34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Development of an Implantable Neuro-Prosthetic System for Neural Stimulation and Recording

M.M. Samani, A. Mahnam, and S.M. Rabiee

Abstract— **Neural prostheses have been used to successfully treat various disabilities and neural diseases by stimulating neural tissues and recording neural signals. In this study, a neural prosthetic system was developed, consisting of a fully implantable unit, and an external control unit. The implant is programmed inductively by the controller to deliver flexible patterns of biphasic current stimuli in two channels to neural tissue. An Inductive link is used to power the implant unit and charge its battery. The implant unit can simultaneously record and transmit neural signals to the controller via an ISM(Intestinal-Scientific-Medical) band radio module. The same RF(Radio Frequency) link is used to send feedback signals from the implant to the control unit. The system is designed for small size (20x15x30mm) and very low power consumption (1.2mA baseline), which makes the system suitable for long term neuroscience and cognitive studies**.

I. INTRODUCTION

Nowadays, implantable neural prostheses are widely used to treat neural diseases such as Parkinson and Tremor, and disabilities such as hearing loss [1]. Many researchers are also working to develop prostheses to treat other neural diseases and disabilities such as Alzheimer, Epilepsy, and Blindness. Although these advances have helped many people with disabilities, there are still many challenges that have to be solved to develop high performance and optimized neural prostheses [2][3].

Limitations in the space and power resources force engineers to design implantable systems in very small dimensions and with ultra low power consumption. However, high performance neural prostheses would be complex and require high speed processing which lead to more power consumption and larger dimensions.

In all of the current neural prostheses, the treatments of diseases or disabilities are achieved by some kind of communication with the neural tissue which is performed by electrical stimulation and potential recording. Therefore, besides developing microelectronic systems, many researchers are working on more efficient methods of electrical stimulation and recording including efficient stimulation patterns and waveforms [4] and electrode tissue interfaces.

M. Mosayebi is with the Department of Biomedical Engineering, School of Engineering, University of Isfahan, Isfahan, IRAN.

A. Mahnam is with the Department of Biomedical Engineering, School of Engineering, University of Isfahan, Isfahan, IRAN. He is also a researcher at the school of cognitive sciences, Institute for research in fundamental sciences (IPM) (corresponding author; e-mail: mahnam@eng.ui.ac.ir).

S.M. Rabiee is with the Mechanical Engineering Department, Babol Noshirvani University of Technology, Babol, Iran.

The required energy to supply the prostheses is usually provided by an internal battery or with an external power supply that transmit power inductively to a coil under the skin. In modern prostheses, this inductive link is also used to transmit the required parameters to the implant and to receive back data from it.

Many researchers have developed neural prostheses with the same general structure described above, but with unique functionalities or applications.

Liang et al. [5] have developed an implantable system for neural recording. The implant receives power via an inductive link at 2MHz and the neural recorded data is transmitted back via the same inductive link with 115kbps data rate. The system has been tested in rabbits for recording the neural activity of the sciatic nerve. Their implant system, which is 45x30x12mm in size, consumes approximately 90mW power. The designed system does not have a battery and needs the inductive link to power up and transmit the recorded data, hence the animal cannot move freely.

Donaldson et al. [6] have designed an implantable telemeter system that is supplied by a Li-ion rechargeable battery. The battery is charged through an inductive link working at 4MHz. The same inductive link was used to return the recorded neural signals at 380 kHz. The implant system is 54x28x7mm in size and has been optimized for long term electroneurographic recording in human and animals. In this system, although the inductive link is not necessary to power up the implanted circuit, it is necessary to receive the recorded neural signals and this confines the area of movements of the animal under test.

Smith et al. [7] have developed an implantable stimulator telemeter system. The system is powered inductively at 6.87MHz. This inductive link is also used to send the required commands to the implant unit. The designed thick-film substrate system has dimensions of 25x37.5mm, and has ten stimulation channels integrated in a designed chip.

The aim of this study was to design and implement a fully implantable stimulator/recorder neural prosthesis that can be used practically in freely moving animal studies. This was considered as a step towards development of neural prosthesis for clinical use.

II. THE DESIGNED SYSTEM

In this study, an implantable neural prosthetic system was developed for both stimulating and recording from neural tissue. The system consists of a fully implantable unit, and an external control unit (Fig.1).

The external controller provides a simple user interface to get the stimulation and recording parameters, and to program and control the implant unit via an inductive link. The link also recharges the battery of the implant. Control feedback from the implant as well as the recorded neural signals are transmitted however, via an ISM band radio module. The inductive link is derived by a high efficiency class-E amplifier, which includes an AM data modulator.

The implant, based on received instructions from the controller, can deliver flexible patterns of biphasic current stimuli in two channels to neural tissue or simultaneously record and transmit neural signals to the controller. The unit is designed for low power consumption (1.2mA baseline), and small dimensions (20x15x30mm), which makes it appropriate for long term cognitive and neuroscience studies.

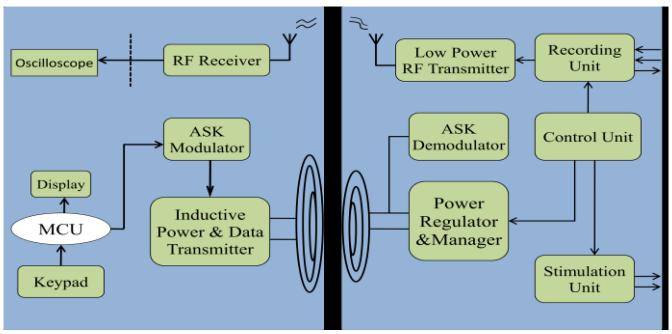

Figure 1. Block diagram of the designed system, including the control unit (left) and the implantable unit (right).

A. External Control Unit

A user interface was implemented in the external control unit using a PIC microcontroller(Microchip Technology Inc). A 4x4 keyboard and a 16x2 liquid crystal display are used to set parameter values, to change the value of any desired parameter, and to send the parameter set to the implant unit. The interface also enables the user to start or stop the stimulation and recording, and shows the user the confirmation signals received from the implant unit.

In order to supply enough power to the receiver coil through the skin, a high-efficiency transmitter/amplifier was developed. Class-E power amplifiers show efficiencies better than 70% and are suitable for low coupling applications [8].

Fig. 2 shows the basic circuit of a class-E amplifier. The switch can be implemented by a power MOSFET which is switched on and off periodically by a driver circuit. C_t and L_t constitutes a resonant circuit adjusted for the resonating frequency, equal to the switching frequency of the MOSFET. L_t actually represents the inductance of the transmitting coil. When the switch is off, the combination of the power supply and the choke, L_{chock}, acts as a current source, charging the resonant network and creating a transient voltage across the switch that rises and falls. When the switch is on, its current rises smoothly until the switch is off again. Losses are kept at minimum by having the transistor switch on at the moment that the voltage across it is zero. The class-E amplifier was designed for 4MHz operation in our circuit.

ASK(Amplitude Shift Keying) modulation was used to transmit data via the same inductive link. This was achieved by a transistor in series with L_{chock}, which changed the effective supply of the class-E amplifier. For our system the data rate of 2kHz was enough, since the link was only used to program the implant unit.

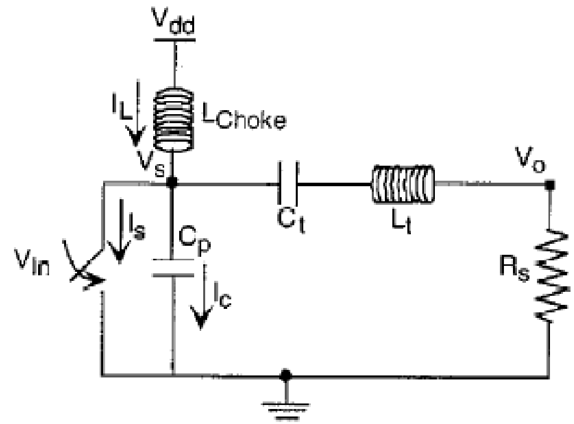

Figure 2. The basic schematic of a class E Power Amplifier.

The transmitted neural bio-signal is received by a 869MHz FM radio module and then filtered and amplified for viewing with an oscilloscope or data acquisition system. A comparator with hysteresis was also implemented in the receiver module to receive digital feedback from the implant unit and pass it to the microcontroller. This feedback indicates the state of the implant and is used as a confirmation for errorless communication between control and implant units.

B. Implantable Unit

In this unit the 4MHz sinusoidal signal from the control unit is received by a tiny flat spiral coil. The signal is rectified by a Schottky diode full bridge to supply the required energy to charge the internal 3.7v Li-ion battery of the implant, and/or power the implant system, itself.

The received signal was also filtered and demodulated using a comparator to extract the received data and pass it to the UART module of the internal microcontroller.

The control unit of the implant system consists of a PIC microcontroller and two analog switches. The microcontroller turns the stimulation and recording unit on and off as necessary to keep the power consumption of the implant as low as possible.

As soon as receiving the activation command, the microcontroller starts producing the stimulation pattern as programmed, by sending appropriate data to a digital to analogue converter (DAC). The DAC uses 2.5V external voltage reference to produce a signal in the range of 0 to 2.5v. The DAC output is applied to a modified Howland voltage controlled current source (VCCS) [9] [10] to produce the output current correspondingly (Fig.3).

The VCCS is directly powered by the 3.7V battery for improved output compliance. To make the Howland current source both sink and source the current, while powered by a single supply, an extra op-amp was used as a biased inverter to create a push-pull current source. This also doubles the output compliance of the current source.

The general pattern of stimulations that can be produced by the system is demonstrated in Fig. 4. The stimulator can deliver specified number of repetitive asymmetric biphasic current pulses, providing good flexibility to produce the stimulation patterns required in different experiments. In addition to the amplitudes and durations of each phase of biphasic stimulus pulses, the user can adjust the inter stimulus intervals and the number of stimulus pulses applied by the stimulator in a run.

An ultra low power precision instrumentation amplifier with gain 10 was used as the pre-amplifier of the recording unit(INA118,). The high input impedance, low input bias current and high common mode rejection ratio of this amplifier is ideal for recording neural bio-potentials. A band pass filter consisting of a high pass filter with gain 10 and a unity gain low pass filter has been used to attenuate the noise outside the desired bandwidth of 100Hz to 10 kHz. A programmable gain amplifier has been designed as the final stage of the recorder to have total gains of 500, 2500, 5000 and 7000, suitable for neural signals.

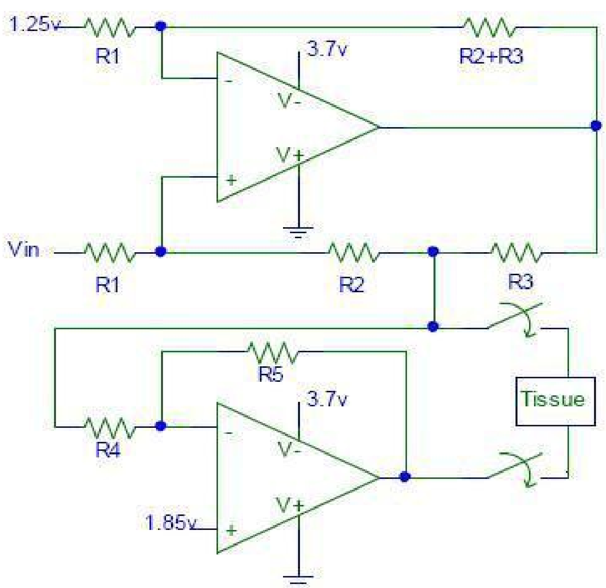

Figure 3. The modified Howland Voltage Controlled Current Source (upper opamp), that works with a single supply, applies a current proportional to its differential input to the tissue via an electrode. Instead of connecting the other electrode to a virtual ground of 1.85V, it is connected to the lower op-amp which doubles the compliance by acting as an inverting amplifier.

C. Packaging

The electronic modules were implemented on two printed circuit boards , sit in front of each other, for lower size. The whole implantable unit was packaged for long term operation inside the body. The electronic modules, as well as the coil, were sealed using PMMA (Poly Methyl Methacrylate) which has a good bio-compatibility. The connecting wires, however, were sealed with silicon rubber, for enough flexibility.

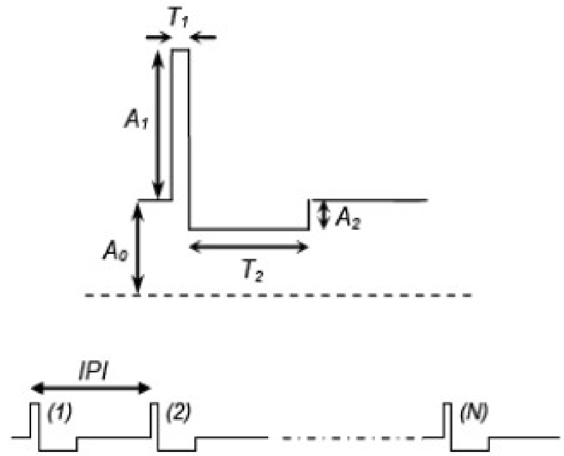

Figure 4. The general pattern of stimulations produced by the stimulator unit. The adjustable parameters of the stimulation pattern are: A0: the baseline amplitude, A1: amplitude of the first phase and A2: amplitude of the second phase of the stimulation pulse, T1: duration of the first phase, and T2: duration of second phase, IPI: Inter pulse interval, N: Number of pulses in a run of the stimulation.

III. RESULT

To confirm the performance and the reliability of the designed system, the stimulation and recording units of the implant was tested both with a resistor network and with the saline solution as a model of the tissue (Fig. 8).

The output compliance of the stimulation unit was evaluated for a maximum load of 1.5kΩ. The system could deliver stimulus pulses up to ±2mA to this load. The pulse widths could be programmed to be as short as 80µA. The VCCS demonstrated high output impedance, so that the current output changes only 0.7µA when the load impedance changes from 0.5 to 1.5KΩ.

A sample stimulation train of asymmetric bipolar pulses produced by the system is demonstrated in Fig. 6. The time constant of the stimulus pulses was 12µs.

Fig. 7 shows the recorded potential from saline solution, when the stimulator is delivering symmetric biphasic current pulses to the solution. The rounded edges and decreasing amplitude of the pulses are expected due to the limited bandwidth of the recorder.

The system can work in stand-by mode for about four days without charging, and can stimulate and record simultaneously for more than 10 hours.

A whole system before sealing is shown in Fig. 8, while the sealed implantable part is demonstrated in Fig. 9.

IV. CONCLUSION

In this study a fully implantable neural prosthesis was developed. The implantable system can deliver trains of asymmetric bipolar stimulus pulses up to 2mA to a maximum load of 1.5kΩ. It also measures neural bio-potentials directly from inside the body and transmit them wirelessly to the external unit. This makes the designed system, an appropriate candidate for a variety of neuro-physiological experiments on freely moving animals.

The implemented system demonstrates reliable performance with very low power consumption, ideal especially for experiments in which hours of continuous stimulation and recording is required.

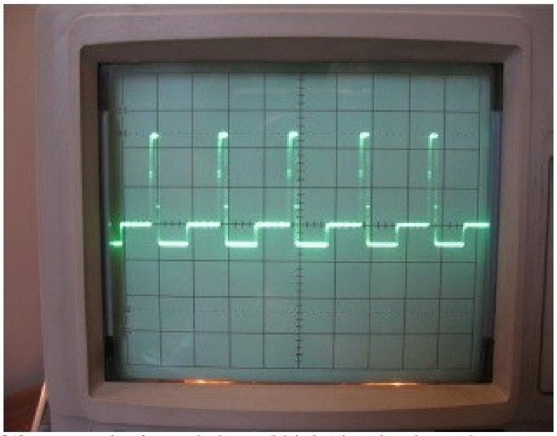

Figure 6. Asymmetric charge balanced biphasic stimulus pulses generated by the stimulator

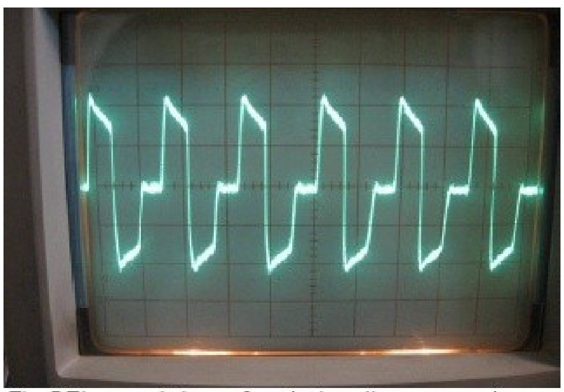

Figure 7. The recorded waveform in the saline test experiment, demonstrates high signal to noise ratio of the recording module.

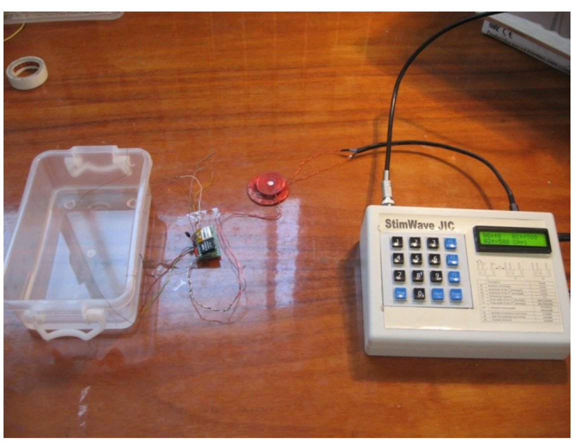

Figure 8. The whole system under saline test for proper electrical functionality prior to sealing. From left to right are the saline solution, the implantable unit, the coils and the control unit.

Figure 9. The sealed implantable unit. The small size of the unit makes it appropriate to be implanted in small animals.

REFERENCES

[1] A. Prochazka, V.K. Mushahwar, D.B. McGreery, "Neural Prostheses", J Physiol, Vol. 533(1), pp. 99-109, 2001.

[2] W.M. Grill, S.E. Norman, R.V. Bellamkonda "Implanted Neural Interfaces: Biochallenges and Engineered Solutions", Annu. Rev. Biomed. Eng., Vol. 11, pp. 1–24, 2009.

[3] A.P. Chandrakasan, N. Verma, D.C. Daly, "Ultralow Power Electronics for Biomedical Applications", Annual Review of Biomedical Engineering", Annu. Rev. Biomed. Eng. Vol. 10, pp. 247-274, 2008.

[4] M. Sahin, Y. Tie, "Non-rectangular waveforms for neural stimulation with practical electrodes", J. Neural Eng., Vol. 4, pp 227, 2007.

[5] C-K. Liang, J.J. Chen, C.L. Chung, C-L Cheng, "An implantable bidirectional wireless transmission system for transcutaneous biological signal recording", J. Physiol. Meas., Vol. 26, pp. 83–97, 2005.

[6] N. Donaldson, L. Zhou, T.A. Perkins, M. Munih, M. Haugland, "Implantable telemeter for long-term electroneurographic recordings in animals and humans", J. Med. Biol. Eng. Comput., Vol. 41, pp. 654-664, 2003.

[7] B. Smith, Z. Tang, M.W. Johanson, S. Pourmehdi, et al, "An Externally Powered Multichannel Implantable Stimulator- Telemeter for Control of Paralyzed Muscle", IEEE Trans. Biomed. Eng. Vol. 48, pp. 397–400, 2001.

[8] B. Ziaie, S.C. Rose, M. Nardin, "A self-oscillating detuning insensitive class-E transmitter for implantable Microsystems", IEEE Trans. Biomed. Eng., Vol. 45, 1998.

[9] D.X. Chen, X. Deng and W.Q. Yang, "Comparison of three current sources for single-electrode capacitance measurements" Rev. Scient. Instrum., Vol. 81(3), 2010.

[10] P. Pouliquen, J. Vogelstein, R. Etienne-Cummings, "Practical considerations for the use of a Howland current source for neurostimulation", proc. BioCAS 2008, pp. 33-36, 2008