Annual Report to Catalyst Foundation

Project: Design of a Low Power Smart Glove for Sensor-Brain-Interface to Reconstruct Somatosensory Feedback and Gestures

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I. Introduction

The sense of touch and proprioception are critical to movement control [1, 2]. Paralysis of the arm robs us of fundamental skills and prevents even basic activities of daily living. Neuroprosthetics is an emerging field of research aims to allow patients to use prosthesis or other artificial devices from decoding the patients' neural signals. However, motor neuroprosthetics would not yield the desired functionality without sensation feedback. Thus a bidirectional sensorimotor neuroprosthesis is required. This project develops a sensor-brain interface (SBI), which can restore the sense of touch and the sense of movement in a paralyzed hand.

An ultra-low power, wireless, wearable SBI system has been developed. The system consists of (1) ultra-low power sensor nodes, which sense the tactile signal from hands, (2) a central processing unit, which converts the signal into electrical stimulation patterns through the use of machine learning, and transmits the commands to (3) an implantable neural stimulator, which conveys the sensory signal to the brain through micro-stimulation of the somatosensory brain areas.

II. System and Circuit Implementation

The overall architecture of the designed SBI system is shown in Fig. 1. The main building blocks of the system include: BMI device, sensors, and computer with user interface. The system can be configured to work in various closed-loop operating modes.

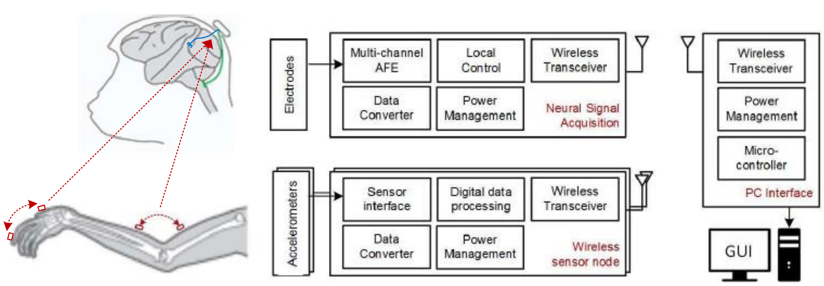

Fig. 1 The SBI system mainly consists of the wearable sensors, neural recorder and neural stimulator.

As the core part the BMI system, the BMI device features a bi-directional neural interface with bi-directional wireless communication. The bi-directional neural interface enables both neural signal recording and electrical neural stimulation. The bi-directional wireless communication allows the BMI device to send data back to the computer, and read commands from the computer or sensor nodes. In addition, the BMI device can process certain neural feature extraction and some pre-defined closed-loop algorithms. The BMI device will be housed in a secure chamber fixed on the animals' skull, or housed in a customized jacket the animal can. A prototype chip of the wireless BMI is shown in Fig. 2(a).

Sensor is another important element in the system. There are mainly two types of sensors: wearable sensors and surveillance sensors. Wearable sensors may include pressure sensor, flex sensor, accelerometers, goniometer, etc. A sensor node is built using commercial sensors and wireless transceiver. Surveillance sensors mainly include a video recorder and a motion tracking sensor, which can be designed in CMOS technology. A prototype chip of the wireless body area sensor is shown in Fig. 2(b).

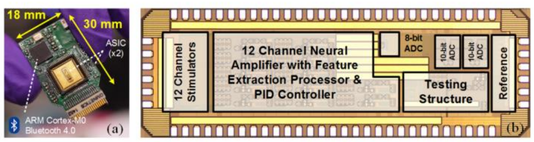

TABLE I
SPECIFICATIONS SUMMARY

Analog Front-end		ADC (Volt Mode/CurrMode)	
LNA Gain	40dB	Sampling Rate	1MSps/250KSps
LNA Bandwidth	0.5 - 10kHz	ENOB	9.1/7.9
LNA Noise	3.02uV	FoM(fJ/step)	34.2/10.7
NEF	3.72	**Stimulator**	
Energy Extraction		Max. Stim. Current	4mA or 250uA
3dB filter	100 - 5kHz	Amplitude Res.	6-bit
Stagger tuning	1Hz - 200Hz	Pulse width	1us - 250us
Quality Factor	0.5 - 32	**Power**	
Window length	10 - 500ms	LNA + PGA	20uW per Ch.
Action Potential Discriminator		Energy Detection + PID	1uW per Ch.
Thresholds	6-bit	Stimulator (standby)	2uW
Latency	10us	Total (avg.)	276uW (12 Ch.)

(a)

Chip Performance

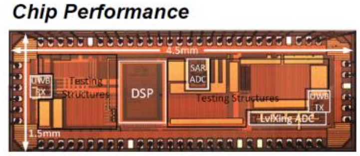

Figure: Wireless electrogoniometer chip photo

Table: Chip performance summary

Fabrication Process	180nm CMOS
Total Area	$0.73mm^2$
Level-Crossing ADC Supply	0.8-2.0V
Level-Crossing ADC Power	8.92uW @ 0.8V
Level-Crossing ADC FOM	13pJ/Conv.
IR-UWB Transceiver Supply	0.8-2.0V
IR-UWB Transceiver FOM	0.32nJ/bit
Electrogoniometer Resolution	4bits

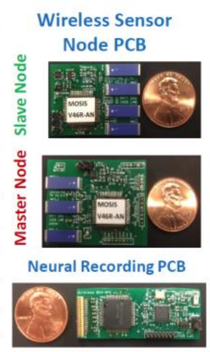

Figure: The master node is battery powered. The slave node is powered by RF energy harvesting.

(b)

Fig. 2 (a) A wireless bi-directional BMI chip, device and die photo, and table of testing specifications. (b) A wireless body area sensor chip, device and table of testing specifications.

III. Experimental Results

The designed chips have been used in animal experiments [3]. Neural recording was performed in an anesthetized monkey with a multi-channel, high-density electrodes array implanted in the brain stem for neural recordings from a large populations of neurons. One of the sensor nodes is mounted on the chest, while the other is mounted on the upper arm.

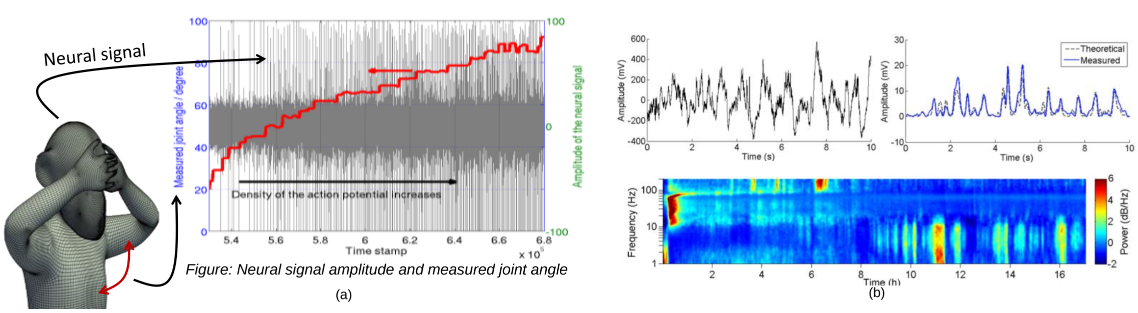

Figure: Neural signal amplitude and measured joint angle

(a) (b)

Fig. 3 (a) In-vivo experiment on a monkey. Action potential signal was measured together with joint angle. (b) In-vivo long term recording and stimulation in a monkey with LFP feature extraction.

A joint angle as well as the accumulated counts of the captured action potentials in every 0.4s intervals, as illustrated in Fig. 3(a). Long term neural signal recording has been conducted using the designed chip. The LFP energy was extracted in real time, as shown in Fig. 3(b).

IV. Key Accomplishments:

This project have achieved significant progress so far. The wireless SBI system is one of the world's first wireless SBI system that is capable for performing closed-loop neural prosthetics experiments with feedback. Animal experiments are being conducted using the devices developed in this project, with more investigation results to be expected. The preliminary results from this project have been presented and published on ISCAS, BioCAS, EMBC, ISSCC SRP, and journals including TCAS and TBioCAS. This work has also won the best paper award (1st Place) on the BioCAS 2016. The supported student received the IEEE Solid-State Circuits Society (SSCS) 2015-16 pre-doctoral achievement award.

Publications:

[1] Liu, X., Zhang, M., Subei, B., Richardson, A. G., Lucas, T. H., & Spiegel, J. Van Der. (2015). The PennBMBI: Design of a General Purpose Wireless Brain-Machine-Brain Interface System. Biomedical Circuits and Systems, IEEE Transactions on, 9(2), 248–258.

[2] Sritharan, S. Y., Richardson, A. G., Weigand, P. K., Planell-mendez, I., Liu, X., Zhu, H., Lucas, T. H. (2016). Somatosensory Encoding with Cuneate Nucleus Microstimulation: Detection of Artificial Stimuli. Accepted for EMBC.

[3] Liu, X., Zhang, M., Richardson, A. G., Lucas, T. H., & Spiegel, J. Van Der. (2015). A 12-Channel Bidirectional Neural Interface Chip with Integrated Channel-level Feature Extraction and PID Controller for Closed-loop Operation. In BioCAS (pp. 8–11).

[4] Richardson, A. G., Attiah, M. A., Berman, J. I., Chen, H. I., Liu, X., Zhang, M., Lucas, T. H. (2016). The effects of acute cortical somatosensory deafferentation on grip force control. Cortex, 74, 1–8.

[5] X. Liu, et al, "A Fully Integrated Wireless Compressed Sensing Neural Signal Acquisition System for Chronic Recording and Brain Machine Interface", Biomedical Circuits and Systems, IEEE Transactions on (TBioCAS), accepted for publica-tion. (Invited paper)

[6] X. Liu, et al, "Design of a Closed-loop, Bi-directional Brain Machine Interface System with Energy Efficient Neural Fea-ture Extraction and PID control", Biomedical Circuits and Systems, IEEE Transactions on (TBioCAS), accepted for pub-lication. (Invited paper)

[7] X. Liu, et al, "The Virtual Trackpad: an Electromyography-based, Wireless, Real-time, Low-Power, Embedded Hand Gesture Recognition System using an Event-driven Artificial Neural Network," Circuits and Systems II, IEEE Transactions on (TCAS-II), accepted for publication.