AN ELECTRONIC INTERFACE FOR NEURAL ACTIVITY RECORDING AND STIMULATION

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Keywords: Neural extracellular recording, Neural Stimulation, Neural signal processing.

Abstract: A portable neural activity acquisition and stimulation system by means of tfLIFE implantable electrodes has been realized. The detecting circuit provides: a selective filtering made up of a 4th order high pass Multiple Feedback filter ($f_{-3dB} = 1.1kHz$) and a 4th order low pass Multiple Feedback filter ($f_{-3dB} = 2kHz$), a variable gain (24dB - 44dB) and a 16 bit analog to digital conversion. The stimulator allows to generate specific electrical signals through a digital-to-analog converter while stimulation parameters as frequency, duration and intensity are controlled by a digital microcontroller. Simulation results and first experimental results of the interface demonstrate how neural signals of a few of microvolts can be filtered, programmable amplified and digitalized without distortion.

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 (Wessberg et al., 2000; Salzman and Newsome, 1994). 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). 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 (Wang et al., 2005; Watkins et al., 2006). 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 (Obeid et al., 2004; Gosselin and Sawan, 2005; Jochum et al., 2009). 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) (Yoshida et al., 2006) and to convert them in digital format and transmit it through the USB connection to the PC to be processed.

2 SYSTEM IMPLEMENTATION

2.1 Architecture

Fig. 1 gives a functional overview of the neural-electronic interface developed. It consists of three main parts: a neural signals recording circuitry, a stimulus generation circuit and a digital system controller.

Recording Unit: The main task of the recording part 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

Angius G., Carboni C., Loi D. and Barbaro M. (2010).
AN ELECTRONIC INTERFACE FOR NEURAL ACTIVITY RECORDING AND STIMULATION.
In *Proceedings of the Third International Conference on Biomedical Electronics and Devices*, pages 211-214
DOI: 10.5220/0002749702110214
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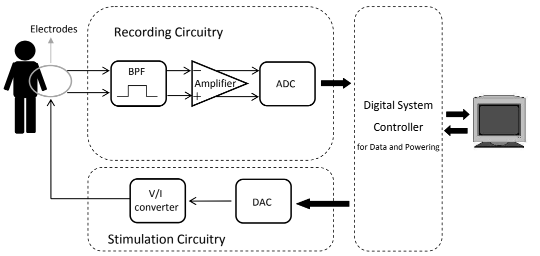


Figure 1: Block diagram of the recording and stimulation system.

unit. 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.
Stimulation Unit: In 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 function electrical stimulation (FES) signal can be software programmable in amplitude, frequency and shape.
Digital Unit: The digital system controller has two main tasks. First, it 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). Main task of the module, however, is managing 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.

2.2 Working Modes

The implemented system works on three independent modes: Recording, Stimulation and Testing mode. This high degree of reconfigurability is guaranteed thanks to the presence of a network of switches driven by three digital signals. In Recording mode, the neural signal is captured from the tfLIFE electrode and is sent to the recording circuitry. The signal is filtered, amplified and digitally converted before being transmitted to the digital system controller through SPI communication. When the system is in Stimulation mode, different digital patterns are generated by system controller and converted into an analog voltage by a DAC.

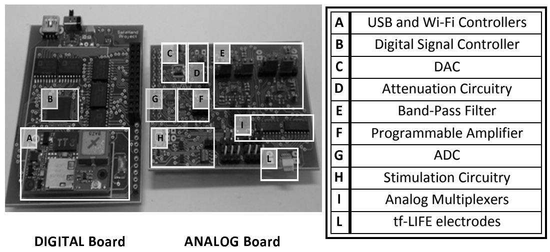


Figure 2: Photograph of the implemented PCB system.

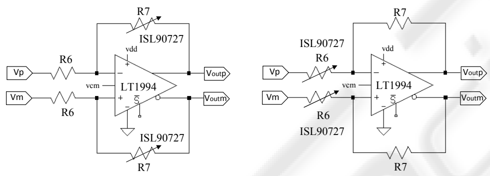
When the system is reconfigured for testing purposes, the digital controller generates a test pattern that emulates neural inputs and sends it to the DAC. Since the converter output voltage swings from $0V$ to $3V$, with a resolution of $45.7\mu V$, in order to manage and generate neural signals in the range of few microvolts, a programmable attenuation circuit has been introduced in the system.

3 CIRCUIT DESCRIPTION

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 separate, sandwich stackable, printed circuit boards (PCB), sizing respectively 7 cm x 6.1 cm and 7.5 cm x 5.8 cm. The chosen solution could be suitable for a future fully implantable version of the interface. The whole system is supplied by a rechargeable battery (3.7V) to ensure the isolation of the patient from the electric grid. Lower supply voltages (3V and 1.5V) are provided by two linear voltage regulators (Maxim, MAX1589 and MAX1792).

3.1 Neural Recording Circuit

Since neural recordings from tfLIFEs appear like spikes with peak-to-peak amplitudes of about $50\mu V$ 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 ($3nV/\sqrt{Hz}$) 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 $250nV$ 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(a) 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. Note that, using $R6$ as potentiometer and $R7$ with a fixed value of 100Ω, it has been possible to use the same circuitry to obtain the programmable attenuation circuit of Fig.3(b) useful during the test operating mode. Finally, the recording system includes an analog-digital converter (Analog Devices, AD7687) with a resolution of 16-bit and a power consumption of $1.3mW$, that by SPI communication provides to the digital control unit the processed signal.



(a) Amplification circuitry (b) Attenuation circuitry

Figure 3: Circuitry used for amplification and attenuation.

3.2 Neural Stimulation Circuit

Key role for the application is played by the neural stimulation circuit. The stimulation is done with current patterns that have programmable amplitude, frequency and shape. Fig. 4 shows the architecture of the stimulation unit. The circuit was 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 $Relectr$ represents the impedance between the measurement ($L1-L4$, $R1-R4$) and reference ($L0-R0$) electrode.

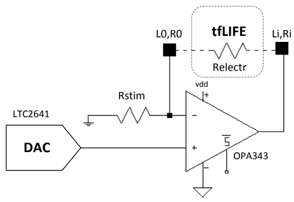


Figure 4: Neural stimulation circuitry.

3.3 Digital System Controller

Two high-performance Microchip Microcontrollers have been used for the bi-directional communication $PC \Longleftrightarrow AnalogBoard$: the dsPIC33Fj256GP506 and the PIC18LF4550. The first one allows to manage the ADC and DAC modules by means of a SPI bus and to choose the value of the digitally potentiometers through an I^2C bus. While the PIC18LF4550 is used as USB controller in the communication $PC-dsPIC$, providing a communication speed of $64KB/s$ per report, according to the specific class of HID (Human Interface Devices).

4 EXPERIMENTAL RESULTS

In order to characterize the filter, sinusoidal signals at different frequencies have been generated by the DAC and applied to the filtering circuitry for testing.

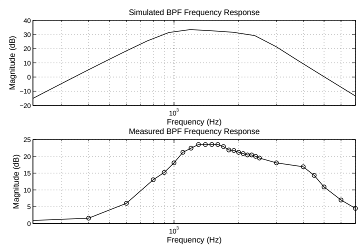
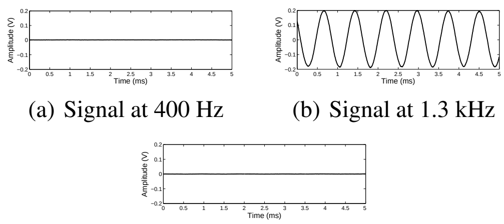


Figure 5: Plot of theoretical and measured frequency response of the band-pass filter.

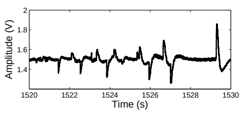


(a) Signal at 400 Hz (b) Signal at 1.3 kHz

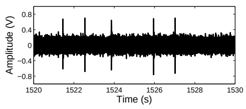
(c) Signal at 5kHz

Figure 6: Band pass filter output signal.

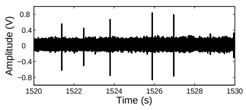
The frequency response of bandpass filter is shown in Fig. 5. The graphic above shows the simulations results, while the lower panel shows the frequency response obtained by the filter test. As shown in the first panel, the designed filter has a gain equal to $32dB$ in bandwidth ($900Hz - 2.3kHz$) while at $400Hz$ and $6kHz$ the attenuation of the signal is over $20dB$. The results of measurements show a lower gain ($24dB$) and a band between $1.1kHz$ and $2kHz$. 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 filter has been tested using as input for the recording circuitry a sinusoidal signal at different frequencies: $400Hz$, $1.3kHz$ and $5kHz$. The effect of the band-pass filtering is evident in Fig. 6(b), where the sine at $1.3kHz$ is allowed to pass. The signals shown in Fig. 6(a) and in Fig. 6(c), prove how out-band frequencies are completely filtered.



(a) Input Signal



(b) Matlab Filtered Signal



(c) PCB Filtered Signal

Figure 7: Neural signal processing: filtering, amplification and digital conversion.

Finally, the whole recording system has been tested in its functionalities using stimuli supplied by the Scuola Superiore di on the basis of recordings made in clinical trials with rabbits. The input pattern represented in Fig. 7(a) is the result of ten recording seconds during which the rabbit was subjected to vibrations at $50Hz$ and $100Hz$ in cutaneous afferents.

In a first phase of simulation, the available input pattern of Fig. 7(a) has been processed with Matlab using an ideal band-pass filter. In Fig. 7(b) the ideal filtered signal obtained is shown. 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. 7(c). The slow components of the input signal coincide with output peaks characterized by higher frequencies.

5 CONCLUSIONS

We have developed and tested a PCB system for neural activity recording and stimulation. 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 $1kHz - 2.2kHz$, 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 tfLIFE 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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