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A wireless 64-channel ECoG recording Electronic for implantable monitoring and BCI applications: WIMAGINE

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***Abstract*— A wireless, low power, 64-channel data acquisition system named WIMAGINE has been designed for ElectroCorticoGram (ECoG) recording. This system is based on a custom integrated circuit (ASIC) for amplification and digitization on 64 channels. It allows the RF transmission (in the MICS band) of 32 ECoG recording channels (among 64 channels available) sampled at 1 kHz per channel with a 12-bit resolution. The device is powered wirelessly through an inductive link at 13.56 MHz able to provide 100mW (30mA at 3.3V). This integration is a first step towards an implantable device for brain activity monitoring and Brain-Computer Interface (BCI) applications. The main features of the WIMAGINE platform and its architecture will be presented, as well as its performances and *in vivo* studies.**

I. Introduction

Disability due to traumatic spinal cord injury (SCI) presents a significant socio-economic concern that, until the advent of Brain-Computer Interface (BCI) technology, allowed little hope to patients. BCI systems may be used to interface devices, such as neuroprostheses, that restore neurological functions to handicapped patients. BCIs analyze the electrical signals from the brain and identify patterns correlated with mental images of movements. Patients with motor deficits secondary to post-traumatic lesions of the spinal cord can still generate motor images that can be registered through surface or implanted electrodes.

Neuronal activity has been recorded using scalp electrodes[1], epidural[2], or subdural electrodes[3], and intraparechymal microelectrode arrays[4]. EEG (Electroencephalogram) recording is comparatively safe but requires the user to wear a non-ergonomic EEG helmet, necessitates daily repositioning and BCI system recalibration, possibly affecting electrode correspondence with a high number of degrees of freedom (DoF) prosthesis. Microelectrodes are exquisitely sensitive tools to record spikes and local field potentials, avoiding low signal to noise ratios and high impedances encountered in EEG. They are however highly invasive, risking neurological deficits. Using epidural or subdural grids for recording ECoG signals, provides significantly better quality than EEG and presents fewer complications than microelectrodes. Permanently implanted ECoG-based BCIs do not require recalibration and provide a long-term, low maintenance solution to quality and lifestyle issues.

To address this challenge, CEA/LETI/CLINATEC® is currently conducting a project to develop a neuroprosthesis, based on ECoG measurements in order to compensate for motor deficits in tetraplegic patients. More precisely, this project aims at developing an implantable medical device for real time multi-electrode recording and wireless transmission of the ECoG signals of each electrode to an external computer housing the algorithms and control software. The present study is a first step towards it.

II. The WIMAGINE electronic architecture

The WIMAGINE [6] (Wireless Implantable Multi-channel Acquisition system for Generic Interface with NEurons) platform was developed as a proof of concept and first functional prototype of an implantable device for recording ECoG signals on a large number of electrodes. The goal of the present work is to develop the miniaturized electronics for a 64-channel ECoG recording system while using as much as possible COTS (commercial-off-the-shelf) components dedicated for implantable applications. The design of the WIMAGINE platform takes into account all the constraints of an implantable medical device: ultra-low power, miniaturization, safety and reliability.

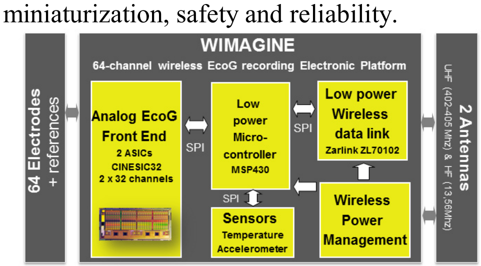

Figure 1: The WIMAGINE Architecture

Our design (Fig. 1) uses an MSP430 ultra-low power microcontroller to control the different modules, a wireless power management module and a Zarlink low power wireless data link module. No component was identified as commercially available for ECoG signal amplification and analog to digital conversion. Therefore, a dedicated Application Specific Integrated Component (ASIC) has been developed.

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A. Analog Front end: ASIC CINESIC32

Interfacing electrodes using discrete components rapidly limits the number of channels, creating the need for highly integrated solutions to achieve sufficient spatial resolution [5]. For this purpose, the dedicated ASIC CINESIC32 [7] (CIrcuit for NEuronal SIgnal Conversion 32 channels) was developed with the constraints of implantable applications in mind: ultra-low power consumption and patient's safety.

The ASIC filters, amplifies and digitizes the ECoG data acquired from the electrodes. The architecture of CINESIC32 is shown in Figure 2.

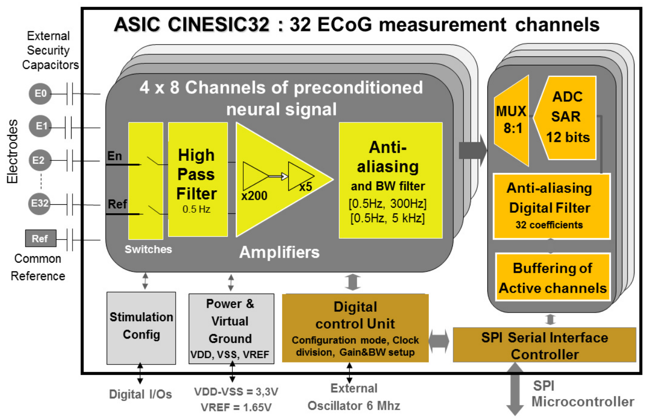

Figure 2: Architecture of the CINESIC32 ASIC

Each input channel is combined with an external capacitor (1.5nF) in order to suppress the risk of leaking current in a first default condition, which is essential for implantable devices. The AC-coupled analog channel comprises a fully differential low-noise amplifier, followed by a voltage gain amplifier and a programmable low-pass filter. Digital peripherals such as configuration registers and a SPI (Serial Peripheral Interface) controller are also integrated on the chip. A dedicated protocol was defined to address configuration registers. Consequently, the user can turn each channel ON or OFF, program the input switches in different modes and put the amplification stages in different gain and bandwidth settings. The analog filter cut-off frequency can be configured to 400Hz or 3kHz. The use of a 32^{nd} order digital low pass filter gives a cut-off frequency of 290Hz. After amplification the signal is sampled and digitized through a 12-bit ADC. The consumption of the ASIC with 32 active channels at 1kHz sampling frequency (typical use) is 3,73mA. The CINESIC32 chip was designed in CMOS 0.35µm technology (fig. 3). It has been tested and its features are listed in Table 1.

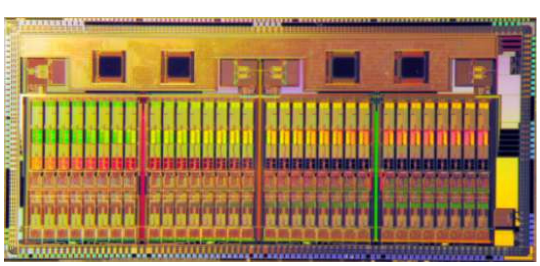

Figure 3: The ASIC CINESIC32 (dimensions: 13.5mm x 6.5mm)

TABLE 1: FEATURES OF ASIC CINESIC32

ASIC CINESIC32 performances summary (32 channels / 30 ASICs tested)		
Number of Channels	**32**	Modularity 4x8 channels
Gain	1 – 5 – 280 – **990** – 1370	Gain selectable on each channel
Bandwidth (selectable for each channel)	[0,25Hz - 400Hz] FIR OFF **[0,25Hz - 290Hz] FIR ON**	4^{th} order analog low pass Filter 32^{nd} order digital low pass Filter
	[0,25Hz - 3kHz]	4^{th} order analog low pass Filter
Input referred noise	**0,7uVrms**	Range [0,25Hz 290 Hz] gain 990
ADC Resolution	10,7 ENOB / 12-bit SAR	Max sample rate 24 kSps (3kHz/channels)
Sampling frequency	Typical: 400Hz, 600Hz, 1kHz, 3kHz	Same sampling frequency for all channels
Serial Interface	Standard SPI interface	Slave SPI
Oscillator	6MHz External Oscillator	6MHz Oscillator supply current : 1,9mA
Supply Current / Voltage	**3,73mA / 3,3V**	Current value for Typical use: gain 990, 32 channels, [0.25Hz, 400Hz] Bandwidth, 1kSps - Oscillator supply not included
	34µA	Supply current of one analog channel
Area	13505µm x 6620µm	Die chip
Process	AMS 0.35µm CMOS	AMS C35B4C3

The test of 30 ASICs CINESIC32 was performed using the WIMAGINE platform. This study aimed at identifying the most suitable selection criteria under given conditions and identifying dispersion due to the fabrication process. Key functionalities as power consumption, offset, RMS noise performances, gain dispersion, low and high cut-off frequencies dispersion have been tested on an automatic test bench to distinguish functional circuits from dysfunctional ones. This step is necessary for guaranteeing that the CINESIC32 ASICs embedded in the WIMAGINE board meet the specifications.

B. Microcontroller module

The MSP430F2618-EP from Texas Instruments was chosen for its ultra-low power characteristics, its multiple communication interfaces and because it belongs to the HiRel series from TI's Enhanced Products program. The MSP430 manages the remote power supply, controls the RF link, the data acquisition from the CINESIC32 and the two embedded sensors located on the WIMAGINE board: a temperature sensor (TMP121-EP from TI), and an accelerometer (ADXL345-EP from Analog Devices).

C. RF link module

Wireless communications for implanted devices use the Medical Implant Communication Service (MICS) band at 402-405 MHz. The RF communication module ZL70102 from Zarlink was chosen for its ultra-low power characteristics (5mA in RX/TX), its high data rate and because it was designed especially for implantable applications. On the WIMAGINE board, a SAW filter was employed to prevent interference from strong out-of-band RF signals. The matching network was defined in order to employ an antenna presenting 50Ω impedance. A specific antenna was designed by using a biocompatible platinum wire within silicone rubber. Throughput tests have been performed by means of an experimental set-up based on the WIMAGINE board and the antenna in a human phantom. An effective data throughput between 400 kbps and 450 kbps was measured over several hours, by employing 4-FSK modulation at few meters distance between the implant and the external device. These tests confirmed the feasibility of transmitting 32 channels with a 12-bit resolution sampled at 1 kHz per channel.

D. Wireless power management module

An implanted battery would require repeated recharge or surgeries. Moreover, there is no commercially available battery certified for implantable applications capable of providing sufficient power to supply the WIMAGINE board. Therefore an inductive link was developed using COTS components in order to remotely supply the WIMAGINE board with the required power. It is designed to provide 30mA at 3.3V with a 10cm² HF antenna made of a biocompatible platinum wire. The RF front-end combined with the implantable antenna comprises a rectifying stage, a shunt regulator and ultra-low noise LDOs (low-dropout linear regulator). The implanted receiving coil and the HF generator antenna were dimensioned together by optimizing the transmitted power for a nominal distance of 2cm between both antennas.

Moreover, this remote power link was designed in compliance with European recommendations for inductive applications (ERC7003) and with European recommendations for human exposure to EM fields (CE519). A theoretical specific absorption rate (SAR) of less than 0.01W/kg was achieved (maximum allowed: 2W/kg).

III. THE WIMAGINE PLATFORM

The WIMAGINE platform was designed to record an ECoG signal through an array of 64 platinum electrodes (diameter: 3mm²) at a pitch of 4.5mm. Two ASICs CINESIC32 were implemented on the WIMAGINE board in order to perform an ECoG signal amplification and analog to digital conversion on 64 channels. The WIMAGINE board was designed to be fitted into a cylindrical titanium housing of (diameter 50mm , height 7mm). As shown in Fig. 4 the WIMAGINE board is made up of two PCBs (diameter ~40mm) linked by a board to board connector. Both ASICs CINESIC32 and their external components are placed on one side of the PCB (at the bottom) while the other PCB (at the top) contains the MSP430 microcontroller, the wireless power module and the RF link components.

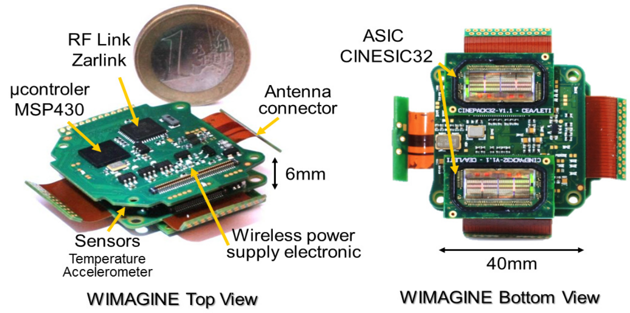

Figure 4: Photos of the WIMAGINE board

The experimental set-up used for BCI applications (Fig. 5) is made up of the WIMAGINE board, a terminal module comprising an EM field generator as power source and a RF receiver from Zarlink connected to a computer running the control software and the data processing algorithms (based on OpenVibe [8]) controlling the effectors. The Graphical user interface (GUI) allows the user to remotely control the implant through the RF link.

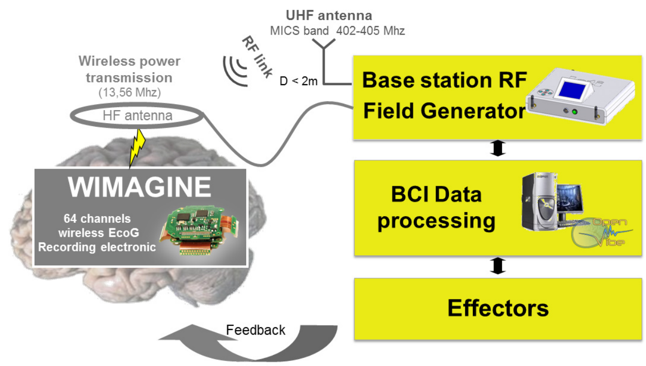

Figure 5: The BCI plateform based on WIMAGINE Board

The general characteristics and typical configuration of the WIMAGINE platform are summarized in Table 2.

TABLE 2: GENERAL CHARACTERISTICS OF THE WIMAGINE PLATFORM

General features of WIMAGINE Platform	
Acquisition analog front end	
Number of channels	64 (based on 2 ASICs CINESIC32)
Variable gain	1, 5, 280 or 990 (adjustable for each electrode)
Detection range	+/- 1.3mV (gain 990)
Bandwidth	0.25Hz to 290Hz
Resolution	12 bits - ADC architecture : SAR
Input referred noise	0.7µV RMS (in gain 990 and on BW [0.5Hz;290Hz])
Sampling frequency	600Hz, 1 kHz, 3kHz per channel (selectable)
Microcontroller and sensors	
Microcontroller	MSP430F2618-EP (Texas Instrument)
Embedded sensors	Temperature, accelerometer
RF link	
COTS component	Transceiver ZL70102 (Zarlink)
Transmission	402-405 MHz (10 MICS channels)
High data rate	400-450 kbps
Range	<2m
Inductive wireless power management	
Frequency	13,56MHz
Wireless power supply	Adjustable, up to 100 mW (30mA @ 3.3V)
WIMAGINE Board	
Power supply	25mA / 3,3V (on typical use: 32 channels sampling at 1kHz wirelessly transmitted)
Dimensions	2 stacked PCBs: 40 mm diameter, 7mm height

A. Graphical user interface

The WIMAGINE platform offers a Graphical User Interface (GUI) allowing rapid and easy setting of acquisition parameters like sampling frequency of the device and the gain of each electrode depending on the measured electrical activity. Furthermore, all data from the 64 channels can be saved and reloaded with the WIMAGINE software or analyzed later using Spike2 software (Cambridge Electronic Design Limited, UK).

IV. *IN VIVO* VALIDATIONS

In order to validate the functionalities of the WIMAGINE platform, we performed *in vivo* validation tests. The goal was to record the ECoG of a non-human primate implanted with a silicone-platinum cortical electrode array. Ethical approval for this experimental procedure was obtained from ComEth (IRB of the University of Grenoble, France) following guidelines of the FELASA (Federation of Laboratory Animal Science Associations), in accordance with the European Communities Council Directive of 1986 (86/609/EEC) for care of laboratory animals.

The electrodes were connected by wire through a transcutaneous connector to the WIMAGINE platform. Brain signals were acquired in a bandwidth 0.25Hz – 290Hz (Fig. 6). The recorded ECoG data was transmitted wirelessly and displayed in the GUI of the WIMAGINE platform. A standard protocol for visual and somato-sensory evoked potentials was applied and the stimulation trigger was recorded simultaneously through the WIMAGINE board. The ECoG measured signals, elicited by the median nerve electrical stimulation or light stimulation in the Non-Human Primate were recorded. The offline data were filtered, baseline corrected, averaged (on hundred answers to stimulation). The results displayed the characteristic shape in the motor cortex for the somato-sensory evoked potentials [9] (at ~10-15ms after electrical stimulation) and in the visual cortex for the visual evoked potentials [10] (at ~100ms after light stimulation). These preliminary results confirm the chosen approach for measuring ECoG signals.

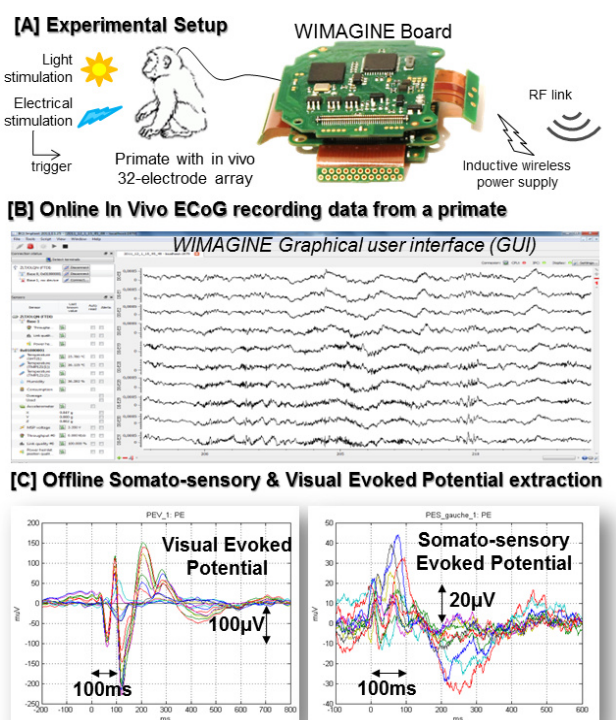

Figure 6: [A] Experimental set-up, [B] *in vivo* ECoG recording on the WIMAGINE user interface, [C], offline visual and somato-sensory evoked potential extraction on several electrode (each color curves) located respectively on visual cortex and motor cortex.

V. CONCLUSION

An innovative platform named WIMAGINE has been developed in the context of the BCI project, currently lead by Prof. A.L. Benabid in the context of the CEA/LETI/CLINATEC®. WIMAGINE platform is a wireless low power 64-channel data acquisition system dedicated to electrocorticogram (ECoG) recordings. *In vivo* tests of the WIMAGINE platform were successfully performed. The design of the WIMAGINE platform takes into account the constraints of an implantable medical device: ultra-low power, miniaturization, safety and reliability. Indeed, the next step is the development of an implanted medical device for wireless multichannel ECoG recording used in the development of a neuroprosthesis.

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REFERENCES

[1] Wolpaw, et al. *An EEG-based brain-computer interface for cursor control*. Electroencephalogr. Clin. Neurophysiol. 78, 252-259 (1991).

[2] Rouse, et al. *Neural adaptation of epidural electrocorticographic signals during closed-loop brain computer interface tasks*. Conf. Proc. IEEE Eng. Med. Biol. Soc. 2009, 5514-5517 (2009).

[3] EC. Leuthardt, et al. *A brain-computer interface using electrocorticographic signals in humans*. J. Neural. Eng. 1, 63-71.

[4] Nicolelis, MA. Brain-machine interfaces to restore motor function and probe neural circuits. *Nat. Rev. Neurosci.* 4(5), 417-422, (2003).

[5] O. Billoint, et al. *A 64-channel ASIC for in-vitro simultaneous recording and stimulation of neurons using microelectrode arrays,* Conf. Proc. IEEE Eng Med. Biol. Soc., vol. 2007, pp. 6070-6073

[6] G. Charvet, et al. "*WIMAGINE: A wireless, low power, 64-channel ECoG recording platform for implantable BCI applications*" 5th IEEE/EMBS Neural Engineering NER 2011 Conf. Proc, April 27-1 May 2011, p. 356-359

[7] S. Robinet, et al. "*A low-power 0.7VRMS 32-channel mixed-signal circuit for ECOG Recordings"* IEEE J. On Emerging and Selected Topics in Circuits and systems JETCAS Vol. 1. N°04 Dec 2011 p 451-460.

[8] Y. Renard, et al. **"***OpenViBE: An Open-Source Software Platform to Design, Test and Use Brain-Computer Interfaces in Real and Virtual Environments"*, Presence : teleoperators and virtual environments, vol. 19, no 1, 2010

[9] E. P. Gardner et al. *« Somatosensory evoked potentials (SEPs) and cortical single unit responses elicited by mechanical tactile stimuli in awake monkeys »* Electroencephalography and clinical Neurophysiologv, 1984, 58:537 552 (1984)

[10] E.W. Snyder et al. "*Visual evoked potentials in monkey*" Electroencephalography and Clinical Neurophysiology, 1979, 47:430--440