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Design of a Multichannel Cortical Stimulator Prototype for Future Neuroprosthetic Research

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Abstract. Intracranial recording and decoding of neural signals for brain-computer interfaces (BCIs) is rapidly progressing. While much work has been done to explore electrical stimulation of muscles, nerves, and the cochlea for prosthetics, far less 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, conceivably allowing for a new means of sensory feedback. These devices could lead to novel, more natural bi-directional BCIs where the user could experience for instance proprioception with a robotic arm. Such devices will undoubtedly require complex spatiotemporal cortical stimulation patterns. Here we present a design of a configurable cortical stimulator prototype based on the Raspberry Pi single-board computer.

Keywords: Cortical stimulation, electrocorticography, functional electrical stimulation

1. Introduction

Past studies have shown that using direct cortical stimulation with bipolar, biphasic pulses to the human visual cortex can create a visual prosthetic to allow individuals to perceive monochromatic shapes in the users' visual field [Schmidt et al., 1996]. Additionally, electrical stimulation of the auditory cortex has produced auditory percepts in humans [Howard et al., 2000; Fukuda et al., 2010]. Functional electrical stimulation (FES) is also considered the gold standard for cortical mapping prior to resection in medically intractable epilepsy and brain tumors. However, in all of these instances the stimulation has typically been performed using very rudimentary and localized bipolar, biphasic stimulation protocols. While traditional 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 necessary for complex BCI feedback. In order to fully realize a bi-directional BCI, i. e., including sensory feedback, it is conceivable that more complex spatiotemporal stimulation patterns need to be developed. Here we present the development of a cortical stimulator prototype capable of satisfying these needs.

2. Material and Methods

Stimulating the cortex is a delicate procedure. By stimulating with too large of a current, irreversible damage can be caused to neuronal structures. However, by stimulating with too little current there is no noticeable effect on the subject. For these reasons, this cortical stimulator device is based on existing clinical devices, e.g., the Ojemann stimulator and the Grass S12X, as well as recent patents [Lombardi et al., 2010; Beuter and Modolo, 2010]. The design of this device is broken into three predominant areas, the stimulus design software, the Raspberry Pi (RPi) control unit, and the output circuitry.

2.1. Stimulus Design Software

The stimulus design software is a MATLAB function that accepts a matrix of eight channels of voltage waveforms up to two seconds in length. It is designed to allow unit-calibrated ECoG data to be fed directly back onto the cortex by means of stimulation currents that are directly proportional to the recorded voltages. The software converts these input voltages to currents that will be applied, and performs error checking to maintain the output currents within safe levels of operation. The created current waveforms are then passed via Ethernet to the RPi control unit.

2.2. The Raspberry Pi

The Raspberry Pi is an inexpensive single-board computer running a full Linux kernel, but also contains a multitude of I/O pins similar to most micro-controllers. This unit, shown in the second stage of Fig. 1, accepts a file describing the current waveforms from the primary computer, and upon a button press outputs the eight channels of activity serially to a DAC. All eight channels are updated every 400 µs. The unit also controls the logic of the output circuitry, e. g., enabling the DAC and OTA.

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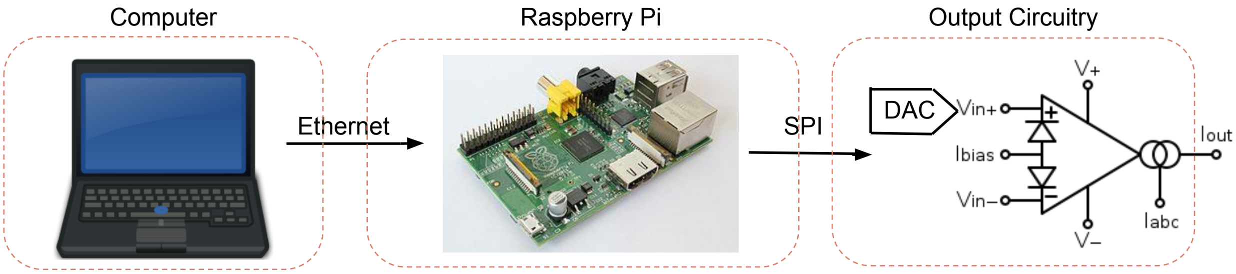

Figure 1: *The three main components to the stimulator prototype include 1) the primary computer running a MATLAB function, 2) the RPi controlling circuitry logic and passing through data, and 3) output circuitry which interfaces with ECoG electrodes.*

2.3. Output Circuitry

The digital waveforms are converted to analog signals using the LTC1660 10-bit DAC. The analog voltage is then converted to a current using traditional transconductance amplifier circuitry, which provides a current output based on a voltage input. The LM13700 operational transconductance amplifier (OTA) with two buffered OTAs in a single package was selected to provide the output currents.

3. Results

To verify the functionality of this prototype, eight simultaneously recorded two-second segments of ECoG data were selected as stimulation waveforms. The waveforms are then output through 1 kΩ loads, which are expected to be comparable to cortical loads. Two of the resulting simultaneous stimulation waveforms captured using a biosignal amplifier are displayed in Fig. 2. The outputs were compared numerically, resulting in the small RMSE of 0.207 ± 0.013. Visually, the output can be shown to nearly perfectly track the desired current on the right of Fig. 2.

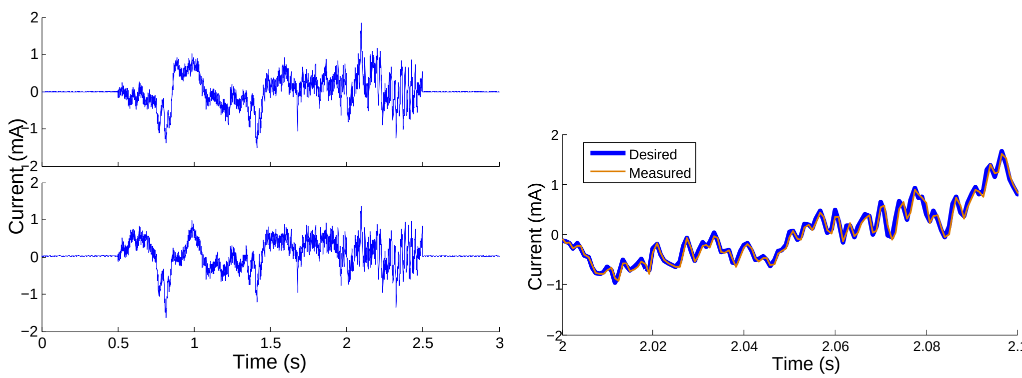

Figure 2: *Two simultaneous outputs from the device are shown on the left. On the right is a comparison showing the desired output tracking the input very well over a 0.1 s interval.*

4. Discussion

This prototype presents a significant and affordable step toward the development of a cortical stimulator unit that is fully programmable and capable of simultaneous multichannel stimulation. One possible limitation of this design is the lack of timing resolution, with a minimal pulse width of 400 µs, compared to 100 µs in predicate devices. However, it should be noted that this device is intended to stimulate in non-traditional waveforms so does not necessitate such short pulses. Additional safety features and testing will need to be pursued prior to any human testing.

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