A low power portable multichannel neural data acquisition system

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Abstract

We present the design and test of a portable multichannel neural data acquisition system. Each analog channel features a low noise (10nV/√Hz), high CMRR (83.4dB) input stage, a 4th order bandpass filter and a selectable gain (60.8dB – 100.8dB). An automatic DC restoration circuit in the input stage rejects the electrodes DC voltage mismatch. The multichannel analog signals are sampled, digitized at 32ksps and transferred through a USB connection. Testing of the device demonstrates its reliability to process neural signals and to be used as a stand-alone recording unit for in-vivo experiments. The implemented printed circuit board consumes up to only 75mW.

1. INTRODUCTION

Cortical activity, acquired from multineuron recordings, had successfully been translated and used to control prosthetics with animals [1, 2]. However, cumbersome and potentially harmful existing multichannel recording apparatus restrict further investigations in freely behaving animals and humans. Portable neural data acquisition systems, which provide full electrical isolation and stand-alone operation, are required. We present the design, physical implementation and testing of a low power, 16 channels, portable neural data acquisition system (NDAQ). This design uses standard commercially available components which make its printed circuit board (PCB) implementation highly reproducible.

2. METHODS

2.1. System design

The NDAQ comprises 16 parallel low noise signal conditioning channels and a common digital part. Each analog channel is made of 3 processing stages: an instrumentation amplifier (IA), a bandpass filter and a selectable gain. Four amplification levels are available for the selectable gain and the filter cutoff frequencies are placed at 150Hz and 10kHz. The channels are time-division multiplexed through an analog multiplexer over a single analog to digital converter (ADC). An embedded controller manages continuous recorded data transfer through the Universal Serial Bus (USB). The NDAQ allows full electrical isolation using low power CMOS digital isolators and batteries as power source. Furthermore, an automatic DC restoration circuit removes any electrodes potential mismatch and confers high input impedance ($10^{10}\Omega$) to this system which avoids necessity for buffering the input electrodes with an active headstage. The schematic of one analog channel is shown on fig. 1.

2.1.1 Front-end stage

The low noise (10nV/√Hz at 1kHz), low power consumption (350µA) IA (INA118) used as analog front-end stage provides a high common mode voltage rejection. Power line interferences and biological noises due to motion artefact and mastication are removed from the input signal (*Vin)* by sensing the common reference (*Vref)* on the 2nd input terminal (fig. 1). An automatic DC restoration circuit is used in combination with the IA to reject the DC voltage mismatch between the input signal electrode and the common reference electrode. This circuit introduces a high pass cutoff frequency in the signal pathway, with $f_{-3dB} = (2\pi R_2C_1)^{-1}$, which is fixed to 23Hz for this design. The gain of the IA, set by the single resistor R_1, is fixed to 10.

2.1.2 Bandpass filter

The filtering stage is composed of a cascaded lowpass and highpass 4th order Sallen-Key filters. It provides a gain of 10 which is set by resistors R_5 and R_6. Each filter uses one quad package, low power consumption (45uA) op-amps (AD8544) per channel.

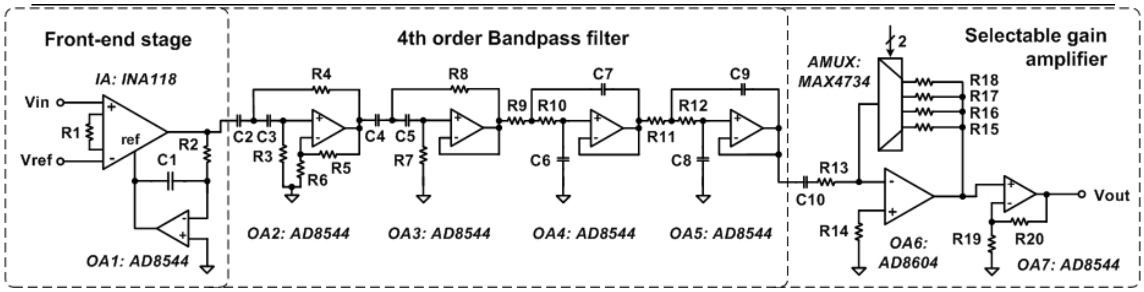

Figure 1: *NDAQ conditioning channel. Vin can be taken from an electrode with or without using a headstage buffer. Vref is taken from a reference electrode common to all channels.*

2.1.3 Selectable gain

This stage increases the NDAQ's input dynamic range by providing four incremental amplification levels. A 4 channels low on-resistance analog multiplexer (MAX4734) sets the appropriate resistor (R_{15}-R_{18}) in the feedback loop of the inverting gain op-amp OA6 (AD8601). Op-amp OA7 is used as a 10V/V gain output buffer. Each channel's gain is set independently.

2.1.4 Mixed-signal part

The 16 analog channels are time-division multiplexed using a 16:1 analog multiplexer (ADG706) and sampled with a 10 bits low power ADC (AD7470) which consumes only 2mW for a maximum requested throughput of 512ksps. A low cost, on board USB driver (FT245BM) is used for continuous data transfer. The timing signals are provided by an embedded PLD based controller. This design uses the low power (~3mW at 4MHz) 144-pin XC2C384 from Xilinx Coolrunner II family. The USB driver is powered by the bus supply terminals. A special operating mode allows to isolate it from other parts by enabling high speed CMOS digital isolators from Agilent Technologies (HCPL-901J), thus providing a complete electrical isolation of the NDAQ board ($V_{isolation} = 2500V_{rms}$).

2.1.5 Power supply

The NDAQ is supplied by 2 low dropout linear voltage regulators (MAX882), one of them is providing the power for the analog channels and the other supplies the digital part. Low supply voltages (3.3V) are used for both parts. The circuits analog ground is derived from the positive rail by a voltage divider and a unity gain follower. The follower's output is used to reference the experimental subject or the patient.

2.2 Physical implementation

A four-layer board was design for the NDAQ and manufactured using standard PCB technology. Manually mounted chips and passive components are used (size 0603). A 40 pins flat cable connector accommodates the digital part implemented as a separate stackable board. The PCB realisation is shown on fig. 2.

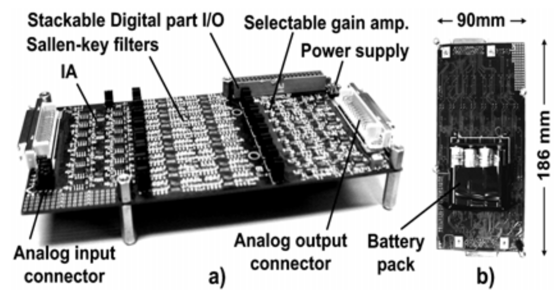

Figure 2: *a) The NDAQ PCB with all analog circuits blocks (digital part not shown), b) Bottom view with the board dimensions.*

2.3 Testing and characterization

Very few distortions are tolerated in the data acquisition pathway when further processing steps, such as spikes detection and sorting, are intended. The linearity of the NDAQ analog conditioning channels is tested in-vitro with a realistic artificial spike train. This test signal is generated with standard lab equipments (a function generator, a signal attenuator and a few electronic components for the filter) in accordance with the characteristics of a real neural spike signal, used as a reference. Fig. 3a) shows the reference neural signal previously recorded from the visual cortex of a rat. The artificial spike train is derived from an original pulse train (fig. 3b) which is bandpass filtered between 300Hz and 6kHz and attenuated. The resulting signal (fig. 3c), presents most features (bandwidth, amplitude and spike duration) of a real neural spike train and is used as input signal for in-vitro testing of the NDAQ.

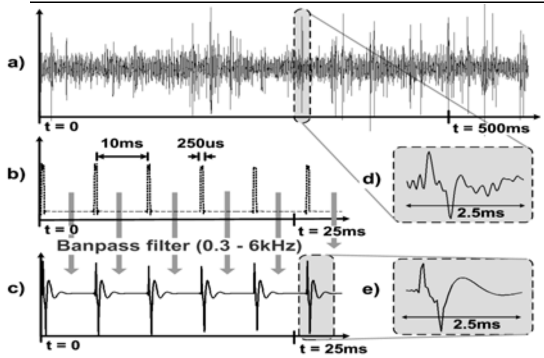

Figure 3: *Generation of the in-vitro test signal. a) The reference neural signal, b) the original pulse train, c) the derived spike signal, d) a real action potential (spike) e) a spike isolated from the test signal. Both are highly similar.*

3. RESULTS

The implemented board measures 186.6mm × 90.3mm and weights 145.1g including all connectors, headers and spacers. With its very low power consumption, the NDAQ achieves a stand-alone time of more than 30 hours of continuous recording with four AA NiMH batteries (1.~2300mA/h) as power source. The system performances are summarized in table 1. The anticipated values are obtained from SPICE simulations and from the components data-sheets. The measured inter-channel isolation at 1kHz is 54.8dB (typical) and the signal to noise ratio plus distortion (SNDR) is of 53.47dB at minimum gain and 12.55dB at max gain (typ.).

Table 1: *Summary of the NDAQ performances*

Parameters	Measured values	Anticipated values
Gains 1, 2, 3, 4	60.8 dB, 80.9 dB, 95.3 dB, 99.5 dB	60.8 dB, 80.8 dB, 94.8 dB, 100.8 dB
f_{-3dB} (low) - f_{-3dB} (high)	163 Hz - 9.792 kHz	150 Hz - 10.1 kHz
CMRR	83.4 dB	76.42 dB
Input referred noise	1.0 µVrms	1.1 µVrms
Full scale input range	1.60 mV	1.33 mV at min. gain
	11.2 µV	13.3 µV at max. gain
DC restoration f_{-3dB} (high)	22.0 Hz	23.4 Hz
DC voltage rejection	115 mV	90 mV at min. gain
	140 mV	103 mV at max. gain
Maximum group delay	4.5 ms	6 ms
Power consumption (CMOS isolators not activated)	75 mW	76 mW

For in-vitro testing, fig. 4 depicts an input test spike fed to the NDAQ, in a), superimposed on the output processed spike, in b). The input and output spikes shapes are almost identical with an *rms* error of 5.71%. Curves c) (the input) and curve d) (the ouput), on fig.4, show that the input test signal power spectrum stays nearly unchanged when conditioned by the NDAQ. The reference signal spectrum is also shown in e) for comparison with the test signal spectrum.

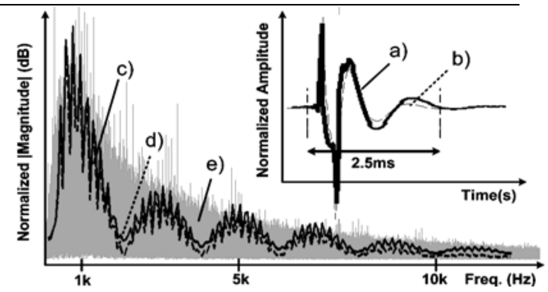

Figure 4: *The NDAQ input signal compared to its processed output. a) Input spike, b) conditioned spike, c) the test signal power spectrum (solid black), d) the NDAQ processed output signal spectrum (dashed black) and e) the reference neural signal spectrum (in grey).*

4. DISCUSSION AND CONCLUSIONS

A highpass transfer function in the input stage is a requisite for such systems since DC offset resulting from electrodes potentials mismatch may reach a hundred millivolts [3]. Using an automatic DC restoration circuit for this design avoids the necessity for input RC networks, which significantly degrade the CMRR and input impedance. Realistic in-vitro testing of the implemented NDAQ board confirmed the reliability of the analog conditioning channels. A group delay of less than 4.5ms and an in-band linear phase delay guarantee low distortion. Moreover, low power consumption and full electrical isolation make the NDAQ suitable for long term clinical applications.

This portable device is intended to facilitate in-vivo multineuron recordings in freely behaving subjects. This effort is part of an on-going research program which aims to develop smart implantable devices dedicated to cortical recording [4].

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