Neural Recording System with 8 Channel Neural Amplifier and Logarithmic ADC

Chirag Mukesh Mehta, Chaejung Lim

Abstract—This work proposes a low-power 8 channel neural recording system for use in advanced closed-loop neurostimulation applications for the detection and treatment of neurological disorders such as Parkinson’s disease. The analog front end senses and filters the neural activity with eight low-noise pre-amplifiers and band-pass filters. The neural sensing signals are multiplexed to a single logarithmic pipelined ADC. Separation of the low frequency local field potentials (LFPs) from the high frequency neural spikes is done using on-chip finite impulse response (FIR) digital filters. The resulting signals can then be used to dynamically control the neurostimulation parameters in a closed-loop system to alleviate the neurological symptoms of the disease.

Keywords—Neural recording, neurostimulation, logarithmic pipelined ADC, finite impulse response.

I. INTRODUCTION

The accelerating pace of research in neuroscience has created a considerable demand for neural sensing microsystems capable of monitoring the activity of large group of neurons. The ability to record signals from neurons is centered around the electric current flow through the neuron. As an action potential propagates through the cell, the electric current flows in and out of the soma and axons at excitable membrane regions. This current creates a measurable, changing voltage potential within and outside the cell.

This allows for two basic types of recordings. Intracellular recordings occur within the neuron and measure the voltage change with respect to time across the membrane during action potentials. This outputs as spikes through the soma or axon. Another type of recording is the local field potential (LFP), which is an electrophysiological signal generated by the summed electric current flowing from multiple nearby neurons within a small volume of nervous tissue. Voltage is produced across the local extracellular space by action potentials and graded potentials in neurons in the area, and varies as a result of synaptic activity.

Recent research has discovered that these internal neural recordings can provide vital information about the symptoms of various neurological disorders. Consistent excessive power of local field neural potentials at 15-30 Hz are associated with symptoms of Parkinsons Disease in an animal model [1]. Both high-frequency, pulsatile neuronal spike trains and low-frequency continuous LFPs contain important information for closed-loop neurostimulation control [2].

In order to simultaneously record both types of signals, a high-dynamic range recording device is required. Our work proposes to incorporate eight low-noise neural front end amplifiers and band pass filters multiplexed to a single high dynamic range logarithmic pipelined ADC. On-chip digital filters separate the neural spikes and the low-frequency field potentials.

II. SYSTEM OVERVIEW

The proposed neural recording system with 8 channel neural amplifiers and logarithmic ADC is shown in figure 1.

A. Measurement Electrodes

In the past decade, neuroscientists and clinicians have begun to use implantable MEMS multielectrode arrays to observe the simultaneous activity of many neurons in the brain [3] [4]. These silicon-based electrode structures are inserted into the cerebral cortex to observe the electrical activity of nearby nerve cells. Neural spikes are pulsatile signals with bandwidth of 100 Hz to 10 kHz and amplitude level from 50 μV to 500 μV [5]. Local field potentials are continuous, lower frequency signals with bandwidth below 100 Hz, and amplitude levels up to 5 mV [6]. Table 1 below lists the specifications of microelectrodes suitable for various applications [7]:

B. Low Noise Neural Amplifier

Due to the microvolt level of the neural spikes recorded extracellularly, neural signals must be amplified before spike/LFP detection or digitization can be accomplished. Low amplitude levels further make it necessary to design a neural amplifier with low input referred noise. However, the power restrictions imposed on small implantable devices limit our ability to simply increase the bias currents in order to lower the amplifier noise, especially since the basic amplifier circuit will be repeated many times across the chip. To optimize the trade-offs between power dissipation and noise, circuit techniques similar to [8] can be used. The low noise neural amplifier is targeted to provide a pass-band gain of about 100 (40dB), to achieve sufficient resolution from the ADC, and a power dissipation of 9 uW per channel. The low-frequency LNA pass-band zero is set to 15 Hz, and the high frequency pole is set to 10 kHz so that the LNA passband covers both the field potential activity and the spike energy.

C. Analog Band Pass Filters

Analog Gm-C band pass filters follow the neural amplifier stages to pass the frequency range of interest. The filters can be designed for a bandwidth of 15 Hz to 10 kHz to allow both the neural spikes and LFPs to pass through. To minimize the power consumption, separation of the neural spikes and LFPs is accomplished using back-end digital filters. The amplified and filtered neural sensing signals are multiplexed to a single logarithmic pipelined ADC.
TABLE I: Summary of Neural Recording Parameters for Different Signal Modalities

<table>
<thead>
<tr>
<th>Neural Signal</th>
<th>Measurement Technique</th>
<th>Amplitude</th>
<th>Bandwidth</th>
<th>Electrodes</th>
<th>Chronic Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracellular Action Potentials</td>
<td>Voltage Amplification</td>
<td>50 to 500 uVpp</td>
<td>100 Hz to 10 kHz</td>
<td>Metal/silicon microelectrode</td>
<td>High</td>
</tr>
<tr>
<td>Intracellular Action Potentials</td>
<td>Voltage Amplification</td>
<td>10 to 70 mVpp</td>
<td>100 Hz to 10 kHz</td>
<td>Glass micropipette</td>
<td>Very low</td>
</tr>
<tr>
<td>Local Field Potentials</td>
<td>Voltage Amplification</td>
<td>0.5 to 5 mVpp</td>
<td>1 mHz to 200 Hz</td>
<td>Metal/silicon microelectrode</td>
<td>High</td>
</tr>
<tr>
<td>Ionic Current</td>
<td>Patch Clamping</td>
<td>1 to 10 nA</td>
<td>1 mHz to 10 kHz</td>
<td>Glass micropipette</td>
<td>Very high</td>
</tr>
<tr>
<td>Redox Current</td>
<td>Amperometry</td>
<td>100 fA to 10 uA</td>
<td>1 mHz to 100 Hz</td>
<td>Iridium oxide/carbon fiber microelectrode</td>
<td>High</td>
</tr>
</tbody>
</table>

D. Logarithmic Pipeline ADC

To save area and power consumption, a high dynamic range logarithmic ADC is used. Logarithmic encoding is well suited and efficient for neural signals since a high dynamic range can be represented by a short word length. An ADC with a dynamic range of 54dB is enough to cover the entire range of spikes and LFPs, considering both the microelectrode noise and the background cortical activity noise. This requires the overall log ADC resolution to be 8 bits with one sign bit and seven magnitude bits [9]. The sampling rate of the logarithmic ADC is 200kS/s and is targeted to minimize the power consumption roughly up to 180 uW [9].

E. Back-end FIR Digital Filters

Unlike the case with other neural recording systems, separation of the low-frequency field-potential from the higher frequency spike energy is done with an on-chip finite-impulse-response (FIR) digital filter. Using a digital filter instead of an analog or mixed-signal filter provides many advantages. First of all, a digital filter is programmable so that its operation can be adjusted without modifying hardware. While analog filters are subject to drift and are sensitive to temperature, a digital filter is extremely robust with respect to both time and temperature. Unlike an analog filter, a digital filter can easily implement higher order filtering but with an extremely low power consumption, especially for low-frequency signals [10]. The filter power consumption is only 9 W per channel.

F. Supply

With low power design considerations, the system is capable of operating autonomously from a single 1.5-2 V battery [11].

TABLE II: Comparison of Proposed Work with State of the Art

<table>
<thead>
<tr>
<th>Position of Electrodes</th>
<th>LNA Channels</th>
<th>LNA Gain</th>
<th>LNA Pass Band</th>
<th>Input Referred Noise</th>
<th>Filters</th>
<th>ADC</th>
<th>Resolution</th>
<th>Sampling Frequency</th>
<th>Total Power</th>
<th>Process Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortex</td>
<td>32</td>
<td>39.5 dB</td>
<td>100 Hz to 7 kHz</td>
<td>3.35 nVrms</td>
<td>Analog</td>
<td>Ext.</td>
<td>13 bits</td>
<td>512 kS/sec</td>
<td>11 mW</td>
<td>0.34 um</td>
</tr>
<tr>
<td>Cortex</td>
<td>128</td>
<td>40 dB</td>
<td>0.1 Hz to 20 kHz</td>
<td>4.9 nVrms</td>
<td>Analog+</td>
<td>SAR</td>
<td>6 to 9 bits</td>
<td>640 kS/sec</td>
<td>6 mW</td>
<td>0.35 um</td>
</tr>
<tr>
<td>Cortex</td>
<td>6</td>
<td>15 Hz</td>
<td>0.1 Hz to 10 kHz</td>
<td>5.0 nVrms</td>
<td>Analog+</td>
<td>Log Pipe</td>
<td>8 bits</td>
<td>200 kS/sec</td>
<td>0.23 mW</td>
<td></td>
</tr>
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</table>

TABLE III: Work Distribution

<table>
<thead>
<tr>
<th>Member</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chirag Mukesh Mehta</td>
<td>Neural Amplifier, BPF, Analog multiplexer</td>
</tr>
<tr>
<td>Chaejung Lim</td>
<td>ADC, Digital Filters</td>
</tr>
</tbody>
</table>

REFERENCES


