A Low-Cost Configurable Multichannel Cortical Stimulator Prototype

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Abstract— The recording and decoding of intracranial neural signals for brain-computer interfaces (BCIs) and neural prosthetics is rapidly evolving. These devices have the objective of augmentation and restoration of lost or impaired function for the disabled. While much work has been done in terms of electrical stimulation of muscles, nerves, and the cochlea for prosthetics, comparatively little work has been done to explore the possibility of direct cortical stimulation of the human brain. It has been shown that simple bipolar, biphasic cortical stimulation can induce a wide range of sensory percepts (i.e., visual, auditory, and tactile sensations). It is envisioned that more sophisticated multichannel stimulation using configurable waveforms may produce predictable and controllable percepts, thus paving the way for the next generation of neural prosthetics. Such sophisticated stimulation could be useful in future bi-directional BCIs, which would allow the user to control a device and receive feedback via the same neural interface, e.g., control and proprioception in a prosthetic limb. This paper presents the preliminary design of an 8-channel configurable cortical stimulator prototype based on the compact and low-cost Raspberry Pi® single-board computer. Promising results from initial non-tissue tests are shown.

I. INTRODUCTION

Electrocortical stimulation (ECS) remains the standard for functional mapping of the brain prior to surgical resection in cases of medically intractable epilepsy and brain tumors. ECS uses a pair of bipolar electrodes to apply regulated current waveforms directly to the surface of the brain to localize functional areas during a craniotomy. Several clinical ECS devices, such as the Grass S12X and the Ojemann stimulators [1], [2], are routinely used in order to safely excite neurons by applying a simple bipolar pulse with variable amplitude, pulse width, and frequency directly to the cortical region of interest [3]. Studies have also shown that direct electric stimulation of the human visual cortex can be used to create a visual prosthesis that allows users to perceive monochromatic shapes in the visual field [4], [5]. Similarly, electrical stimulation of the auditory cortex has been shown to produce auditory percepts in humans [6]–[8]. These studies have also used very rudimentary localized pulsed bipolar stimulation.

The electrocorticogram (ECoG) measures the electrical activity of the brain from electrode arrays placed on the surface of the cortex. These same electrode arrays are also routinely used for ECS and can be fully chronically implanted for neurostimulation treatment of conditions such as epilepsy [9]–[13]. In addition to direct stimulation of the cortex, recent research has shown ECoG signals can be

directly decoded and used to synthesize the speech stimuli using the measured brain signals [14]. This provides a clear indication that electrical signals measured from the cortex contain the relevant and robust spatiotemporal information for representing complex motor, auditory, and language activity, and therefore additional motivation for exploring more sophisticated spatiotemporal cortical stimulation to induce more natural sensory percepts for future neuroprosthetics. While the traditional localized bipolar biphasic stimulation devices may be sufficient for functional mapping and inducing simple sensory percepts, they are not capable of providing the desired fully-configurable spatiotemporal stimulation patterns.

The proposed multichannel stimulation prototype is based on the low-cost Raspberry Pi® (RPi) [15] single-board computer. It is designed to be easily configured via the unit's Ethernet port and is capable of simultaneously outputting multiple user-defined current waveforms (eight in the current prototype). Upon the depression of a push-button switch, the stimulation routine is executed and output to conventional transconductance amplifier circuitry to provide the necessary current to the stimulation electrodes. This paper details the technical design of an early prototype, and concludes with a discussion of future work and improvements.

II. DESIGN FEATURES AND OVERVIEW

Stimulating the cortex is a delicate balancing procedure. By stimulating with insufficient current, no noticeable effect is obtained on the subject. By stimulating with too much current, irreversible damage can be caused to the neuronal structures. For these reasons, the design of this cortical stimulation device is based on existing clinical devices, such as the Ojemann stimulator [1] and Grass S12X [2], as well as recent patents [16], [17]. The design of this particular device can be broken into three predominant components shown in Fig. 1: the stimulus design software, the RPi control unit, and the output circuitry.

A. Stimulus Design Software

The stimulus software accepts as an input the desired stimulus waveforms for eight channels, and communicates with the RPi unit seamlessly. The computer software performs the majority of the calculations because the RPi, although running a full Linux kernel, has limited computing power. For instance, the software performs safety checks (e.g., safe current ranges) based on the investigators desired input waveforms. A MATLAB script was created to generate the eight current waveforms and the waveform data in a hexadecimal ASCII-text file for transfer to the RPi.
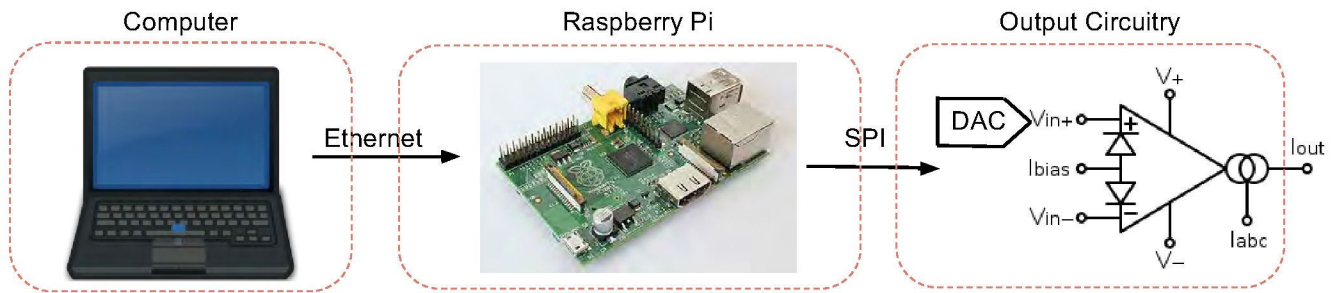
Fig. 1. The three main components to the cortical stimulator device include 1) the computer running the MATLAB script, 2) the RPi parsing input data data and controlling the circuitry logic, and 3) the output circuitry which interfaces with the ECoG electrodes.

B. The Raspberry Pi Unit

The RPi unit communicates with the primary computer over Ethernet. It also provides the logic for the circuitry. The unit, upon powering up, configures itself to allow for communication with the host computer. It also clears any previous stimulation commands from its memory so as to not erroneously stimulate the individual with the last waveform from the previous session. After booting, the RPi also initiates the program that will ultimately send the digital version of the waveform that is loaded from a specified file over the serial peripheral interface (SPI) to a Digital to Analog Converter.

C. Output Circuitry

The output circuitry must convert the digital waveform to an analog signal. This occurs through the use of a Digital to Analog Converter (DAC). Since the brain is stimulated with current, and not necessarily voltage, the voltage generated by the DAC is converted to a bipolar current using a transconductance amplifier circuit. The circuitry is limited to a maximum applied current of 5 mA, based on the predicate devices.

III. STIMULUS DESIGN SOFTWARE

Since the waveforms that represent the stimuli are frequently generated in MATLAB, the software at the front-end of this system is also written in MATLAB. A function was written that accepts a matrix as an input. Each column represents an independent channel that the stimulator is connected to. The proposed waveforms are initially re-sampled to match the update rate of the SPI output and DAC hardware. The maximum rate that the RPi can output all 8 channels worth of information via the SPI to the DAC is at a 400 μs pulse period. This corresponds to a sampling frequency of 2500 Hz. This is slightly longer than the minimum pulse periods of 100 μs for the predicate devices, and is a limitation of the RPi. However, the intention of this device is to stimulate waveforms in a nontraditional means, as opposed to simple pulse trains.

Next the MATLAB function hard limits the input values to between ±1000 by means of clipping. This was chosen based on the typical dynamic range of ECoG recordings, which will serve as the exemplar stimulation waveforms for

testing. This is designed to allow unit-calibrated, high-pass filtered data to be fed directly back onto the subjects cortex by means of stimulation at a current directly proportional to the recorded voltages.

The hard limited data is then verified to fall within the safe limits of stimulation, 20 micro-Coulombs, equivalent to predicate devices. To verify the signal falls within the safety range, a sliding window of 1s is passed over the data for all channels. If the mean value of this window exceeds this threshold, the program returns an error and terminates.

Next, the software prepares the data into a format that the RPi and DAC can interpret. This means converting the input signal to a 10-bit value. For this, -1000 is converted to 0, and +1000 is converted to 1023, and the values between are adjusted accordingly. This 10-bit value is then appended with the 4 bit address used by the DAC to identify the output channel. Two 'don't care' bits are appended on the end as 0s, bringing the total number of bits required to send a single output value to a single channel of the DAC at 16. This is recorded in a file as two pairs of ASCII-text hexadecimal values per channel per time point. Finally, the MATLAB function transfers the file via Ethernet to the RPi using SSH to securely copy the file to the RPi transparently to the user.

IV. THE RASPBERRY PI UNIT

The Raspberry Pi is essentially a miniature computer with an ARM processor operating at 700 MHz and running a Debian based Linux installation using kernel 3.2.27. Specifically, the RPi uses the Broadcom BCM2835 chipset and runs on 3.3V CMOS logic. The unit, shown in Fig. 2, has an Ethernet connection, HDMI output, 2 USB ports, I/O pins accessible via the header, and an SPI among other features. It is powered by a 5 V power supply and draws roughly 300 mA of current.

Upon boot-up, the RPi is configured to setup the network connection such that a host computer can connect to it. Immediately thereafter any previous configuration file that was stored on the flash drive memory is replaced with an empty file. This prevents an incorrect waveform being applied accidentally to the subject from previously loaded waveforms. A C-program, the main program on the RPi, is then automatically executed and runs continuously until shutdown.

Fig. 2. A Raspberry Pi, without any attached connections. I/O headers are at the bottom right, and the Ethernet connection is on the top left. The system runs off an SD memory card, which contains the operating system.

This C-program performs 3 main functions: it loads data from the file that is placed on the RPi by the host machine, it pushes the acquired data over the SPI to the DAC, and it controls the logic of the hardware via GPIO.

Typically the RPi is idle. A push-button switch is connected to a GPIO pin available on the header connector. When this button is depressed, the main routine executes. The SPI is enabled, and the mode for transferring data is set. The SPI is setup to operate at 16 MHz, and transmit data 8 bits at a time, as required by the DAC. Next, the file is read into an array in memory for rapid access times. The DAC is enabled by setting a GPIO pin high and the program loops through the array, every 400 μs sending out all eight 16-bit values (32 hex values), then toggling another GPIO pin to update the DAC outputs. Upon completion of the array, the DAC is turned off, and the SPI unit is shutdown. The RPi then waits for a subsequent button press.

V. EXTERNAL HARDWARE COMPONENTS

There are two major external hardware components connected to the Raspberry Pi: the Digital to Analog Converter (DAC), and the Operational Transconductance Amplifier (OTA) circuit. The DAC is the LTC1660 by Linear Technology. It contains eight 10-bit serially addressable DACs in a single package. Each DAC is buffered and draws 56 μA of current, but is capable of supplying DC currents of up to 10mA while maintaining a steady output voltage.

The LTC1660 is powered via the same 5V power supply as the RPi, which is also used as the reference voltage. Therefore the output voltages also range between 0 and 5 V. The DAC communicates via SPI, and is connected to the SPI Clock output available on the RPi header. The D$_{IN}$ pin of the DAC is tied to the transmit pin of the RPi, and is where the serial data is loaded. When the LD pin is pulled low the voltage updates with a settling time of no more than 30 μs.

The output of the DAC is used to drive a transconductance amplifier, because the cortex is stimulated with current. As such the positive voltage needs to be converted into a voltage controlled constant current source. An operational transconductance amplifier effectively creates an output current I_{out}

that is a gain multiplied by the difference between the input voltages. In order to achieve a bipolar current output from the 0 to 5 V output of the DAC, a reference of 2.5 V is used at the V_{in-} terminal shown in Fig. 3. Any voltage above or below this level will be converted to a positive or negative current, respectively. This 2.5 V is achieved with a simple voltage divider using matched resistors. The amplifier uses an additional power supply of ±15 V to drive the currents of the OTA. This means the maximum applied cortical voltages are ±15 V, and follow comparable ranges used by predicate devices.
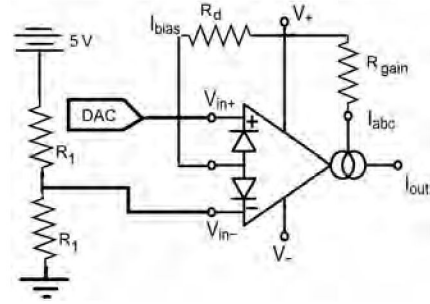

Fig. 3. The operational transconductance amplifier schematic used for the output of the circuit. The resistor values for R_d and R_{gain} are provided below. R_1 is set at 100 kΩ.

The LM13700 is an OTA with two operational transconductance amplifiers in a single package, having output buffers on each. The amplifiers each have linearizing diodes which improve their function over a greater range of voltage differences. The relationship between the input voltage and the output current for an operational transconductance amplifier is

$$I_{out} = V_{in} \left[\frac{I_{abc}q}{2KT} \right] \tag{1}$$

where q is the charge of an electron, K is Boltzmann's constant, and T is temperature. Knowing that KT/q is 26 mV at room temperature, and that a $V_{in(max)} = 2.5$, which necessitates the 5 mA output current, and following the circuit schematic shown in Fig. 5, I_{abc} is found to be 104μA. Using the rail voltage of +15V, this gives $R_{gain} = V^+/I_{abc} = 144.23k\Omega$. The LM13700 datasheet indicates that the diode current I_{bias} should be 1 mA, so it follows that $R_D = 15$kΩ.

VI. TESTING AND RESULTS

To verify the functionality of the prototype, eight simultaneously recorded two-second segments of prerecorded ECoG data were selected as stimulation waveforms. Two seconds of stimulation is comparable in duration to bipolar pulse trains from predicate devices. The waveforms are then output through 1 kΩ loads, which are expected to be comparable to cortical loads. No tissue tests have been performed with this early prototype. Three of the resulting waveforms are shown in Fig. 4. The prototype output was captured using a digital biosignal amplifier and compared to the desired programed
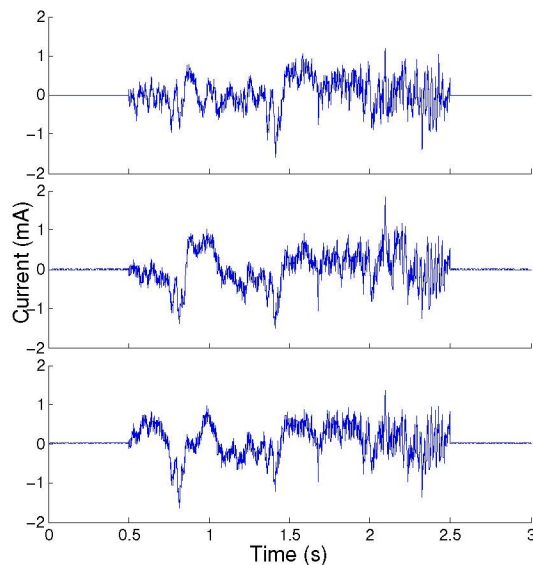
Fig. 4. Example of 2 seconds of ECoG voltage data converted to simultaneous current waveforms for 3 channels for a nontraditional stimulation method.

output. The outputs were then compared numerically to the desired outputs for all eight channels, resulting in a small root-mean-square error of 0.15 ± 0.03 mA. A segment of the data in Fig. 5 demonstrates visually how well the measured output tracks the desired output.
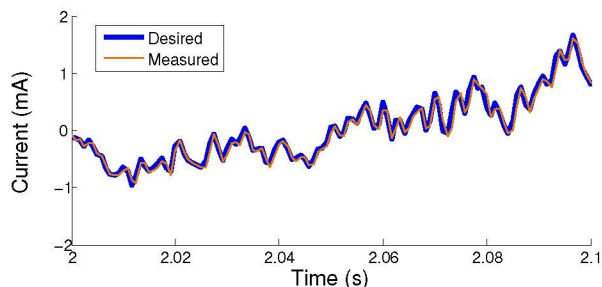

Fig. 5. Demonstrating the negligible differences between actual and expected measurements over a period of 0.1s from a single channel.

VII. DISCUSSION

This prototype presents a significant and affordable step toward the development of a cortical stimulator unit that is capable of simultaneous and arbitrary multichannel stimulation. Predicate devices currently allow for programmable stimulation, but none currently generate arbitrary waveforms across multiple sites. The entire cost of the prototype is under $50, including the RPi, DAC, transconductance amplifiers, and miscellaneous electronic components. Furthermore, with straightforward modifications, this low-cost prototype could be used in a variety of multichannel functional electrical stimulation applications, e.g., providing custom stimulation waveforms to obtain complex muscle contraction sequences.

A major limitation of the present design is the lack of timing resolution. Using all eight channels, the RPi is capable of 400 μs step sizes for the pulse widths, which is slightly higher than current clinical stimulators of 100 μs. One possible way to increase the timing resolution is to limit the number of channels for the RPi to below eight, for instance by syncing multiple RPis together. This would allow the SPI transfer of data from the RPi to the DAC to occur over a much shorter time period, allowing for faster, more frequent updates to the DAC. However, it should be noted that this device is designed to stimulate via non-traditional waveforms which do not necessitate such short pulses. Additional features will be added, and electrical isolation and current limiting circuitry will be included for safety. Prior to being tested on any humans, this device will need to undergo significant safety and animal testing.

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