# A Wireless Neuroprosthetic for Augmenting Perception Through Modulated Electrical Stimulation of Somatosensory Cortex

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***Abstract*—This paper presents a novel neuroprosthetic system for perception encoding. The system consists of a wireless waterproof bi-directional neural interface and an object tracking image sensor. The neural interface features a fully programmable 8-channel neural stimulator, a compliance voltage and impedance monitoring module, a 16-channel neural recording front-end, and a duplex wireless transceiver. The image sensor features a 180×180 pixel array, with in-pixel comparator for energy efficient color thresholding based object detection tracking. A unique experiment was designed in which rats navigate a water maze using only brain stimulation to inform their location relative to a hidden platform. Custom hardware and software have been developed to support the investigation, with special attention paid to the safety of the animals during the experiment. The proposed chip designs have been fabricated in 180nm CMOS technology. This work demonstrates a novel experimental paradigm, and that the developed wireless neuroprosthetic system can be used to conduct extensive sensory encoding experiments in freely behaving animals.**

***Index Terms*—Brain Machine Interface (BMI), neuroprosthetic, electrical stimulation, bi-directional neural interface**

## I. Introduction

Sensory feedback is essential for goal-directed behavior. Loss of sensation due to nerve damage prevents even basic activities of daily living. Even though many recently developed brain-controlled prosthetics successfully replaced motor pathways, somatosensory feedback is critical for paralyzed individuals to adequately use them. Recently, there has been increasing interest in conveying lost sensory information through direct brain stimulation using a neuroprosthetic device [1]. This strategy relies on the brain learning to use artificial stimuli to inform actions. A common paradigm to study this learning process involves using brain stimulation to guide rats through a maze [2]. These so-called “rat-robot” studies have mapped a number of different navigation signals to brain stimulation [3, 4]. All used land-based mazes with a discrete number of actions and goal locations. A concern with these studies is that the rats could simply memorize a few stimulus-response contingencies rather than learn a more generalized stimulus-dependent navigation strategy [4].

In this work, we developed a new rat-robot paradigm using a classic test of rodent navigation: the Morris water maze (MWM) [5]. In the MWM, the rat swims in a large circular tank looking for a hidden, submerged platform on which to stand. In our task, the submerged platform was positioned randomly on each trial to dissociate visual cues from the platform location. The rats navigated to the platform using only the sensation encoded from the brain stimulation. The experiment setup is illustrated in Fig. 1. Custom hardware and software were developed for this experiment. Our findings suggest that rats can quickly interpret artificial percepts to guide behavior, which is important for sensorimotor neuroprostheses.

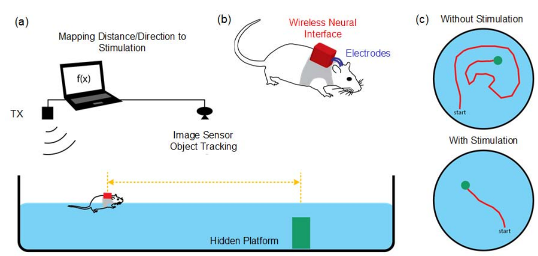


Fig. 1. Illustration of the developed perception augmentation experiment. (a) shows a rat wearing the developed wireless waterproof neuroprosthetic. The electrodes are chronically implanted in the somatosensory cortex. (b) shows the experiment setup. A rat navigates to a hidden platform using only the perception established from the stimulation. (c) illustrates the estimated rat's swimming traces with/without the simulation guidance.

This paper is organized as follows. Section II presents an overview of the system. Section III describes the hardware implementation of the system, including the wireless neuroprosthetic and the object tracking image sensor. The software implementation is presented in section IV. Section V shows the experimental results, while section VI concludes the paper.

## II. System Overview

Fig. 2 shows the block diagram of the overall system. The system consists of a wireless neuroprosthetic device, an object tracking image sensor, and a computer with a user interface. The developed wireless neuroprosthetic includes a custom designed integrated circuit chip and off-the-shelf electronics.

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The integrated circuit chip consists of i) an 8-channel neural stimulator, ii) a 16-channel neural recording front-end, iii) an analog-to-digital converter (ADC), iv) a digital signal processor, and v) a timing and logic control circuit. The off-the-shelf electronics includes i) a general purpose low-power microcontroller, ii) a 2.4GHz wireless transceiver, iii) battery and power management units.

The object tracking image sensor mainly consists of i) a $180\times180$ pixel array with in-pixel comparator and event generation unit, ii) row and column control chains, iii) an object detection module, and iv) an ADC. The computer interfaces with the image sensor through an FPGA, and communicates with the neuroprosthetic through a wireless dongle.

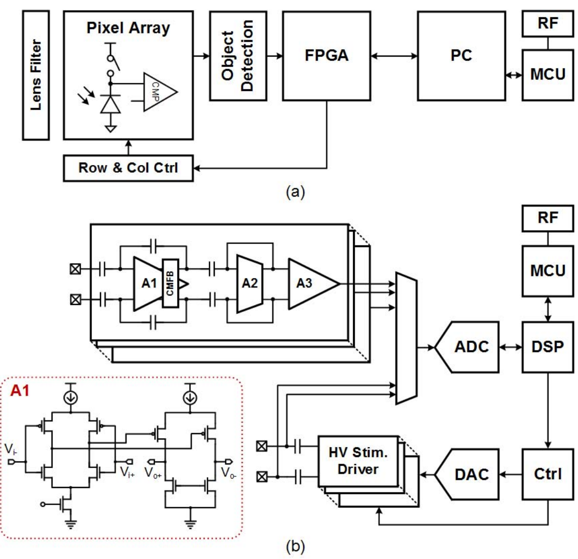


Fig. 2. The block diagram for the neuroprosthetic system. (a) shows the proposed object tracking image sensor and the computer with wireless dongle, and (b) shows the wireless bi-directional neural interface. The circuit schematic of the fully differential neural amplifier is shown in the box.

## III. Hardware Implementation

### A. The Wireless Neuroprosthetic

The 8-channel neural stimulator is capable of delivering unipolar or bipolar charge-balanced current pulses with programmable pulse width, amplitude, pulse train frequency and latency. When configured for bipolar stimulation, two arbitrary channels can be selected from the 8 channels to drive the cathodic and anodic electrodes. A 6-bit current mode DAC is shared between the channels. The output current is programmable from 0 to 255uA. Regulating amplifiers are used to increase the output impedance of the current sink and source. The electrodes of the stimulator are multiplexed to the ADC. The compliance voltages of the electrodes are measured at the beginning and the end of the stimulation phase, as shown in Fig. 3. The spreading resistance can be estimated by $R_s = V_1/I_S$, where $V_1$ is the voltage between the two electrodes at the beginning of the stimulating phase, and $I_S$ is the stimulation current. An impedance baseline is measured every time before an experiment. During the experiment, if $V_1$ is much less than the baseline compliance voltage, it indicates that the equivalent resistance between the electrodes drops significantly, possibly because the electrodes are shorted by water. The experiment should stop since little current is actually passing between the electrodes. On the other hand, if $V_1$ is much larger than the baseline, the electrodes may lose connection with the tissue, or a much larger current than the designed value is passing the tissue, possibly because of an electronic failure. The experiment must be halted in both cases to keep the animal safe from tissue damage.

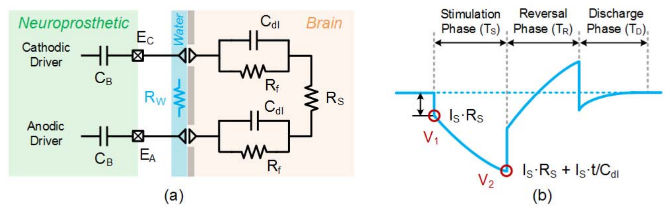


Fig. 3. (a) The equivalent circuit model for the electrode interface. (b) A typical stimulation waveform between the electrodes $E_A$ and $E_C$. Compliance voltages at the beginning and end of the stimulation phase are measured for estimating the impedance.

The neural recording channel consists of a fully-differential capacitor-coupled low-noise amplifier A1, a gm-C based high-pass filter A2, and a programmable gain amplifier A3. The output of each channel is multiplexed to the shared ADC. The input capacitors of A1 block the large electrode offset and half-cell potential from the interface. A maximum input range is important in this work given the large stimulation artifacts. A complementary input stage is designed to achieve the optimal power and noise efficiency. The overall gain of the recording channel is programmable from 400 to 2000. A 10-bit successive approximation register (SAR) ADC is implemented for signal digitization. A split capacitor array is used to reduce the area and power consumption. Monotonic switching procedure is used to minimize the power consumption resulting from unnecessary switching [7].

The microcontroller used in this neuroprosthetic device is an 8/16-bit Atmel XMEGA microcontroller, and the wireless module is nRF24l01+ from Nordic Semiconductor. The overall neuroprosthetic device is coated with silicon to be waterproof. A cable with waterproof connector is used for mating with the implanted electrodes. Two LEDs are designed for illustrating the status of the device for debugging purposes.

### B. The Object Tracking Image Sensor

The block diagram of the image sensor has been illustrated in Fig. 2. The image sensor has three operating modes: i) the video output mode, ii) the object tracking mode, and iii) the region-of-interest readout mode. The circuit schematic of the pixel is shown in Fig. 4. During the experiment, the rat's jacket is dyed to be red, and a red color filter is set in front of the lens.

In the video output mode, the image sensor continuously captures frames in full-resolution. The rolling shutter sequence is used for pixel exposure and readout. An on-chip 10-bit ADC

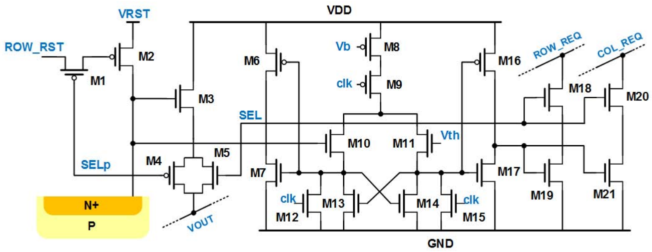


Fig. 4. The photo-diode and the in-pixel intensity thresholding circuit. When the intensity crosses the threshold, an event signal is generated and combines with all the other pixels in the same row and column in a wired-OR logic.

is used for intensity digitization. In the object tracking mode, each pixel's output is a 1-bit comparison result with a pre-defined threshold. The global shutter is used in the object tracking mode. Once a high intensity is detected in a pixel, an event signal is generated and combines with all the other pixels in the row and column in a wired-OR logic. The output registers buffer the outputs, and are used as the addresses for the detected object. In practice, the addresses are sent off-chip and filtered by a one-dimensional Gaussian smooth filter in the FPGA to suppress the noise in the detection [6]. The center address of the detected area is used as the location of the subject in the frame. In the ROI readout mode, a global-shutter object detection is first used for identifying the location of the animal, and a rolling shutter readout is only performed within the addresses corresponding to the animal's position..

## IV. Software Implementation

The software is developed using Matlab on the computer, and C language on the microcontroller. The flowchart of the computer program is shown in Fig. 5 (a). The program mainly has three operation modes, i) the testing mode ii) the animal training mode, and iii) the experiment mode. The

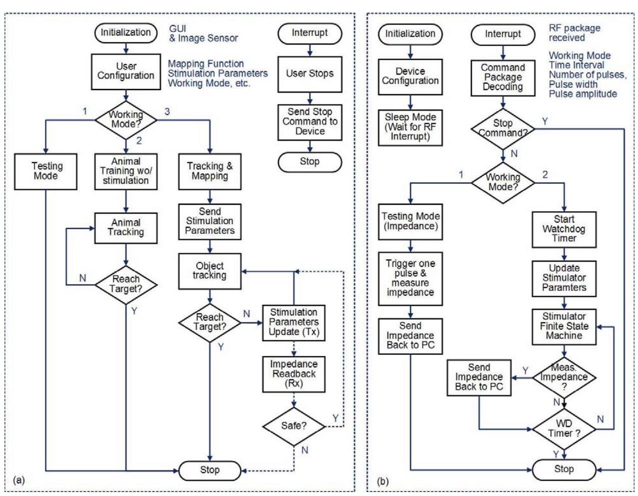


Fig. 5. The flowchart of (a) the computer program, and the (b) neuroprosthetic device.

testing mode includes both wireless communication test and electrode impedance test. Both tests need to be run every time before the animal is set into the water for the experiment. In the animal training mode, the image sensor tracks the rat swimming but no stimulation is delivered. In the experiment mode, the image sensor tracks the rat swimming, and the computer maps the location and/or direction of the rat to a stimulation sequence. The established mapping algorithms include i) binary mapping, ii) linear mapping and iii) Gaussian mapping. In the binary mapping, the rat receives a simulation train only if it's heading towards the hidden platform. In the linear mapping, the simulation frequency is modulated by the distance between the rat's location and the platform in a linear relation, as

$$f_{stim} = \alpha \cdot \sqrt{(x-x_0)^2 + (y-y_0)^2} + \beta \qquad (1)$$

where $x$, $y$ are the location of the rat, $x_0$, $y_0$ are the location of the platform. $\alpha$ is the gain factor, and $\beta$ is the offset parameter. Notice that if $\alpha$ is positive, the rat receives a higher frequency stimulation when it swims away from the target. If $\alpha$ is negative, it receives higher stimulation frequency when it swims towards the platform. The offset $\beta$ should be set so that the stimulation frequency is a positive parameter in the range of 0.5Hz to 300Hz. In the Gaussian mapping, the animal's distance to the platform maps to the stimulation frequency according to the Gaussian distribution, as

$$f_{stim} = f_{max} \cdot e^{-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2}} \qquad (2)$$

where $f_{max}$ is the designed maximum frequency, and $\sigma$ is the standard deviation.

The computer program updates 10 frames per second, and sends the updated stimulation parameters to the wireless neuroprosthetic. The program stops when the animal reaches the hidden platform. The user can set the radius of the target. The program checks the load impedance, and the experiment stops immediately if the measured impedance or compliance voltage is out of the safe range.

An interrupt service also allows the user to stop the experiment at any time. The program always sends the stop command to halt the stimulation before the computer program ends. A friendly user interface has been designed for controlling the experiment. Besides the mapping functions, the user can configure the program to save the animal's location and time stamps for each frame, stimulation parameters, measured compliance voltage and impedance, and all the program setups.

The flowchart of the neuroprosthetic device is shown in Fig. 5 (b). The program has a main routine and an interrupt service routine. After powering on, the device performs the initializations. The wireless module will be configured in the receiving mode and then the CPU will be put in the sleep mode to lower the power consumption. Once an RF package is received, the device first checks if this is a stop command. If the stop command is received, the device disconnects the output driver from the electrodes to prevent any potential damage to the animal. Then the device sends back to the computer indicating the stop command has been executed. The stop command is also used for testing the wireless communication. A wireless communication is established if the computer can successfully read back the response from the device. The computer program retries to establish the wireless handshake ten times before timeout.

If the received package is not a stop command, the device checks the working mode, and performs accordingly. In the impedance testing mode, the device delivers a pulse train and signals back the compliance voltage. In the normal experiment mode, a watchdog timer is first started. The timer counts 6 seconds, and if no new RF package is received, the stimulation stops. This is to prevent the failure of wireless communication during an experiment. The DAC will be set according to the stimulation amplitude, and the local finite state machine will be set according to the timing parameters. The stimulator will run according to the current time interval until the next command is received.

## V. Experimental Results

The proposed ASIC design has been fabricated in IBM 180nm standard CMOS technology. The object tracking image sensor occupies a silicon area of 2.3mm×2.3mm. The microphotograph of the fabricated chip is shown in Fig. 6 (a), with a layout of one pixel. The bi-directional neuroprosthetic chip microphotograph is shown in Fig. 6 (b), with major building blocks highlighted. The measured performance of the system is listed in Table I.

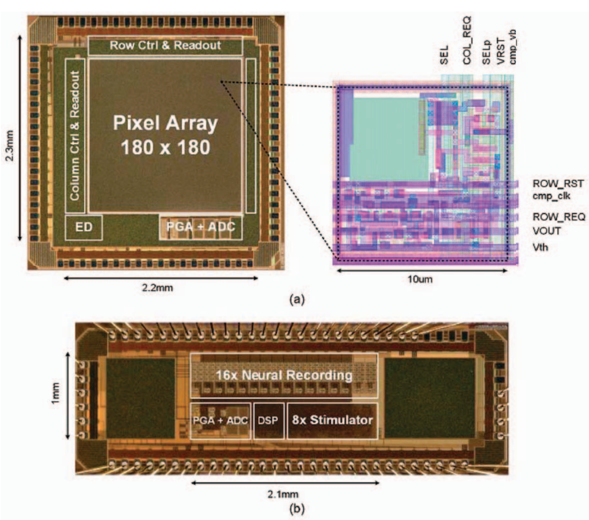


Fig. 6. The microphotograph of the (a) fabricated object tracking image sensor, and the layout of a pixel with embedded motion detection unit. The pixel size is 10$\mu$m by 10$\mu$m, with a fill factor of 23%. (b) The microphotography of the bi-directional neural interface.

Fig. 7 (a) shows a prototype of the wireless waterproof neuroprosthetic, and (b) shows a rat wearing the device. Initially, the rats swam in random directions until the platform was found or the trial timed out (60 s). A typical example of the swimming trace before the simulation is shown in Fig. 7 (c-1). The performance significantly improved over the course of about 50 trials, as illustrated in Fig. 7 (c-2). Poor performance on catch trials, in which no stimulation was delivered, confirmed that the learned behaviors were guided by

TABLE I
Measured Specifications Summary

| Analog | | Image Sensor | |
|---|---|---|---|
| LNA Gain | 40dB | Pixel Array | 180×180 |
| LNA Bandwidth | 0.5Hz - 7kHz | Pixel Size | 10$\mu$m×10$\mu$m |
| LNA Noise | 2.85$\mu$V | Fill Factor | 23% |
| LNA NEF/PEF | 1.58/4.5 | Dynamic Range | 47.1dB |
| ADC Fs | 1MSps | ADC Fs | 5MSps |
| ADC ENOB | 9.1 | Frame Rate | <100 Frames/s |
| **Neural Stimulator** | | **Wireless Neuroprosthetic Device** | |
| Stim. Current | 1-255uA | Device dimension | 25×20×15 mm |
| Amplitude Res. | 6-bit | Device weight | 12g |
| Pulse width | 1$\mu$s - 250$\mu$s | Wireless coverage | 10m indoor |
| Stim. Frequency | 0.5Hz - 300Hz | Battery life | >2hours |

the stimulation. The experimental results suggest that animals can quickly interpret artificial percepts to guide behavior, which is important for sensorimotor neuroprostheses.

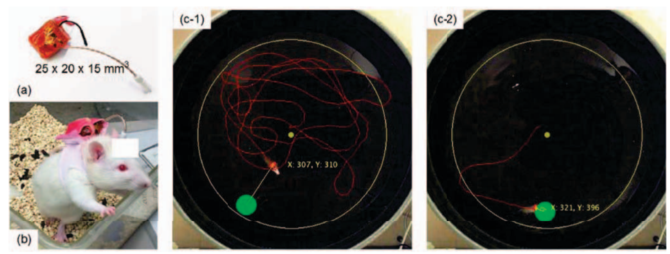


Fig. 7. The *In-Vivo* experimental results. (a) shows the prototype wireless neuroprosthetic with silicon coating, and (b) shows a rat wearing the wireless neuroprosthetic. (c-1&2) are webcam captured frames during the experiments. The small yellow and large green circles indicates the start and platform locations, respectively. These were superimposed on the video frame and not visible to the rat. (c-1) shows the swimming trace of the rat without the simulation, and (c-2) shows the swimming trace with the simulation guidance.

## VI. Conclusion

In this work, a wireless waterproof neuroprosthetic and an object tracking image sensor have been developed. The design features failure prevention mechanism for animal safety. A custom software framework has also been developed to support the experiment, including a user-friendly computer interface. With the fully programmable wireless interface to the neuroprosthetic, the developed system can be used as a general purpose platform for investigating different sensory encoding experiments in freely behaving animals.

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