Wireless Sensor Brain Machine Interfaces for Closed-loop Neuroscience Studies

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Abstract—Closed-loop bidirectional Sensor-Brain-Machine Interface (SBMI) systems with wireless communication capability have shown significant value in neuroscience studies recently. However, most rack-mount medical instrumentation currently used in neuroscience research labs only allow experiments in tethered or sedated animals. Customized miniature wireless SBMI devices, which operate reliably on freely behaving animals, are highly desirable. The design of such system places significant challenges in both circuit and system level. This paper analyzes the system requirements and discusses the design strategies, followed by an example of a fully integrated wireless SBMI for augmenting perception. The design paradigm presented in this work can be used in extensive range of neuroscience studies in unrestrained animals.

Index Terms—Brain machine interface (BMI), bi-directional neural interface, CMOS sensors, neuroprosthetic

I. Introduction

A Sensor-Brain-Machine Interface (SBMI) system establishes bidirectional communication between the brain and peripheral sensors, and includes motor decoding as well as sensory feedback [1, 2]. Both motor and sensory pathways are important for neuroscience studies and neuroprothetics development. However, most current research and publications have exclusively focused on decoding neural activities. This is partially due to the challenges in the sensory perception research and the modeling in animals, as well as the lack of proper sensor design from the engineering perspective [3].

Fig. 1 illustrates the architectures of different BMI systems. Fig. 1(a) shows an open-loop neural recording paradigm. Neural signals can be decoded and used to move a cursor on a computer screen or to drive external devices such as a robotic prosthetic [4]. Fig. 1(b) shows an open-loop stimulation paradigm. The stimulation parameters are determined and adjusted by an external algorithm or by medical doctors with expertise in stimulation therapy [5]. Fig. 1(c) shows a bidirectional BMI with both recording and stimulation interface. A machine learning based decoder can be used to extract features in the neural signal and detect biomarkers [6]. In a closed-loop operation, biomarkers can be used to trigger stimulation, for example, a seizure suppression BMI system can detect or even predict a seizure event and deliver pre-defined deep brain stimulation (DBS) to prevent it [7]. Fig. 1(d) shows a complete SBMI system where sensors are used to collect sensory data from the subjects, or to monitor the subjects' behaviors. The neural responses can be recorded and used to confirm the

reaction, while delivering brain-state dependent stimulation. The parameters of the stimulation or the modulation algorithm can be updated in real time.
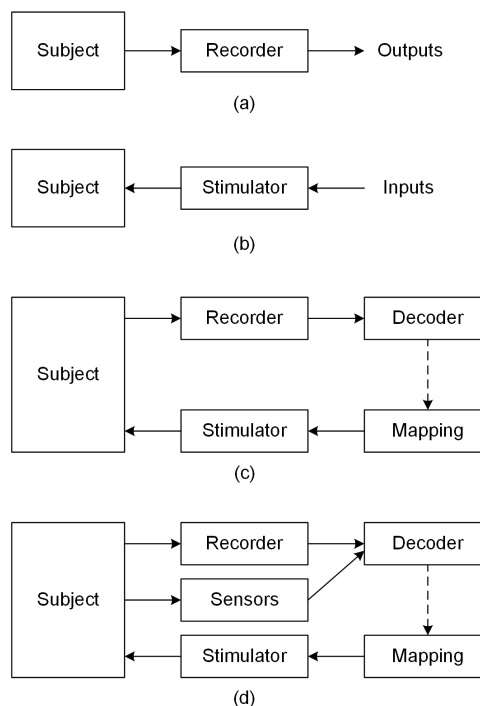

Fig. 1. Block diagrams of conventional BMIs and the proposed the SBMI: (a) an open-loop recording paradigm, which can be used to analyze neural signal and/or to decode motor cortex, e.g. control a prosthetic arm; (b) an open-loop stimulation paradigm, which can be used to deliver functional neural stimulations or a stimulation-based therapy; (c) a bidirectional neural interface with both recorder and stimulator, which can be used to link two brain sites or deliver a brain event triggered stimulation; and (d) the proposed SBMI with sensors and bidirectional neural interface for closed-loop neuroscience studies.

Closed-loop neuroscience studies in freely behaving animals require custom designed miniaturized sensor nodes, which are usually not available off-the-shelf. The bidirectional neural interface requires an ultra low-noise recorder as well as a fully programmable micro-stimulator with minimum damages to the neurons. In addition, many experiments require a wireless operation to allow the animals under test to freely behave in a natural environment [8]. All these challenges must be addressed to support a robust real-time closed-loop

experiment.

This paper is organized as follows. Section II discusses the design strategies. Section III describes an example of a complete closed-loop wireless SBMI system for augmenting perception through modulated electrical stimulation. Section IV concludes the paper.

II. DESIGN STRATEGIES

The key components of a complete wireless SBMI includes a neural recorder, a neural stimulator, sensor nodes, and a computer host with a user interface. Wireless communication channel should be established between nodes if there is a signal path. The computer host should be able to configure the devices wirelessly, or through a wired interface when the devices power up. In some cases, the stimulator and the neural recorder can be integrated on a sample chip or PCB board. If an on-chip algorithm is built-in for a closed-loop operation, it reduces the latency and also eliminates the power dissipation for wireless communication, thus is generally more robust and secure. However, a bidirectional neural interface needs to be very carefully designed to minimize the stimulation artifacts, especially if the stimulating site is close to the recording site. The following section analyzes the design strategies for each module.

A. Neural Interface

Choosing the proper neural recording site, signal type and channel count are very important for a SBMI system. Both non-invasive and invasive neural recording have been widely used [9]. Electroencephalogram (EEG) can be collected by non-invasive electrodes on the scalp, while invasive recordings require the electrodes or the whole recording device to be implanted. Electrocorticography (ECoG) is recorded beneath the skull, and local field potential (LFP) and single neuron action potentials (AP) are recorded within the parenchyma. While non-invasive EEG recording is relatively safe and has been demonstrated to be able to drive prosthetics, the time and frequency resolutions are very limited. Invasive recording, on the other hand, can provide much more information down to a single neuron level, at the cost of surgery and long-term electrodes implant.

An EEG signal typically has frequency contents between 0.5Hz and 50Hz, and a signal amplitude from sub-microvolts to several microvolts. Ultra low noise amplifiers are usually required for EEG recording, and noise shaping techniques including chopping, auto-zeroing, digital assisted trimming are often used [3, 7]. In addition, analog and digital filters are helpful to remove out-of-band noise. Special attention needs to be paid to minimize the common-mode noise including mains interference, which can be orders of magnitude higher than the signal. Shielding, right leg driving, and twisted-wire routing are usually required. The signal amplitude of invasive recording can be up to 1mV as the electrode approaching a neuron. On the other hand, electrode impedance can be very high (up to Megaohms) in a high-density microelectrode array, which requires a high input impedance of the recording front-end. Chopping and sampling based low-noise techniques may lower the input impedance, thus boosting or compensation of the input impedance is recommended [10].

Electrical stimulation of excitable neurons is one of the most prevalent functions of biomedical implantable devices and closed-loop neuroscience studies. Electrical stimulators can be used for deep brain stimulation (DBS), functional electrical stimulation (FES), spinal cord stimulation (SCS), visual and auditory neural stimulation, neuroprosthetics and clinical therapeutic treatments. There are three different modes of electrical stimulation: voltage-regulated mode, current-regulated mode and charge-regulated mode [3, 5]. Voltage-regulated mode applies a voltage between two electrodes, current-regulated mode passes a current between two electrodes, while charge-regulated mode sets the total amount of charges and uses the discharging current to excite the neurons. Voltage-regulated mode stimulation usually has the highest energy efficiency, current-regulated mode has the best controllability, while charge-regulated mode can achieve a balance between them [11]. The most critical requirement of electrical stimulation is to minimize residue charges, which may generate toxic chemical products and damage the neural system. The development of high density, tissue-friendly electrodes and novel methods of recording and stimulation, including optical and magnetic approaches, are promising research areas [9].

B. Sensors for Neuroscience Studies

Our everyday behavioral goals are achieved by sampling the environment with available sensory modalities and modifying actions accordingly. No actions can be completely without sensation. The brain processes complicated sensations all the time, including vision, sound, temperature, vibration, pressure, and other sensations. Artificial sensors can be designed to collect such information, and SBMIs potentially can help patients to restore sensations. In addition, sensory feedback also improves the effectiveness and efficiency of closed-loop neuromodulation efficiency [2].

Depending on the applications, sensors can be implantable, wearable, or to be used externally. For example, vision sensors used for retinal prosthesis can be a miniature wearable image sensor integrated in the glasses for patients with image data wirelessly transmitted to the implanted stimulator array; or the image sensor and the stimulator array can be integrated together to reduce the delay and power dissipation for wireless communication. Another example can be pressure and vibration sensors for paralyzed individuals who lost sensation. The sensors can be implanted under the patients' skin of their hands or limbs, or integrated in a robotic prosthetics [13].

Taking advantage of the characteristics of semiconductors, lots of sensors can be implemented directly in CMOS technology, including image sensor, temperature sensor, pressure sensor and others [14]. Some sensors can be implemented in standard CMOS with simple post-fabrication processing. In addition, many other sensor devices using MEMS or similar technologies can be bonded or stacked with CMOS chips in a

single package. As long as a sensor's output can be converted to an electrical signal, CMOS circuits can easily process the signal, including amplification, filtering, digitization, and transmission. In extreme cases, energy harvesting technologies can be used to power both the sensors and the processing circuits to make a battery-less solution, which can significantly reduce the constraints in many experiments.

C. Wireless Communication

Low power, high data rate and reliable wireless communication has been one of the major bottlenecks in SBMI development. SBMI devices usually have a much higher wireless data rate than IoT devices with a more stringent power budget. Low power dissipation is required not only to extend the battery life, but also to reduce the heat dissipation of implanted devices which may cause damage to the tissue environment.

Commonly used wireless communication techniques including Industrial, Scientific and Medical radio (ISM) band frequency-shift keying (FSK), amplitude/frequency modulation (AM/FM), ultra-wideband transceiver (UWB) and backscattering transmitter. Among them UWB usually gives the highest data-rate, thus is suitable for high-channel count recording; backscattering usually can achieve ultra low power on the transmitter side with the drawback of a limited working distance; ISM band transceivers with various modulation techniques can achieve a moderate data-rate and a balance in the power dissipation [15]. Custom designed wireless transceivers with programmable transmitter power levels are usually suitable for neuroscience studies within an operating room or a research lab where there is limited transmitting distance requirement. However, it should be mentioned that the scattering from metal cages for animal experiments could be complicated and making the antenna design significantly more challenging [12].

D. System Integration

The importance of system integration is often underestimated during the design of SBMI for neuroscience studies. A typical device, including neural recorder, stimulator and sensor nodes, consists of an analog interface, a timing and logic control block, a clock generation block, a wireless interface, and a power management block. If advanced signal processing is required, a custom DSP or a general-purpose CPU should be integrated. General-purpose micro-controllers (MCUs) or low-power FPGAs are also popular choices in system integration. Many off-the-shelf MCUs and FPGAs have a clock generation block integrated, also general-purpose IOs and digital ports designed for data transfer. Lithium polymer batteries are commonly used for powering medical devices given their high energy-density and reliability.

Even if all the important blocks function as expected in individual bench testing, they may not necessarily work well together. The noise coupling between digital blocks and analog and RF circuitry is a very common issue. Given the restraint power budget and device size, each block may not have individual supply network with dedicated power managing

circuity. In addition, designers need to pay attention to the stimulation artifacts. When a strong stimulation is used to trigger the desired neural response, the evoked neural features may be completely buried in the artifacts and cannot be detected. Both electrode design and circuit techniques have been developed to avoid these issues [3, 12].

User interface is another important part of the system. Neuroscience investigators or medical doctors are not necessarily experts in operating electronic devices. As a result, the configuration and device programming must be done through a user friendly computer interface. Software engineers need to make sure warning and error messages can be properly generated to inform the operators, in case of false experimental data generated, which contaminate the results and conclusion. Both hardware and software researchers and engineers need to work together to design a robust and reliable system.

III. A WIRELESS CLOSED-LOOP SBMI DESIGN FOR AUGMENTING PERCEPTION

In this section, we present one of our recent SBMI designs for a closed-loop augmenting perception experiment in freely behaving rodents [16]. Sensory feedback is essential for goal-directed behavior, and there has been an increasing interest in conveying lost sensory information through direct brain stimulation. We developed a novel closed-loop paradigm using a classic test of rodent navigation: the Morris water maze (MWM) [17]. In the MWM, a rat swims in a large circular tank looking for a hidden submerged platform. In our task, the platform is positioned randomly on each trial to dissociate visual cues form the location, so the rats can only navigate using the sensation encoded from the wireless stimulation.

Fig. 2 illustrates the experimental setup and the basic operating principle. The system consists of a wireless SBMI,
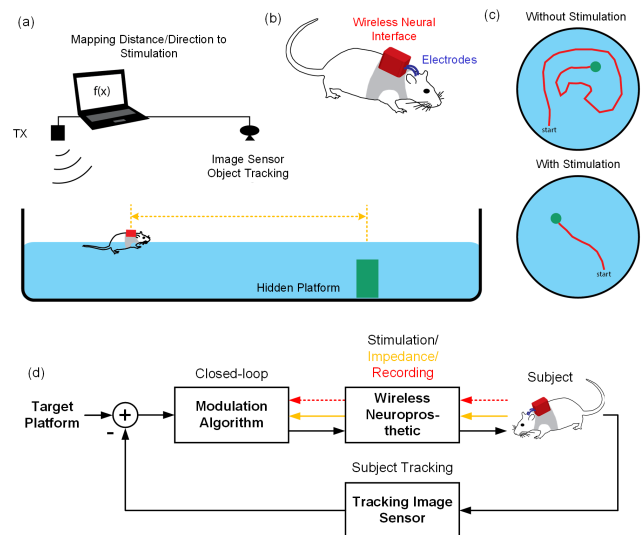

Fig. 2. (a) Illustration of the experimental setup. (b) shows a rat wearing a custom designed waterproof wireless neural interface. (c) illustrates the estimated swimming traces with/without the stimulation guidance. (d) shows the high-level closed-loop diagram of the experiment.

an object tracking image sensor, and a computer with a graphic

user interface. Based on the experimental requirements, we designed the wireless SBMI with a custom neural interface ASIC and a general-purpose Bluetooth wireless transceiver. The block diagram of the device is shown in Fig. 3 (a). The neural interface ASIC integrates 8-channel current-regulated mode fully programmable neural stimulator with charge-balancing and electrode impedance monitoring circuity. Electrode impedance monitoring is critical to detect electrode falling off or shorting by water during the experiment. 16-channel low-noise amplifiers with programmable gain, high input impedance, and high CMRR are also integrated for recording the evoked neural responses. A 10-bit SAR ADC and a digital filter are also integrated. The Bluetooth transceiver easily communicates with a computer workstation over a reliable link, which is important for the required continuous stimulation in this experiment. The ASIC was fabricated in 180nm CMOS technology. The whole SBMI device is coated with Silicon to be waterproofed, as shown in Fig. 3. Waterproofed connectors are used for electrode connection.
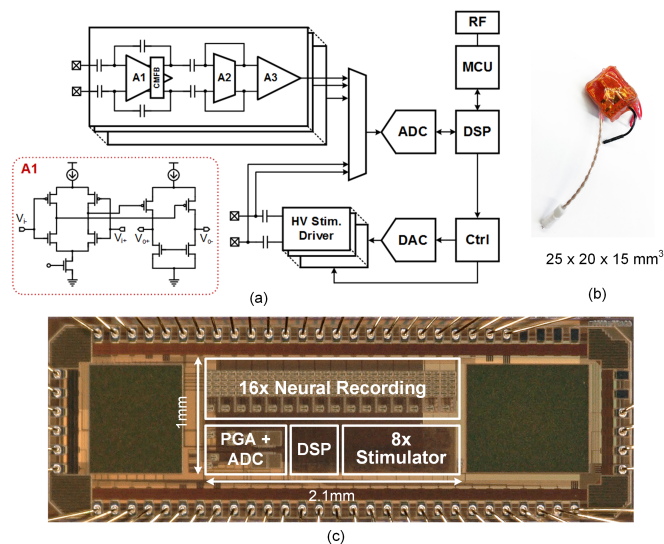

Fig. 3. (a) The block diagram of the neural interface ASIC. (b) The fully waterproofed wireless SBMI device. (c) The fabricated neural interface ASIC in 180nm standard CMOS technology.

The animal tracking sensor in this work consists of an object tracking image sensor ASIC and a general-purpose FPGA. A very short latency between the detection of the rat's swimming angle and the delivery of the corresponding stimulation is required for this experiment. Thus a real-time high frame-rate image sensor is needed, but a high image quality video output is not necessary. A custom-designed motion-based object tracking is very suitable for this application. The general-purpose FPGA buffers the image data and implements the tracking algorithm before transmitting the data back to computer to further reduce the computation delay.

Both safety and reliability are critical for this experiment. The electrode impedance is monitored locally in the SBMI device and any on-going stimulation will be terminated immediately in cases of electrodes falling off or shorting by

water. The SBMI device also have a built-in timer to terminate stimulation if the wireless communication is lost or corrupted during an experiment. Handshaking is checked in each cycle to confirm that the desired stimulation parameters have been correctly received by the SBMI device and the current stimulation have been delivered accordingly. The developed SBMI system have been successfully tested in a couple of rats and the results suggest that rats can learn to interpret artificial percepts to guide behaviors.

IV. CONCLUSION

In this paper, we introduced the paradigm of closed-loop wireless SBMI for neuroscience studies and neuroprosthetics development. We discussed design strategies and key trade-offs in each building block and in system integration. Then we presented a design example of a typical wireless SBMI system for experiments in freely behaving rodents. The experiment was only possible with the custom designed SBMI system. We believe that SBMI technology has an extraordinary potential to provide a revolutionary understanding of the brain and benefits millions of populations.

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