PROGRAMMABLE STIMULATION-RECORDING CIRCUITRY FOR CUFF AND SIEVE ELECTRODES

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Abstract

In this paper, an ASIC Stim/Rec circuit to be used with different type of electrodes has been designed, implemented in a CMOS technology and tested in acute experiments with rats. The performances of this Stim/Rec are: fully programmability of waveform parameters, 4 stimulation and 1 recording channel extensible to 16 and 4 respectively, anodes and cathodes can be chosen independently allowing the current to go in a longitudinal or transversal way for cuff electrodes. A very low noise (5nV/ÖHz) amplifier has been got with digitally programmable bandwidth and gain.

Introduction

The use of functional electrical stimulation (FES) technique [1] is used not only restoring motor activity in SCI subjects but also for therapeutic or prosthesis control. Nowadays, there is not much work done on development of implantable systems with stimulation and recording capability into the same ASIC with the benefit of a reduction in the size of the resulting implantable device although it seems a new line on this direction is starting [2]. In this paper a stimulation/recording circuitry implemented in the same ASIC is presented. The system is designed without being tied to a specific application and allowing to operate in a closed loop system using the stimulator to provide information to the subject and the recording to sense a certain motor action as in the case of controlling a hand prosthesis or inversely for a motor action in SCI people. The parameters of the system are digitally programmable from the external control and once programmed the only requirement for an autonomous operation is the power supply. The hierarchical strategy allows modifying the number of channels in an easy way.

Material and Methods

1. System structure.

The system proposed consists in a four channels electrical stimulator, an external electrode selector, full channel ENG signal recording, two step/up voltage regulators providing the high voltage for the stimulator and a control digital block to program and control the above blocks. This system corresponds with the internal unit (without telemetry) in an implantable stimulation-recording system like that shown in Fig. 1.

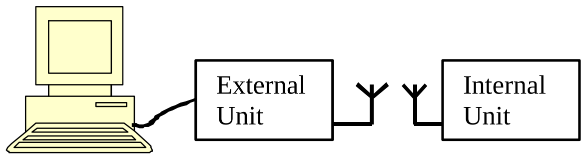


Fig. 1: Implantable system

A simplified blocks schema for the mentioned system is shown in Fig. 2. This system is designed to work with sieve and cuff electrodes then an electrode selection module for the sieve and independents anode-cathode pairs for cuff have been implemented. Moreover, all these blocks have been designed in an ASIC using a high voltage technology I2T CMOS 0.7 micron. This is a preliminary version of a multiple channel stimulator–recording circuitry provided with a bi-directional telemetric link for energy and data transmission that is being developed in the framework of Cyberhand project.

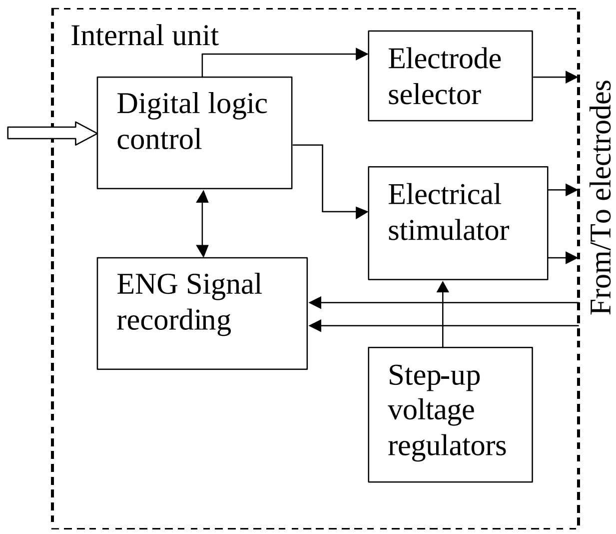


Fig. 2: Blocks schema for stimulation-recording circuitry

2. Digital logic control.

The structure for the digital logic control (**DLC**) is based on an internal memory that can be programmed according with the kind of electrode and the application to be implemented. The functionality associated to this block has been split in several simple blocks, as shown in Fig. 3, all of them connected by an internal bus whose access will be managed by the main block named **MainCtrl**. Each block has its own internal address through which they can intercommunicate. The functionality associated to each module is briefly described in the following paragraphs.

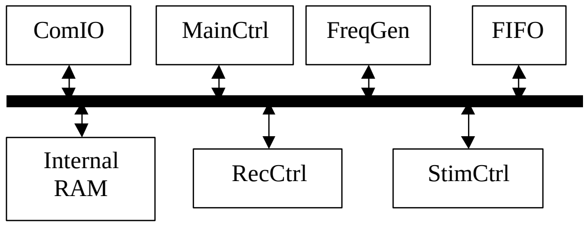


Fig. 3: Structure of logic control

ComIO: This block acts as interface between the DLC and the external controller or telemetry system. Frames are identified and processed activating the internal signals addressing the information to destination. **FreqGen**: This block is responsible for generating the frequencies of stimuli. Is based in a general counter of 19 bits, containing the period of the stimuli, with a clock of 4MHz, only the 12 most significant bits are needed for the frequency control in a range of 7 to 200 Hz with 1 Hz resolution. When more than one frequency is activated before generating the stimuli, a collision is produced and the pending stimulation waveform is sent to a FIFO for a later activation. **Internal Ram**: In this block all the stimulator parameters are stored. This is a RAM of 256 words of 12 bits that allows programming 16 frequencies for 16 different stimulation waveforms. The parameters for the programmed waveform will be stored in consecutive positions. A normal waveform consists in a prepulse followed by a stimulation pulse an interdelay and finally a recovery phase. An exponential charge recovery phase can be programmed to compensate the residual charge due to finite resolution in parameters definition. **FIFO 8x4:** This FIFO of 8 levels deep and 4 bits wide is used to solve the collisions problem. Then when a stimulation is activated from FreqGen module, this is introduced in the FIFO and will be read after finishing the actual stimulation. **MainCtrl**: The task of this module is to control the access to the internal bus. Any module can need the bus at any time for accessing to any of the other blocks, then a request is sent and the MainCtrl block assigns the bus based in a priority table already established. The highest priority is assigned to the FreqGen module to avoid any frequency loss, second ComIO to assure the reception of data coming from outside, third StimCtrl and finally the RecCtrl. **StimCtrl:** This block implements the algorithm for stimuli generation reading parameters from memory and generating signals controlling the stimulator. Single stimulus or bursts at the programmed frequency can be generated. The process for a stimulus generation follows the sequence below:

1. The module **FreqGen** finish the count for a frequency
2. Module **FreqGen** write in the **FIFO** the frequency identifier
3. If the **FIFO** is not empty, the **StimCtrl** reads from the **FIFO** the pointer to one of the 16 waveforms
4. **StimCtrl** reads the initial **RAM** address for this waveform
5. **StimCtrl** reads the parameter and execute the sequence for stimulus generation
6. The **RAM** address is increased to the next one
7. Step 5 and 6 are repeated as many times as the number of parameters in the waveform
8. When the contents of the **RAM** is equal 0 then the waveform is finished and next position of the **FIFO** is read.

Finally, the **RecCtrl**: It is the last module in the DLC generating the control signals required for amplifier activation, electrode selection, sampling of information and control signals for ADC conversion. Moreover, digital data from ADC will be stored in in specific registers for a posterior transmission to the exterior controlled by the ComIO module. Although only one channel has been implemented, the module has been designed to fulfil the final specifications concerning the number of recording channels.

3. Electrical stimulator.

The electrical stimulator is based in programmable current sources providing biphasic stimuli of constant current in the range of 2 to 126 μA with resolution 2μA or 20 to 1260 μA with resolution 20 μA.

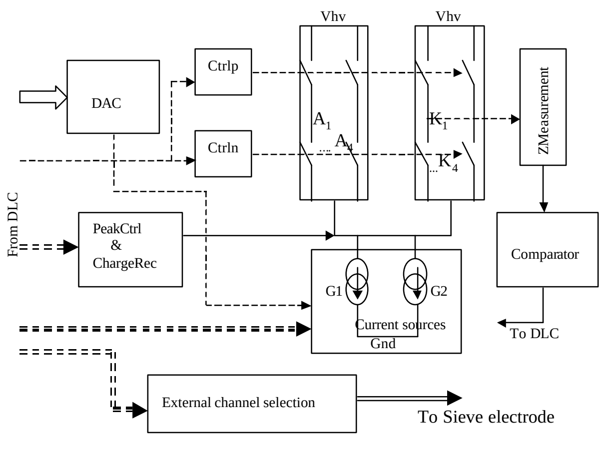


Fig. 4: Blocks structure of electrical stimulator

The H-structure used for the output stage assures the same current amplitude in the positive and negative phase because the same current source is used and only the current through the electrode is reversed. A blocks schema for the stimulator is shown in Fig. 4. The DLC will generate all the control signals for the stimulus shape, amplitude/duration of the stimulation and recovery phase, frequency and channel activation among other programmable features.

When using the stimulator with cuff electrodes, any anode can be associated to any cathode allowing not only longitudinal stimulation but also transversal. The sieve electrode has been housed with a multiplexer to reduce the number of wires to access any specific electrode contact then the external channel selector will generate the number of pulses to select an specific cathode in the sieve. Stimuli are applied between the selected cathode and a common anode.

Specific circuitry and channel activation sequence has been implemented to reduce initial spikes in stimuli generation and also an impedance measurement module with electrode testing purposes has been added to each cathode terminal.

4. One channel recording.

A full differential preamplifier followed by two signal amplifiers has been designed, fabricated and tested to have very good performances such as a low noise (5nV/√Hz), very low input (1-200 μV), low frequency range (100-5000 Hz), high gain (70-100 dB) and high common mode rejection ratio (90 dB). A linear implementation with a CMOS technology has been used to assure the high CMRR because there are not components between the electrode and amplifier inputs. Specific design techniques have been used to obtain high time constants in a reduced silicon area to solve one of the most important problems appearing working with neural signals. The solution implemented has been proven to be very efficient to obtain a band pass amplifier for the above range of frequencies.

5. Method to use the Stim/Rec

The Stim/Rec circuit has been developed thinking that it can be used in different applications like a general-purpose stimulator or as a part of an implantable stimulator [Cyber]. If it is used in a local bus, for example with a microcontroller to control the stimulator, the system uses a 8 bits bus for Data, Rd/Wr and CS signals. On the other hand if the Stim/Rec is used in an implantable system a 3 wires serial bus for data and 2 for power supply will allow placing the system as near as possible to the electrodes and far from the telemetry. For programming the Stim/Rec a frame with the format (Ic-Number, Command, Parameters) is used. To implement all possibilities and make the design simple each command is the internal bus address used in the Stim/Rec. In Table 1 can be shown 3 different actions and its frames.

Action	Command	Parameter
Program Frequency 1	0x100	Period
Enable Frequency 9 & 1	0x009	0x021
Force Stimulation Ch 2	0x010	0x002

Table 1: Example of frames for programming

The methodology used to implement the proposed stimulation-recording circuitry is that followed in a mixed (analogue/digital) circuit. The recording block and the analogue part of the stimulator is a full custom analogue CMOS design while for the digital logic block a semi-custom strategy is followed. Because the high voltage requirement of the analogue part of stimulator, a high voltage technology is needed then, I2T100 compatible with CMOS 0.7 micron has been used. A micro-photograph of the developed circuit is shown in Fig. 5.

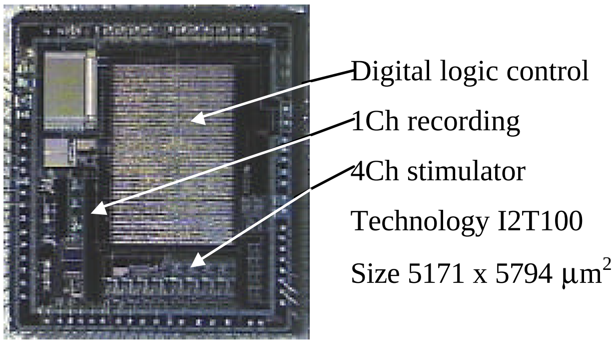


Fig. 5: Picture of recording-stimulation circuitry

Results

The full operation of stimulator and recording circuitry including the digital part for programming and controlling the two blocks have been tested at the laboratory and also the monolithic prototype developed with the test application has been used in experiments with animals. Results in Table 2 show the electrical characterization of stimulator.

The resolution in the amplitude is higher than specified resulting in a higher full range. Moreover, a higher stimulation frequency can be programmed with a lower resolution if necessary but this is not considered of interest in biomedical applications. Table 3 shows typical parameters defining the full amplifier operation, it is important to notice the perfect correspondence between the experimental and simulation results.

In this amplifier the gain in the band as well as the low cut-off frequency are digitally programmed for a better adaptation to input signal.

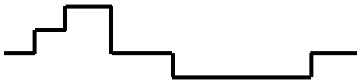
Parameter	Value
Amplitude	3 - 184 μA resolution 3 μA 30 - 1840 μA resolution 30 μA
Pulse duration and Inter-delay	4 – 1024 μs resolution 1 μs
Standard waveform	16 different waveforms 
Charge recovery	Exponential programmable extra charge recovery
Stimulation frequency	7 - 200 Hz resolution 1 H 200 - 300 Hz resolution 3 Hz 16 different frequencies
Impedance measurement	500 – 22 kΩ

Table 2: Stimulator electrical characterization

When the higher low cut-off frequency is programmed a better noise performance is got and the rejection of muscular and electrode interface contamination is also higher. The decay of gain for the low and high corners is 60 and 40 dB respectively.

Parameter	Simulation	Experimental
Gain in the band (dB)	75, 83, 97, 103	76, 80, 96, 102
Noise (nV/√Hz)	4.9	5
CMRR (dB)	96	94
Low cut-off freq. (Hz)	97,116,206,385	106,119, 201,352
High cut-off freq. (Hz)	5.3 kHz	8 kHz

Table 3: Results for recording amplifier

The developed monolithic prototype optically isolated has been used in experiments with animals. It was used to test muscular activity produced with biphasic charge compensated stimuli applied at different frequencies and also spatial selectivity is accomplished using amplitude and pulse width modulation. In Fig. 6 results obtained with a Sprague-Dawley rat stimulating the tibial nerve and signal recording in plantar muscle using microneedle electrodes for the recruitment with amplitude modulation is shown.

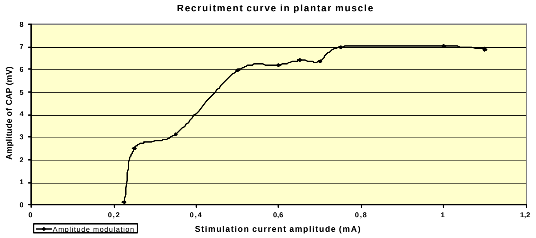


Fig. 6: Recruitment curve with amplitude modulation

Finally, in Fig. 7 the ENG signal recorded with a cuff electrode [3] in sciatic nerve in response to repeated pinpricks on hind limb skin is shown.

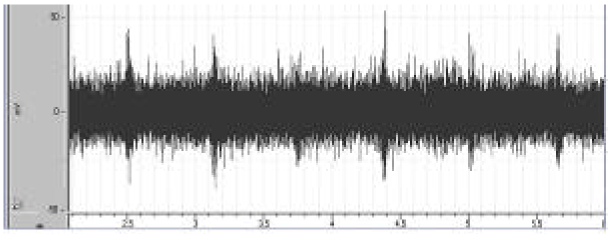


Fig. 7: Response to mechanical stimulation

Discussion

Actually functional electrical stimulation is being used in many applications and also in closed loop operation in order to improve restoring functions but there is not reported any system including natural sensors (stimulation and recording circuitry in the same ASIC) to implement the full system. Here we are presenting a general purpose stimulation-recording circuitry that can be used to fulfil these requirements in SCI subjects or in amputees. The system characterization obtained by electrical measurement at the laboratory and also the work carried out in acute experiments with rats has proven to work properly. Moreover, and because of its modular implementation, the system performances can be improved concerning the number of channels for the Stim/Rec device and also logical control flexibility allows to connect several devices with a few wires to the telemetric unit in implantable systems.

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