A portable system for recording neural activity in indoor and outdoor environments.

Farhan Baluch[1] and Laurent Itti[2]

***Abstract*— We present a self-contained portable USB based device that can amplify and record small bioelectric signals from insects and animals. The system combines a purpose built low noise amplifier with off the shelf components to provide a low cost low power system for recording electrophysiological signals. Using open source software the system is programmed as a simple USB device and can be connected to any USB capable computer for recording data. This simple and universal interface provides the ability to connect to a variety of systems. Open source acquisition software was also written to record signals under the linux operating system. Performance analysis shows that our device is able to record good quality signals both indoors and outdoors and delivers this performance at a very low cost. Compared to larger systems our device provides the additional advantage of portability given that it can fit into a pocket and costs a fraction of large systems used in electrophysiology labs.**

I. INTRODUCTION

Since the first recordings made by Galvani in the 1770's measuring bioelectric signals in animals has been one of the key methods in neuroscience to understand how neural activity gives rise to behavior. Recent efforts in prosthetics used to restore various bodily functions have also relied on recordings from multiple neurons in the central and peripheral nervous systems (CNS & PNS) [1]. Systems long used in the laboratory for making such recordings are composed of large amplifiers and digitizers that are both expensive and not suited to use in outdoor or mobile environments.

Recent advances in analog integrated circuit (IC) design have allowed much smaller systems to be built [2]. Much focus has been on wireless systems which now have achieved remarkable miniaturization in size and maximization of efficiency using low power designs [3], [4], [5], [6], [7]. While many of these systems are capable of recording from multiple neurons for extended periods of time much experimentation continues to be performed on larger systems in the laboratory. There has been a limited effort in building portable self-contained general-purpose systems that bypass the difficulties associated with wireless neural telemetry.

Here we present a portable low-cost multi-channel neural recording device that can transmit up to 16 channels of neural data over Universal Serial Bus (USB). The system is small in size and uses off-the-shelf components together with open-source software providing a simple low cost solution to providing high quality recordings of small bioelectric signals.

[1]F. Baluch is with Neuroscience Graduate Program, University of Southern California, Los Angeles, CA 90089 `fbaluch@usc.edu`

[2]L. Itti is with the Neuroscience Graduate Program and the faculty of the Dept. of Computer Science, Viterbi School of Engineering, University of Southern California, Los Angeles, CA, 90089 `itti@usc.edu`

We have tested the system in indoor and outdoor conditions recording from an identified locust visual neuron. The system yields results that are comparable to much larger systems.

II. SYSTEM DESIGN

A. Hardware

The device is a custom printed circuit board (PCB) measuring 60mm X 30mm with its components and weighs only 10.7 grams. The three main components of the system are a neural amplifier chip RHA 2116 (Intan tech.), a fast 16-bit parallel analog digital converter ADS8401 (Texas instruments.) and a RISC-based microcontroller AT90USB1287 (Atmel inc.) with native USB 2.0 support.

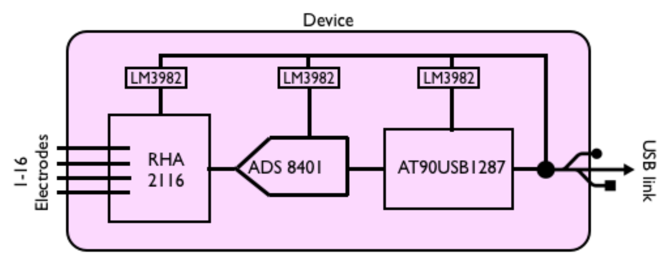


Fig. 1. High level Schematic of portable electrophysiology device with 3 major components. RHA2116 (Intan tech.) is the neural amplifier with 16 channels, ADS8401 (Texas Instruments) is the ADC, AT90USB1287 (Atmel) microcontroller and linear regulators LM3982 (National Instruments inc.).

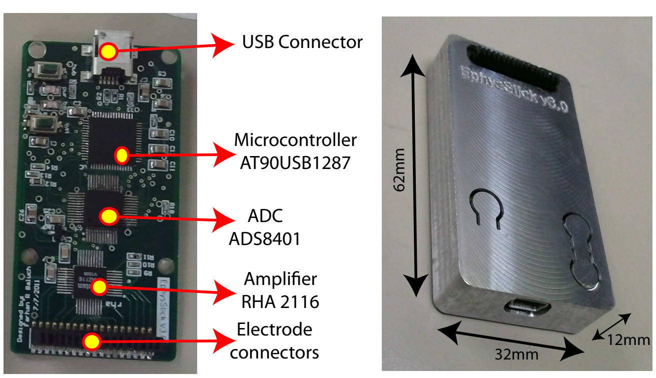
Fig. 1 provides a high level schematic of the device. Up to 16 electrodes can be attached to the device and feed straight into a low noise amplifier (RHA 2116) that provides amplification with a gain of 200 and common mode rejection ratio (CMRR) of 82dB and a power supply rejection ratio (PSRR) of 75dB. The amplifier provides adjustable low and high frequency cutoffs these were set at 10Hz and 10kHz respectively. The amplified signals are fed to a fast (1.25 MSPS) ADC that converts the analog to a digital one with 16 bit resolution. The ADC uses a high precision band gap external reference. After conversion the signal is passed to the microcontroller that packages the data and sends it over USB at 12Mbps.

The total cost of building the device was $521 and the breakdown of the costs is presented in table I. This is significantly lower than traditional rack mount systems used in laboratories conducting electrophysiological experiments that cost thousands of dollars. As discussed in the experimental results section our device is able to record physiological signals that are comparable to much larger systems and does so at a fraction of the cost, while additionally providing portability.

TABLE I
MAIN COMPONENTS AND ASSOCIATED COST

Component	**Description**	**Cost**
RHA2116	16-Channel amplifier	$360
ADS 8401	16 bit ADC	$16
AT90USB1287	Microcontroller	$12
LP3982	CMOS regulator	$1x3
PCB	PCB manufacturing	$100
Other parts	Capacitors, resistors, etc.	$30
Total cost		**$521**

The PCB is a 4-layer board with the data signals running along the top and bottom layers and power and ground lines sandwiched in the middle. Individual ground and power planes ensure that common mode EMI is reduced to a minimum. The board is powered via USB and this may introduce noise in the power supply. To minimize this source of noise each major component has a dedicated linear regulator to provide a steady power supply and bypass capacitors are used to ensure stable power supply to each chip. The amplifier operates at 3.3V while the ADC and microcontroller require 5V supply. The power layer of the PCB consists of 3 planes one serving each component and its respective supporting capacitors and resistors. The ground layer is split into digital and analog ground planes the two being connected by a 0 Ohm resistor. The analog ground is connected to a pin for connection to the body of the animal being experimented upon.



(a) (b)

Fig. 2. (a) shows the PCB with all the major components including microcontroller, ADC, amplifier, electrode connectors etc. (b) shows the device in its aluminum case which provides both electrical and physical shielding for the device. The dimensions provide a sense of the small size of the device when enclosed in its casing.

A custom aluminum housing was designed and constructed to enclose the device and provide shielding. The housing, shown in Fig. 2 (b), shields the device from interference as well as providing protection from physical damage during outdoor or other out of laboratory recordings.

B. Software

There are two parts to the software development effort that enable the device to provide flexible functionality. The system consists of custom firmware written in C/C++. The firmware makes use of an open source USB stack [8] and is programmed as a USB Audio Input class device that uses the isochronous USB transfer mode [9]. This mode ensures that a pre-selected data rate is maintained throughout the transfer period and this rate is pre-negotiated with the host device (computer). Using this method we can select from a wide range of sampling rates from 100Hz to 44.1kHz depending upon the sound card available on the computer. While we tested the device using the full speed mode that provides a data rate 12Mbps, rates of up to 480Mbps (USB high-speed mode) are supported by the microprocessor.

The advantage of programming the device as a simple USB based audio input device is that any available program for sound recording can be used to record data. However, for optimization we wrote a custom open-source data acquisition software in C++ to access the raw data from the device and store it to a file readable in MATLAB (Mathworks Inc.). Data from multiple channels are multiplexed and we perform low pass filtering between (300 - 5000Hz) to ensure that bursts of spikes from the nervous system of animals are retained while eliminating external noise. The acquisition software is open source and easily accessible as part of the iLab neuromorphic vision toolkit (iNVT) available at http://ilab.usc.edu/toolkit.

III. EXPERIMENTAL RESULTS

A. Performance characteristics

The device provides stable performance utilizing 45.1mW when run with a single channel at 20kHz sampling rate. Fig. 3 shows the manner in which power consumption changes with increasing number of channels and sampling rate.

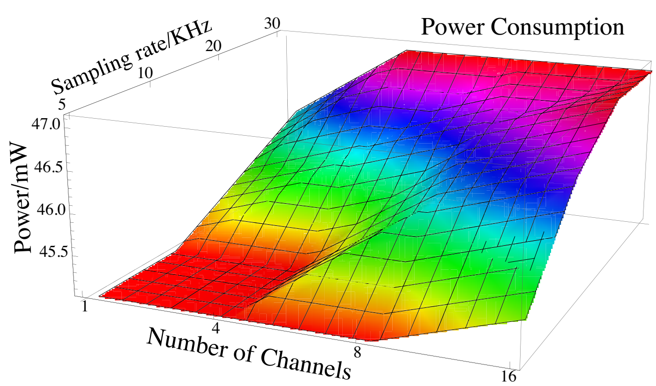


Fig. 3. Performance Characteristics of the device. The plot shows the power consumption of the device as a function of number of channels and sampling frequency.

The power consumption rises as the number of channels and sampling rate increases. The device consumes a maximum of 47.1mW when recording 16 channels at 30Khz. On average the device consumes very low power and is therefore suited for portable and outdoor use for extended periods of time given a portable or handheld computer is available.

B. Electrophysiological recordings

The system was tested by obtaining recordings from the locust nervous system. An identified neuron the DCMD (descending contralateral movement detector) in the locust responds robustly to looming stimuli. Simulations of looming objects presented on a computer monitor also evoke robust responses in this neuron [10]. Adult female locusts (*Schistocerca americana*) were used in these experiments. Teflon coated Stablohm wires of $50\mu m$ diameter (California Fine wire, Grover Beach, CA) were prepared for extracellular recordings by removing the coating at the desired recording site and shaping the wire into a hook. Two such electrodes were then surgical implanted around the nerve cord between the pro and mesothoracic ganglia with a small separation in the position of the two electrodes. One electrode serves as the signal wire and one as the reference. The ground wire was attached to the outside of the animal to minimize EMG (electromyogram) noise from wing beats and animal movement. When well grounded the peak-to-peak noise is between $5 - 8\mu V$.

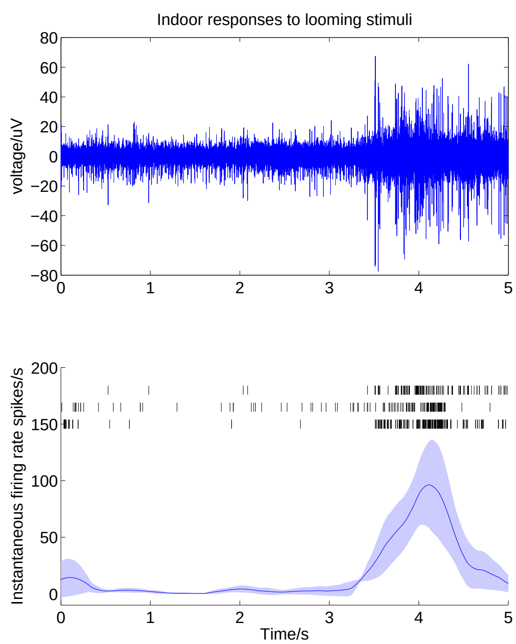


Fig. 4. Indoor recordings from locust DCMD neuron. Top shows an example trace from one recording. Bottom shows the average instantaneous firing rate along with the standard deviation shown by the shaded region. The top raster shows the 3 sample recordings from which the average was computed.

1) Indoor electrophysiological recording results: Indoor experiments were conducted with the locust tethered to a post and placed near a computer monitor displaying a growing square that simulated object approach. Physical objects were also brought on a collision path with the locust and evoked robust responses. Neural responses were recorded during the approach and results of this recording are shown in Fig. 4.

Three sample trials have been shown where either a simulated growing square approached or a physical object was brought close to the locust. The device is able to record the signals with accuracy and one can sort the DCMD spikes with a simple threshold (in Fig. 4 the threshold was set at $28\mu V$). The instantaneous firing rate was then computed by convolving a gaussian with each of the raster plots and taking the mean. The instantaneous firing rate shows a clear rise reaching the peak at 4s corresponding to the signaling of an impending collision consistent with previous literature [10], [11].

2) Outdoor electrophysiological recordings results: Outdoor experiments were performed in a courtyard near grass and vegetation to mimic a natural environment. A similar surgical preparation was used as in the case of indoor recordings. In order to minimize movement the legs were removed and the locust was fixed to a pole on a platform by attaching a magnet to ventral side. Obstacles of different sizes were driven toward the locust at constant speed of $2ms^-1$. Example trials from these outdoors recordings are shown in Fig. 5.

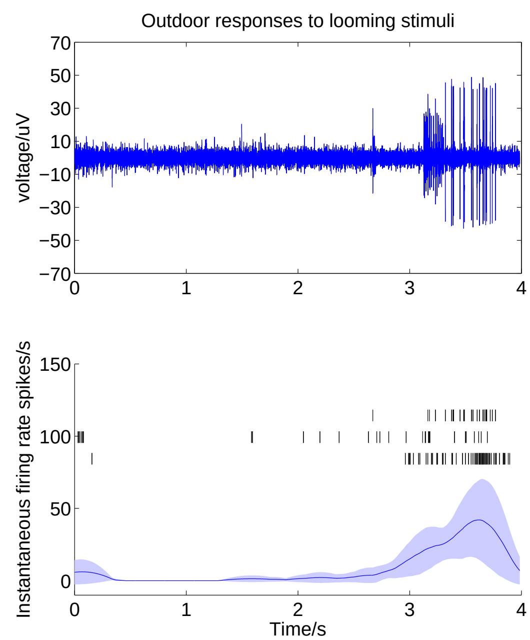


Fig. 5. Outdoor recordings from locust DCMD neuron. Top shows an example trace from one recording. Bottom shows the average instantaneous firing rate along with the standard deviation shown by the shaded region. The top raster shows the 3 sample recordings from which the average was computed.

The outdoor recordings were obtained by connecting the device to an ultra portable hand held computer (Viliv S7). As can be seen in Fig. 5 the device is able to provide high quality recordings in outdoor environments and we quantified the difference between the indoor and outdoor recordings by computing the signal-to-noise ratio (SNR). This was computed by first finding the spikes in the data calculating their peak-to-peak (PP) size and then similarly sections of data between two spikes were automatically selected and the PP size was computed. SNR was then computed as:

$$SNR_{DCMD} = 20log\left(\frac{RMS(PP_{sp})}{RMS(PP_{ns})}\right) \qquad (1)$$

Where PP_{sp} is the mean PP size of the spikes and PP_{ns} is the PP size of the baseline noise and RMS is the root mean square. Note that this is not the SNR as typically computed for an audio device but rather the SNR of the DCMD spikes in locusts. The noise includes several sources including small spikes from other axons as well as noise introduced due to imperfect contact between the electrode and the nerve cord as well as external and device noise. Despite these noise sources DCMD spikes ride well above the noise level and are easily detected using a simple threshold filter.

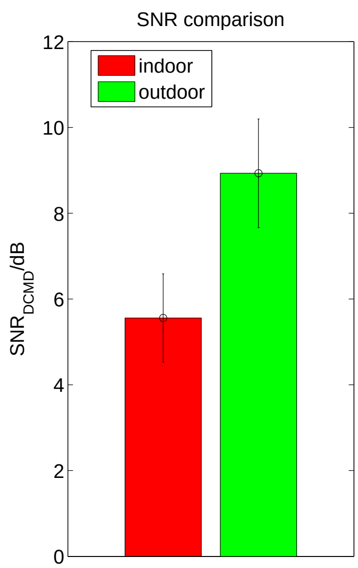


Fig. 6. SNR analysis. The bar plot shows the difference in SNR between indoor and outdoor recordings. The mean SNR for 3 recordings in each case is shown the error bars are SEM.

It can be seen from Fig. 6 that the SNR improves slightly in the outdoor recordings since there are fewer sources of electrical interference such as 60Hz power supply noise and other sources. The device therefore provides sufficient SNR both indoors and outdoors to sort spikes and analyze neural responses to stimuli.

IV. CONCLUSIONS

We have presented a portable 16-channel electrophysiological recording system that can be produced at a low cost. The system provides good quality signals both indoors and in outdoor environments. The baseline peak-to-peak noise with good grounding is $5 - 8\mu V$ which is comparable to much larger systems that cost orders of magnitude more than ours. The system additionally provides a high level of portability due to its small size. The system will further the ability of neuroscientists and electrophysiologists to 1) obtain neural recordings fairly cheaply while retaining the signal quality and 2) conduct field recordings in outdoor conditions.

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