A PCB SYSTEM IMPLEMENTATION FOR NEURAL SIGNALS RECORDING AND PNS STIMULATION

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ABSTRACT
A bidirectional interface for neural recording and stimulation is proposed. The recording circuitry eliminates the out-band interferences thanks to a high selectivity band pass filter in the 1.1kHz-2kHz band, providing a gain of 24dB. Further amplification is obtained by means of a programmable gain amplifier that can bring the gain to 44dB. The signal is then digitalized with a 16 bit ADC and sent to a microcontroller. In order to minimize the input referred noise, the whole signal acquisition chain has been designed with a Fully Differential approach, by this way an IRN of 364nV has been achieved. Stimulation signals are biphasic current pulses with programmable duration, frequency and amplitude. These patterns are generated by a DAC followed by a Voltage to Current converter. The programmability of the pulse parameters is guaranteed by the microcontroller: the current amplitude can range from 5μA to 20μA, the pulse duration varies from 50μs to 150μs while the frequency can cover from 10Hz to 400Hz. The system has been implemented in a PCB and successfully tested with a pre-recorded neural signal extracted by the peripheral nervous system of a rabbit with a tfLIFE electrode.

KEY WORDS
Neural Bandpass Amplifier, PCB Neural Interface, PNS Stimulation, Biomedical Instrumentation

1 Introduction
In recent years there has been an explosion of interest in the development of technologies whose end goal is to analyze the human nervous system and in particular, the correlation between the neural activity and specific cognitive, sensory and motor functions [1, 2]. Recent developments in microelectronic system technology have made easier the design of neural-controlled interfaces by means of appropriate electrodes which allow a selective link with the peripheral nervous system (PNS). The main aim is to electrically record and stimulate the nerve fascicles. In this context, the development of implantable bio-electronic devices for neural acquisition and stimulation have a big impact in bioengineering and neuroscience research. Examples of useful applications include clinical treatment of epilepsy, tremors associated with Parkinson’s disease, retinal and cochlear implants and multiple sclerosis [3, 4, 5, 6]. The reasons behind the increasing interest of researchers in the design of electronic neural systems are then evident. A major problem in such applications is the morphology of the signals to record. As a matter of fact, extracellular neural signals (ENG) are characterized by a low-amplitude signal (in the order of microvolts) and low-frequency bandwidth (main energy spectrum concentrated close to 2kHz). The acquisition of this kind of signals is therefore affected by noise, mainly due to electro-myographic signals (EMG) interference and to biological environment [7, 8, 9]. EMG signals have an amplitude of the order of millivolts (several orders of magnitude greater than useful ones) but are limited in frequency below 300Hz. Low-noise amplification and selective filtering represent then the two basic operations of any recording circuit proposed in the past [10, 11, 12, 13]. This work presents the design and test of a low power electronic neural system which allows a bi-directional interaction between the brain and “smart” artificial devices. The main goal was to realize a portable, easily reproducible and programmable interface with a highly selective filter and low power consumption. The implemented interface is able to record spontaneous and/or evoked activity of neurons from eight electric contacts of multi-site “thin-film Longitudinal Intra-Fascicular Electrode” (tfLIFE) [14] and to convert them in digital format and transmit it through the USB connection to the PC to be processed.

2 System Architecture
The neural-electronic interface consists of three main parts: a neural signals recording circuitry, a stimulus generation circuit and a digital control module. Fig. 1 gives a functional overview of the implemented system. The main task of the recording unit is to capture the neural signal from the implanted tfLIFE and to bandpass filter it in order to remove unwanted components from the neural spectrum. Once that the neural signal has been cleaned, it can be digitally converted before being transmitted to the digital control unit through SPI communication. A programmable amplification stage is required in order to exploit the full scale range of the ADC. The architecture of the recording unit provides a fully differential path for the signal so as to maximize the common mode rejection and
reduce the effect of interferences. Regarding the stimulation circuitry, nerve afferent activities towards the electrode are generated by the digital system controller and converted first into an analog voltage through the DAC then, into a stimulation current signal by means of a V/I converter. The electrical stimulation signal can be software programmable in amplitude, frequency and shape. The digital system controller provides power from a rechargeable battery to ensure the isolation of the patient from the electric grid (both for safety reasons and to reduce the noise injected by the grid) but its main task is the configuration of the whole system with the generation of timing signals (for multiplexers, ADC, DAC), programmable gain and stimulation patterns. For a high-speed real time data transmission and control, two different units were integrated in the system: a Universal Serial Bus (USB) controller and a wireless IEEE 802.11 module.

3 Circuit Implementation

Commercially available devices were adopted to build up the interface and to validate the function of the circuits design. The main benefits of this solution are highly reproducible, simple portable and low cost.

The fabricated prototype is shown in Fig. 2. Special attention has been paid on how to isolate the analog module from the interferences (especially on supplies) generated by the digital unit. For this reason the system has been divided into analog and digital parts and implemented in two

3.1 Analog System

The analog board is made up of a filtering, amplification and digitization circuitry concerning the recording unit and of a current pattern generator used as stimulator.

- **Neural Recording Circuitry:** Since neural recordings from tLIFEs appear like spikes with peak-to-peak amplitudes of about 50µV and frequency band in range from 900Hz to 2kHz, it is mandatory to eliminate DC components (50Hz) as well as EMG and biological unwanted components. Fortunately, these interferences are band-limited below 300Hz and can be separated from the neural signal through an appropriate band-pass filtering inside the frequency band of interest. For this reason, a selective filter was integrated in the registration unit. It is made up of a 4th order high-pass filter, cascaded with a 4th order low-pass filter. The basic filter cell has been implemented with Multiple Feedback topology, using a very low noise density (3nV/√Hz) and fully differential input/output amplifier (Linear Technology, LT1994). The filter design specification required a gain of 32dB and a frequency band between 900Hz and 2.3kHz. The RC filter network was sized to reduce the input-referred noise (IRN) to 364nV in the band of interest. Once that the signal has been filtered, it can be further amplified through a programmable gain amplifier before being digitized. In Fig.3 the chosen amplification circuitry is shown. A digitally controlled potentiometer (R7) (Intersil, ISL90727), in pair with a resistor of 100Ω (R6), allows to obtain a gain factor between 1 and 100, for a total of 127 different values. Moreover, the recording system includes an analog-digital converter (Analog Devices, AD7687) with a resolution of
Figure 4. Bi-phasic stimulus waveform

Figure 5. Neural stimulation circuitry

16-bit and a power consumption of 1.3mW, that by an SPI communication, provides to the digital control unit the processed signal.

- **Stimulator:** Key role for the application is played by the neural stimulation circuit. The stimulation system must be capable to generate a wide range of electrical signals for nerve stimulation via the implantable nerve electrodes used. Current-controlled method has been applied as stimulation. Stimulus parameters are programmable in amplitude, frequency and width according to the basic scheme of Fig.4. From a circuitual point of view the architecture chosen for the stimulation unit is shown in Fig. 5. The stimulator has been implemented using a 16-bit D/A converter (Linear Technology, LTC2641) followed by a V/I converter (Texas Instruments, OPA343). The basic idea is to convert a programmable voltage, generated by the DAC, into a stimulation current that will flow through the electrodes. Note that resistor $R_{\text{electr}}$ represents the impedance between the measurement ($L1 - L4$, $R1 - R4$) and reference ($L0 - R0$) electrode. The output circuit provides appropriate current limiting structures in order to prevent inadvertent damage to tissues.

### 3.2 Digital Module

The digital system unit is mandatory for configuration (electrode choice, amplifier parameters, switches selection) and for normal operation (receiving stimulation patterns, transmitting recorded samples, timing signals).

- **Digital system controller:** As main Digital Signal Controller (DSC), the high-performance Microchip dsPIC33FJ256GP506 is used. The DSC employs a powerful 16-bit architecture that integrates the control features of a Microcontroller (MCU) with the computational capabilities of a Digital Signal Processor (DSP). The resulting functionality is ideal for high-speed applications, repetitive computations, as well as control. The device includes several modules to communicate with other peripheral or microcontroller devices: 3-wire Serial Peripheral Interface (SPI), Inter-Integrated Circuit ($I^2C$) and UART. In the analog recording and stimulation management, two SPI modules are used for the communication between dsPIC/ADC and dsPIC/DAC while an $I^2C$ bus is employed to control the value of the digitally potentiometers of the amplification circuit. The DSC is used also for the external wired USB and wireless Wi-Fi communication modules, exploiting respectively an $I^2C$ and an UART interface. Finally, the controller unit contains all the circuitry for power management, namely the battery, the recharging circuit and all the voltage regulators needed to power the analog circuitry and the digital board itself.

- **Transmission unit:** The communication unit consists of an USB controller (Microchip PIC18LF4550) and a Wireless IEEE 802.11 module (EZURIO WISM01B1). The PIC18 is a microcontroller that has been used to control the bi-directional transmission $PC \iff dsPIC$, providing a communication speed of 64KB/s per report, according to the specific class of HID (Human Interface Devices). To manage the acquisition and the generation of neural patterns, a graphical user interface (GUI) has been developed. It is capable to communicate with the DSC through the USB/Wi-Fi modules, with respect to signal controls set by the user. The acquired neural signal from the tfLIFE electrode can be viewed in real time and saved in a .dat file during recording mode with the possibility to change gain and channel on-board. In order to test the system, a neural pattern stored in a file text in the PC can be set as DAC input and processed offline by the recording circuitry, before being saved in a data output file. In stimulation mode, the neural pattern is generated in the DSC and sent to the DAC. The GUI allows to change amplitude, duration, form and period of the stimulation current obtained on-board. For flexibility purposes, a wireless connection is also available. It is managed by the stand-alone Wireless LAN EZURiO module, which hosts an ARM7 pro-
cessor. Through the use of a real-time operating system (RTOS), a complete embedded suite TCP/IP and a simple extracted scripting interface (UWscript), the module performs a bidirectional wireless communication to a computer or server TCP/IP, ensuring the electrical insulation of the patient and avoiding the clutter of cables in the clinical trial.

4 Preliminary Experimental Results

A preliminary phase of test, directed to verify the correct working of the interface, has been performed. Thanks to a network of switches, it has been possible to configure the system in order that a test pattern emulating neural inputs can be generated by the digital controller and sent to the recording unit. As first testing approach, sinusoidal signals at different frequencies have been used as input.

The frequency response obtained in this way by the band-pass filter, is shown in Fig. 6. The graphic above shows the simulations results, while the lower panel shows the frequency response obtained by the filter test. As shown in the first panel, the designed filter has a gain equal to $20\text{dB}$ in bandwidth $(900\text{Hz}$ $- 2.3k\text{Hz})$ while at $400\text{Hz}$ and $6k\text{Hz}$ the attenuation of the signal is over $20\text{dB}$. The results of measurements show a lower gain $(24\text{dB})$ and a band between $1.1k\text{Hz}$ and $2k\text{Hz}$. The deviations from the ideal behavior are due to manufacturing tolerances of the resistances and capacities used in the feedback network of the filter. The selectivity of the band-pass filtering is evident in Fig. 7(e), where a sine at $1.3k\text{Hz}$ is allowed to pass while out-band frequencies at $400\text{Hz}$ and $7k\text{Hz}$ displayed in Fig. 7(a) and in Fig. 7(g), are completely filtered. Once that the basic working principles of the acquisition and filtering circuitry had been verified, the whole recording system has been tested in its functionalities using stimuli supplied by the Scuola Superiore di Studi Universitari e di Perfezionamento Sant’ Anna in Pisa (SSSA) on the basis of recordings made in clinical trials with rabbits. The input pattern represented in Fig. 8(a) is the result of ten recording seconds during which the rabbit was subjected to vibra-

tions at $50\text{Hz}$ and $100\text{Hz}$ in cutaneous afferents. Since the dsPIC data space memory is limited to $16\text{Kbytes}$ and ten seconds of recording correspond to $960\text{Kbytes}$, the trace has been sent to the digital controller divided in blocks of $14.4\text{Kbytes}$.

In a first phase of simulation, the available input pattern of Fig. 8(a) has been processed with Matlab using an ideal band-pass filter. In Fig. 8(b) is shown the ideal filtered signal obtained. The heavy influence of low-frequencies noise has been deleted and is clear the presence of the useful signal components that in the input pattern were completely masked. The filtered signal obtained with the implemented neural recording circuitry, is represented in Fig. 8(c). The slow components of the input signal coincide with output peaks characterized by higher frequencies. The programmability of the stimulation signals is displayed in Fig. 9, where different amplitudes for the stimulus are presented. The output current can range from $5\mu\text{A}$ to $20\mu\text{A}$, these values have been obtained considering an electrode impedance of $50k\Omega$. With a lower impedance value the current can be further increased. Fig.10(c) and Fig.10(d) show how the current pulse width can vary from $50\mu\text{s}$ to $150\mu\text{s}$ following the voltage pulses in Fig.10(a) and Fig.10(b) applied to the V/I converter.
5 Conclusion

We have presented a prototype for neural activity recording and stimulation system. Given the nature of the signals to be acquired, special design techniques for low noise and low power consumption have been adopted. The first experimental results prove that the system works correctly and stably, with the possibility to acquire and process neural signal in microvolts order. The recording circuitry allows to filter the neural signals in the band of 1.1kHz – 2kHz, providing a programmable gain that covers values from 24dB to 44dB. The resulting signal can be digitally converted and sent to PC for further processing through USB or Wi-Fi transmission. The acquisition system has been tested using pre-recorded neural patterns extracted by rabbit with tLIFE electrodes. The system has been studied in order to generate also electrical stimuli with controlled current amplitude, duration and shape. This effort is part of an on-going research program which aims to develop smart implantable devices dedicated to neural activity recording and stimulation.

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References


