spike recording. Future tests will include validating the system with microelectrode array in PBS solution and with rodents in a backpack platform *in vivo*.

Acknowledgments

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Fig. 1.

Functional block diagram of the neuroprosthetic system consists of a user interface, a PCB board (including the microprocessor), a stimulation pattern generator, a voltage-to-current conversion unit, 16 SPST switches, an evoked neural response recording unit, a stimulus voltage waveform monitoring unit, a Bluetooth, and micro/bipolar electrodes. This block diagram is adapted from [5] and the microelectrode picture was referenced from [6] (Tx: Transmitted; Rx; Received).

Fig. 2.

The user interface of the system. Major functions are: Bluetooth communication, stimulation parameters, stimulation electrode selection, stimulation polarity, battery monitor, and amplitude modulation.

Fig. 3.

Assembled neurostimulation and recording circuit board with six layers. The first, third, fourth, and sixth layers accommodate signal flows, and the second and fifth layers the ground and power layers, respectively. The overall dimension of the board is 52.56 mm × 64.13 mm.

Fig. 4.
Output ripple voltages of three different linear regulators in power management part on the PCB.

Fig. 5.

Biphasic voltage transient over an 11k Ω load connected to output of the Howland current pump through an OmneticsTM connector. The injected current is 30 μ A.

Figure 6.

Emulated neural response recording from a Plexon sound board. (A) General view of the recorded test signals; (B) High frequency spike-like potential waveforms

TABLE I.

Power consumption of the Main Components in the Neurostimulator circuit

Function	IC Model	Key Features	Power Consumption
Analog Switch	PS393ESE, Pericom Inc.	4-SPST switch in a single chip	<1 μ A
Bluetooth Module	SH-M08, DSD Tech	Bluetooth 4.0 BLE. -84 dBm (Acuity)	8.5mA (During transmission)
Micro-processor	STM32F76VIT ST Micro-electronic	521 Kbytes SRAM; 2 Mbytes Flash Memory; Dual Mode Quad-SPI; USARTs/ UARTs	4 μ A (In standby mode)