The PennBMBI: A General Purpose Wireless Brain-Machine-Brain Interface System for Unrestrained Animals

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***Abstract*—In this paper, a general purpose wireless Brain-Machine-Brain Interface (BMBI) system is proposed. The system provides all the necessary hardware for a closed-loop sensorimotor neural interface. The system integrates a neural signal analyzer, two neural stimulators with different specifications, multiple body area sensory devices and a user-friendly computer interface. The neural signal analyzer features four channel analog front-end with configurable bandpass filter, gain stage, digitization resolution, and sampling rate. Digital filtering, neural feature extraction, spike detection, sensing-stimulating modulation, and compressed sensing measurement are realized in a central processing unit integrated in the analyzer. Flash memory card is activated for low power operation, compressed sensing recovery verification and/or data backup. An 8-channel stimulator with high driving capability (±10 mA with compliance voltage ±22V), and a 2-channel stimulator for deep brain stimulation are included in the proposed system. Both stimulators are capable of delivering bipolar, biphasic capacitive coupled current pulses in programmable pulse shape, amplitude, width, pulse train frequency and latency. Multi-functional wireless sensor node, including an accelerometer, a temperature sensor, and a general sensor extension port has been designed. Surveillance camera is implemented for the monitoring of the animal's behavior. A user-friendly computer interface is designed to monitor, control and configure all aforementioned devices via wireless link. Wireless closed-loop operation between the sensory devices, neural stimulators, and neural signal analyzer can be configured. Bench test and *in vivo* experiments are performed to verify the functions and performance of the system.**

***Index Terms*—Brain-Machine-Brain Interface (BMBI), neural recording, neural stimulation, closed-loop**

I. INTRODUCTION

Neural stimulation and recording can be used to communicate bidirectionally between the brain and external hardware. The artificial pathways created by these neural interfaces have shown promise in replacing sensory and motor pathways lost to neurological injury or disease [1, 2].

Most existing sensorimotor interfaces are proof-of-concept systems using wired connections and rack-mounted equipment. As the field has matured, researchers have begun to develop less-confining systems that could lend themselves to continuous use in daily life. Development to date has focused mostly on wireless links for multichannel neural recording [3, 4] and stimulation [5, 6].

In this paper, we present a wireless Brain-Machine-Brain Interface (BMBI) that is, to our knowledge, the first portable system to provide all the necessary hardware for a closed-loop sensorimotor neural interface. Previous closed-loop neural recording and stimulating devices were designed to link two sites in the brain using neural-activity-dependent stimulation to create new neural pathways [7, 8]. In contrast, our device links the brain to external hardware to create new sensory and motor pathways. In particular, our BMBI can communicate sensory information to the brain with sensor-controlled wireless neural stimulation, and communicate motor information to an effector with wireless neural recording and processing. These functions are accomplished using three separate wirelessly linked devices (neural signal analyzer, stimulator, and sensor node) that can be flexibly configured with a user-friendly graphic interface.

The paper is organized as follows. Section II first introduces an overview of the system architecture. The circuit design of both the signal analyzer and the stimulating devices are proposed in the same section. Experimental results are presented in Section III followed by *in vivo* testing results, while Section IV concludes the whole paper.

II. DESIGN OF THE BMBI SYSTEM

A. System Overview

The BMBI system integrates four kinds of devices: i) neural signal analyzer, ii) neural stimulators, iii) multi-functional body-area sensor nodes, and iv) computer interface. An overview of the system, the photographs of devices and functional diagrams are illustrated in Fig. 1.

A neural signal analyzer (Fig. 1 (a)) of size 56mm × 36mm × 15mm is employed to perform general neural signal recording and analysis. A four channel analog front-end featuring configurable pass-band, gain stage and analog to digital convertor (ADC) are employed. Digital filtering, neural feature extraction, spike detection, sensing-stimulating modulation, and compressed sensing measurement are realized in digital domain in a central processing unit integrated on board. A wireless link has been built for command and data transfer. On-board Flash memory card is activated under low power

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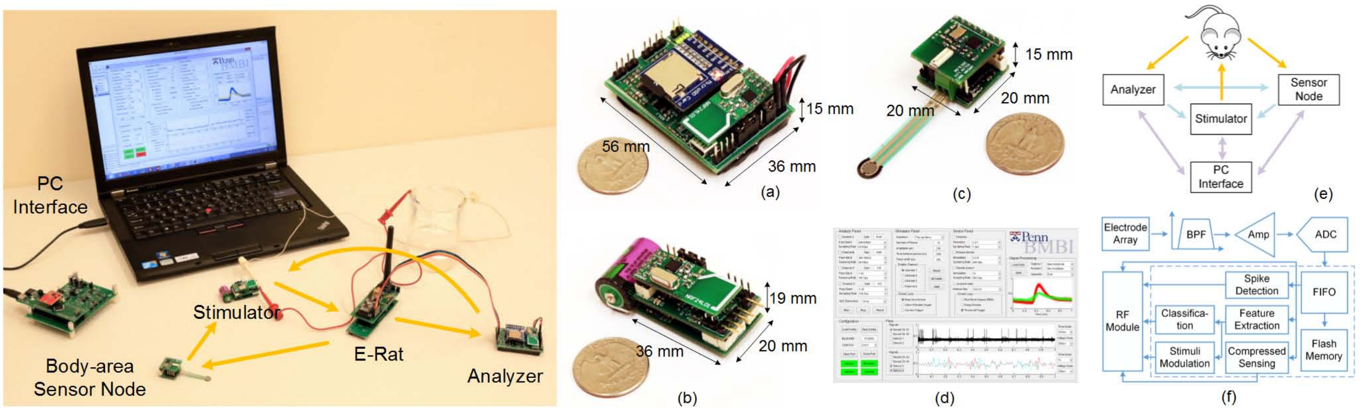


Fig. 1. The BMBI system include four kinds of devices: (a) neural signal analyzer, (b) stimulators, (c) body-area sensor nodes and computer interface (surveillance camera not shown). All devices can be configured wirelessly in (d) a user-friendly computer GUI. "E-Rat" in the figure stands for the subject under test. (e) illustrates the system function diagram, while yellow arrow in the left picture shows the possible closed-loop path, (f) illustrates the blocking diagram of the neural analyzer.

operation mode, compressed sensing recovery verification, and/or data backup.

Two stimulators with different specifications are included in the system. An 8-channel stimulator of size 83mm × 34mm × 28mm is designed with high driving capability, which provides constant current stimulation up to ±10 mA with compliance voltage of ± 22V. A 2-channel stimulator (Fig. 1 (b)) of size 36mm × 20mm × 19mm provides constant current stimulation up to 400 μA with compliance voltage ±16V for deep brain stimulation. Both devices are wirelessly controlled to deliver bipolar, biphasic capacitive coupled current pulses in programmable pulse shape, width, pulse train frequency and latency.

Multiple sensors are also presented in the system, including multi-functional sensor nodes and an external surveillance camera. The multi-functional sensor node (Fig. 1 (c)) with a dimension of 20mm × 20mm × 15mm, integrates a 3-axis accelerometer, a temperature sensor, and a general extension port which is compatible with a wide variety of commercial sensors, including flexible sensor, pressure sensor, motion sensor, etc.

Wireless links using off-the-shelf transceivers have been built between all devices for configuration, data transfer and closed-loop operation. A custom protocol has been designed for communication with all the devices in the system to avoid confliction.

A Matlab based user-friendly graphic user interface (GUI) (Fig. 1 (d)) has been built for wireless monitoring, controlling and configuring all devices. Closed-loop operation can also be easily configured in the GUI. Possible closed-loop paths are illustrated in Fig. 1 (e).

B. Neural Signal Analyzer

The neural signal analyzer implements a four-channel analog front-end, a digital signal processing unit, a RF transceiver, a power management unit, and other peripheral circuits. The device is powered up by rechargeable 3.7 V lithium-ion batteries (Ultralife UBP002). This 950 mAh battery supports the device up to 78 hours in continuous recording mode.

The circuit of one analog recording channel is shown in Fig. 2. Neural signals are capacitively coupled to the board via a well shielded cable. Large biasing resistors and a JFET input amplifier are chosen to make sure the input impedance is higher than 100 $M\Omega$, which is compatible with standard micro-electrodes. $A2 \sim A4$ forms an instrumentation amplifier. $A5$ provides the high-pass filtering with a configurable cut-off frequency. $A6$ works as the second gain stage with a low-pass filter with a configurable cut-off frequency. The third gain stage is programmable from 1/2 to 64. The total gain the analog front-end can be configured to be 54 dB$\sim$96 dB. A pipeline ADC with configurable resolution (8-bit/12-bit) performs at a sampling rate up to 30 KSps per channel. Digitized results are pushed into a circular FIFO for the subsequent digital signal processing. Digital bandpass and notch filtering are performed in the central processing unit to provide clean data for feature extraction, spike sorting, compressed sensing and other algorithms. The on-board RF transceiver is capable of sending recorded raw data, neural features, spike time stamps, and compressed sensing measurements to the computer in real-time. It is also capable of sending mapped stimuli patterns to the stimulating device, or receive triggers for recording from other devices. A removable flash memory card is employed for low power recording, verification of compressed sensing or data backup. The function diagram of the analyzer is illustrated in Fig. 1 (f).

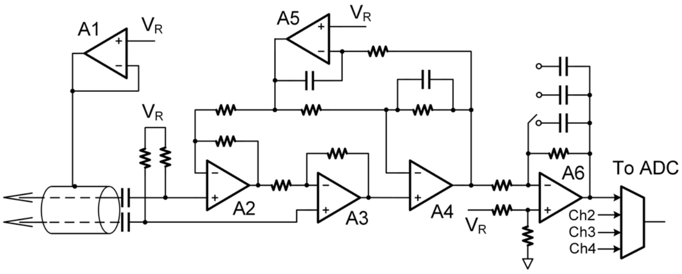


Fig. 2. Circuit schematic of one recording channel.

C. Stimulating Devices

Two stimulator devices are included in this system. Both of the two devices include a current driving back-end, a micro-controller, a RF transceiver, a power management unit, and other peripheral circuits.

A modified Howland current source is employed as bi-direction current driving stage, as illustrated in Fig. 3. $A1$ works as a DC level shifting circuit. The common mode voltage of the DAC is shifted to the relative ground of the current source circuits. $A2$ is a high-voltage dual supply op-amp with JFETs inputs. A resistor trimmer is used to trim the equal-value resistor network to achieve good common mode rejection ratio (CMRR) and high output impedance. Different transconductances can be selected by setting gain resistor in order to get a large dynamic range. $A3$ is a unity-gain buffer used to reduce the requirement for calibration under different gain settings. A blocking capacitor is used to prevent direct current injection and limits the maximum net charges. The size of the capacitor is chosen to be large enough to reduce the additional compliance voltage. A feedback integrator $A4$ is used in idle mode (switch S_1 closed) to stabilize the circuit and minimize the current leakage [8]. High voltage analog switches are employed for reset and channel select functions.

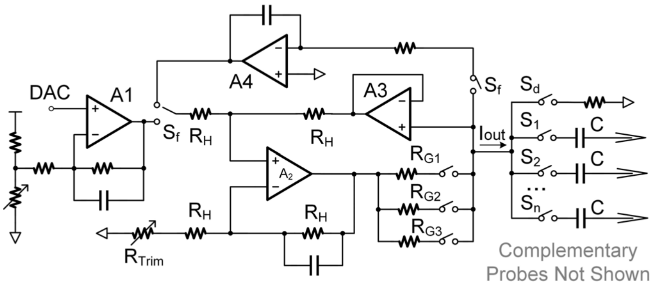


Fig. 3. Circuit schematic for the high compliance voltage current source. Arbitrary stimuli waveform is generated by digital to analog converter. V-to-I gain is programmable to provide high dynamic range.

A on-board micro-controller decodes commands and data from the RF transceiver and uses an 8-bit digital-to-analog converter (DAC) to control the amplitudes, waveform and timing of the output stimulation currents. The high driving current version of the stimulator is powered using 3.7 V lithium-ion batteries (Ultralife UBP002), while the miniature version is powered using a 3.7V polymer lithium-ion battery (Sounddon LP-402025). Dual DC-DC converters are used to provide the high dual supply voltages for the current sources.

D. Body Area Sensors

A multi-functional sensor node has been designed integrating i) a 3-axis accelerometer, which senses animal's motion; ii) a temperature sensor, which measures animal's body temperature; and iii) a general extension port with analog to digital conversion capability. A wild variety of commercial sensors, including flexible sensors, pressure sensors, and motion sensors can be easily integrated in the system through the extension port. Up to 12 multi-functional sensor nodes can work simultaneously in the system, which can be mounted at animal's head, finger tips, forearms and other body regions of interest. The sensor node can be powered by 3 V manganese dioxide lithium coin battery in low power mode. An external surveillance camera with object detection is also integrated in the system for monitoring the behaviors of animals.

E. Computer Interface

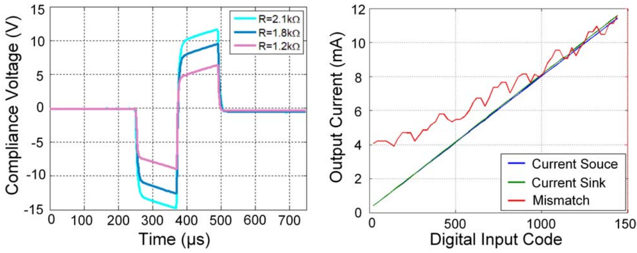
A Matlab-based GUI has been designed for real-time data monitoring, device control and configuration. An interface board was connected to computer via full speed USB 2.0. The board relays and interprets the commands from the GUI and talks to the target device using the corresponding channel via RF link.

There are six major panels of the GUI, including: 1) PC configuration panel, where the communication port can be configured. All the configurations (including other panels) can be exported or loaded; 2) analyzer configuration panel, where the gain, sampling rate/resolution, filter pass-band can be configured for each individual channel. In hardware signal processing modes, the time window size and threshold for spike detection can also be configured; 3) stimulator configuration panel, where the amplitude, pulse width, pulse train number, and time interval of the stimuli can be configured; 4) body-area sensors configuration, where parameters for sensor nodes can be configured; 5) closed-loop configuration, where closed-loop operation between different devices can be configured; 6) display windows, where output from analyzers and sensor nodes can be configured to be displayed in real time in parallel.

III. EXPERIMENTAL RESULTS

A. Bench Testing

Several bench-top tests were performed to evaluate the performance of the proposed system. For the analyzer, the measured input referred noise is 4.72 μV_{rms} in wide band, which is lower than the background thermal noise. The mid-band gain error is 0.87%. The CMRR measured at 1 KHz is 67.4 dB. For the stimulator, the measured compliance voltage in different resistance load is shown in Fig. 4 (a), and the measured output current from the positive and negative current sources and the mismatches are shown in Fig. 4 (b). For wireless communication, a lower than 10^{-3} BER is



(a) (b)

Fig. 4. Bench test of stimulators. (a) measured compliance voltages under fixed current and different resistance loads; (b) measured Output versus digital input codes and mismatch between the positive and negative current sources.

measured in a distance of 3m in a normal animal experiment environment.

B. *In Vivo Testing*

To further evaluate the PennBMBI, we performed several basic tests of wireless neural recording, stimulating and sensing functions in both anesthetized and awake rats. Neural recording was performed in an anesthetized rat with a tungsten microelectrode placed in whisker motor cortex. The analyzer was configured to have a passband of 300∼6KHz, a sampling rate of 21 KSps, and a gain of 72dB. The recorded action potentials (APs) are shown in Fig. 5. In order to evaluate the quality of the captured data, the neural signal was simultaneously recorded by a rack-mounted commercial system (RZ2 Workstation, Tucker-Davis Technologies). A comparison of the signals recorded by the two systems is shown in Fig. 6 (a). The recording shows two different neurons firing APs in close succession. A cluster analysis of the APs recorded by the PennBMBI analyzer, demonstrating the stereotyped AP waveform shape of the two neurons, is shown in Fig. 6 (b).

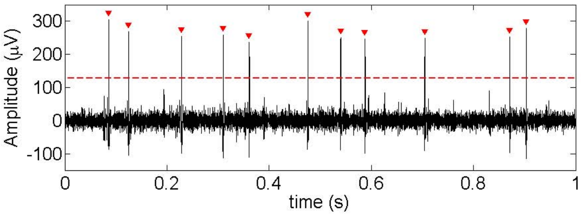
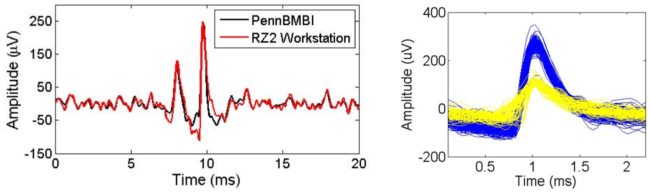


Fig. 5. Action potentials recorded by the neural signal analyzer. Detected spikes are marked by red triangles.



(a) (b)

Fig. 6. (a) Comparison between data captured by the PennBMBI analyzer (black) and RZ2 Neurophysiology Workstation (red). (b) a cluster analysis of the APs recorded by the PennBMBI analyzer.

To demonstrate the sensor and stimulator nodes, an awake rat with a chronically implanted stimulating microelectrode in the lateral hypothalamus was placed in an operant conditioning chamber with a lever press. The sensor node detected the lever press and wireless sent a trigger to the stimulator worn on the rats back to deliver a stimulus train (30 of $100\mu A$, $200\mu s$ constant current pulses) to the microelectrode. This setup allowed the rat to associate the lever press with the rewarding sensation of hypothalamic stimulation.

IV. CONCLUSION

This paper proposed a portable wireless Brain-Machine-Brain Interface (BMBI) system links the brain to external hardware, creating new sensory and motor pathways to neural signal studies. Four kinds of devices: i) neural signal analyzer, ii) neural stimulators, iii) multiple sensor nodes, and iv) PC interface are implemented in the system. All the devices can be wirelessly configured with a user-friendly graphic interface. A system summary of the proposed design as well as a comparison with reported works are listed in table I. Bench tests evaluate the performance of the proposed system, and *in vivo* experiments illustrate a close-loop application of the system. The tests demonstrated the basic neural recording and stimulating function of the system. Future tests will focus on demonstrating the intended therapeutic function of the PennBMBI; namely linking the brain to external hardware to create new sensory and motor pathways.

TABLE I
SYSTEM SUMMARY AND COMPARISON TO OTHER WORKS

Features	[8]	[7]	[3]	This Work
Year	2011	2011	2013	2013
Recordor	3 unipolar bipolar	4 bipolar	100 unipolar	4 unipolar/bipolar
Adjustable gain/filter	Yes	Yes	No	Yes
Hardware signal processing	Spike detection	Spike detection	N/A	Spike detection Feature extraction Compressed sensing
Stimulator	3 unipolar bipolar	4 bipolar	N/A	6 & 2 unipolar/bipolar
Body-area sensors	Acceler-ometer	N/A	N/A	Accelerometer Pressure sensor Temperature sensor Surveillance camera
Wireless link	N/A	N/A	24 Mbps	2 Mbps
Flash memory	Yes	N/A	N/A	Yes
GUI	Yes	N/A	N/A	Yes
Closed-loop operation	Recording -Stimulating	Recording -Stimulating	No	Recording-Stimulating Sensor-Stimulating

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