CLINATEC® BCI platform based on the ECoG-recording implant WIMAGINE® and the innovative signal-processing: preclinical results

Andrey Eliseyev, Corinne Mestais-*IEEE Member*, Guillaume Charvet, Fabien Sauter, Neil Abroug, Nana Arizumi, Serpil Cokgungor, Thomas Costecalde, Michael Foerster, Louis Korczowski, Boris Morinière, Jean Porcherot, Jérémy Pradal, David Ratel, Nicolas Tarrin, Napoleon Torres-Martinez, Alexandre Verney, Tetiana Aksenova-*IEEE Member*, Alim-Louis Benabid

***Abstract*— The goal of the CLINATEC® Brain Computer Interface (BCI) Project is to improve tetraplegic subjects' quality of life by allowing them to interact with their environment through the control of effectors, such as an exoskeleton. The BCI platform is based on a wireless 64-channel ElectroCorticoGram (ECoG) recording implant WIMAGINE®, designed for long-term clinical application, and a BCI software environment associated to a 4-limb exoskeleton EMY (Enhancing MobilitY). Innovative ECoG signal decoding algorithms will allow the control of the exoskeleton by the subject's brain activity. Currently, the whole BCI platform was tested in real-time in preclinical experiments carried out in non-human primates. In these experiments, the exoskeleton arm was controlled by means of the decoded neuronal activity.**

I. Introduction

A Brain Computer Interface (BCI) aims at providing an alternative non-muscular communication pathway to send commands to the external world for individuals suffering from severe motor disabilities. Commands are generated by means of decoding of brain neuronal activity. ElectroEncephaloGram (EEG) recordings of neuronal activity are widely used in BCI applications but require the user to wear a non-ergonomic EEG helmet, necessitate daily repositioning and recalibration, and the signal quality is not sufficient to control effectors with large number of degrees of freedom. Microelectrode recordings have performed successfully in BCI experiments in the laboratory, enabling closed-loop control of a computer cursor and a robotic arm. Despite encouraging successes in clinical applications [1], microelectrode recordings have yielded limited success outside of the laboratory, mainly due to unsolved problems regarding the long-term robustness of the recorded signals. Subdural or epidural ECoG electrode arrays recordings are less sensitive to artifacts, offer higher frequency and spatial resolution than EEG and are less invasive than microelectrode arrays. ECoG electrode arrays are a practical way to measure the electrical activity of the brain for BCI purpose. Minimally invasive less traumatic epidural ECoG chronic recording was chosen as a basic concept of the BCI project at CLINATEC®. The goal of the project is to improve the quality of life of tetraplegic subjects, by allowing them to interact with their environment through the control of effectors with multiple degrees of freedom. Most of the studies of ECoG based BCI have been limited to short-term experiments, and have been carried out in laboratory conditions [2]. An ultimate daily and "out-of-the-lab" BCI application requires longer durations of usage, and also requires the BCI system to be controlled by the users at their will without any external stimulus. Thanks to the innovative wireless 64-channel ECoG recording implant WIMAGINE® (Wireless Implantable Multi-channel Acquisition system for Generic Interface with NEurons) [3] as well as the original ECoG signal processing, the subject should be able to control a 4-limbs exoskeleton EMY after training.

Before applying the BCI platform to humans, a set of preclinical experiments are carried out with monkeys. These experiments allow preliminary evaluation of the system, as well as early identification and elimination of its shortcomings.

A. Eliseyev is with CEA, LETI, CLINATEC; MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex, France (corresponding author, phone: +33-438-785-375; e-mail: eliseyev.andrey@gmail.com).

C. Mestais, G. Charvet, F. Sauter, N. Arizumi, S. Cokgungor, T. Costecalde, M. Foerster, J. Pradal, D. Ratel, N. Tarrin, N. Torres-Martinez, T. Aksenova, A.-L. Benabid are with CEA, LETI, CLINATEC; MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex, France (e-mail: corinne.mestais@cea.fr, guillaume.charvet@cea.fr, fabien.sauter@cea.fr, arizumi@gmail.com, serpil.cokgungor@cea.fr, thomas.costecalde@cea.fr, michael.foerster@cea.fr, louis.korczowski@gmail.com, jeremy.pradal@gmail.com, david.ratel@cea.fr, nicolas.tarrrin@cea.fr, napoleon.torres-martinez@cea.fr, tetiana.aksenova@cea.fr, alimlouis@sfr.fr.

J. Porcherot is with CEA, LETI, DTBS; MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex, France (e-mail: jean.porcherot@cea.fr)

N. Abroug, B. Morinière, A. Verney are with CEA LIST, DIASI/LRI; DIGITEO Labs; rue Noetzlin, 91190 Gif sur Yvette (e-mail: neil.abroug@cea.fr, boris.moriniere@cea.fr, alexandre.verney@cea.fr).

II. CLINATEC® BCI platform

A. ECoG recording implant WIMAGINE®

BCI clinical applications are related to the technical challenges intrinsic to implantable medical devices [4, 5]. In the CLINATEC® BCI project, the ECoG signals from the subject's brain are recorded and wirelessly transmitted to a base station by the WIMAGINE® implant [3]. This implant is composed of an array of 64 biocompatible electrodes, a hermetic titanium housing which includes electronic boards,

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biocompatible antennae for wireless transmission of the data, and a remote power supply. The general view of the implant is represented in Fig. 1.

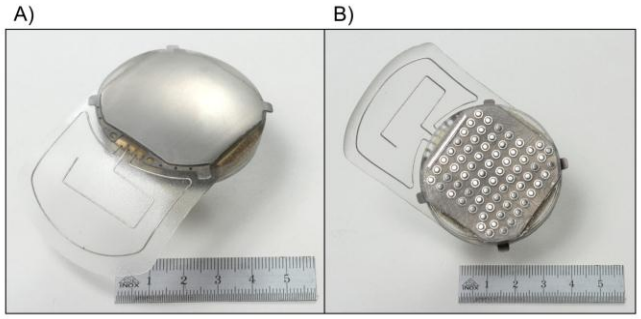

Figure 1: WIMAGINE® implant. A) top view, B) bottom view

The design of the WIMAGINE® implant addresses all the constraints of a fully implantable medical device, such as ultra-low power, miniaturization, safety and reliability. The required tests to demonstrate the implant's compliance to the European Directives for Active Implantable Medical Device (Directive 90/385/EEC and European standard EN 45502-2-1) are in progress in certified laboratories.

The BCI Platform can include up to two WIMAGINE® implants with a base station and a PC application (Fig. 2A). The base station acts as a gateway between the PC application and the WIMAGINE® implants. A headset is used to position and maintain antennae dedicated to provide the remote power supply to each implant and to receive the raw ECoG data over a proprietary UHF link in the Medical Implant Communication Service (MICS) band.

B. *Software platform*

CLINATEC® BCI software platform (Fig. 2B) aims at providing the environment for coordinated operation of all the components of the system from the signal acquisition to the exoskeleton control. In particular, the ECoG signal is processed using a dedicated algorithm to extract predictions of movement which are converted into commands to control the exoskeleton.

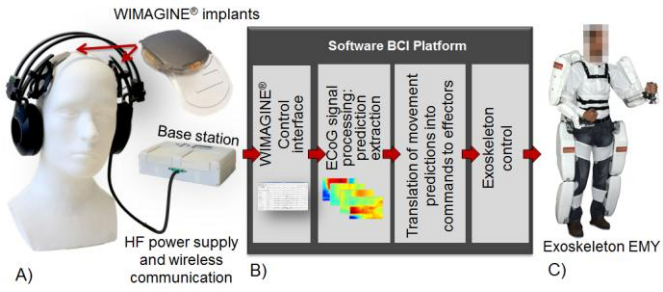

Figure 2: CLINATEC® BCI Platform. A) Two WIMAGINE® implants record ECoG activity of the brain and send signals wirelessly to the base station. B) The software platform analyzes ECoG data in real-time and generates the commands to the external effector. C) A full-body exoskeleton, dedicated to medical purposes, allows the subject to interact with the surrounding environment

The software platform consists of several software modules specially developed (in C/C++) for this application. The ECoG recording part (based on WIMAGINE® implants) is carried by the following software modules: Implant Software (IS), Terminal Software (TS), Wireless Implant Software Control Interface (WISCI) & Embedded Device Controller (MEDOC). The Online ECoG signal decoding part is performed by the Online Cerebral Decoder (OCD), and the exoskeleton control part is ensured by EMY Motion Manager (EMM), and EMY Motion Controller (EMC). The detailed block scheme of the software system is represented in Fig. 3.

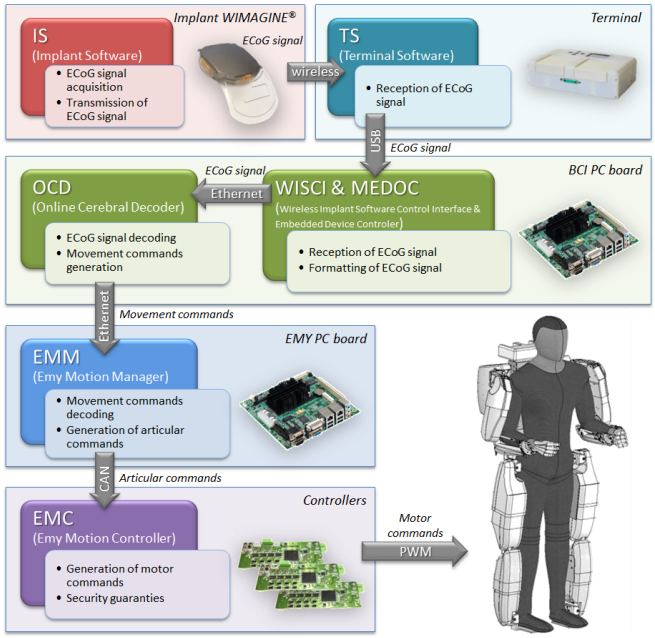

Figure 3: Block scheme of CLINATEC® BCI software system

C. *ECoG signal decoding*

The neuronal signal processing (patented) approach of CLINATEC® [6, 7] (Fig. 2B) is based on a tensor data analysis. It allows simultaneous treatment of the signal in several domains, namely, frequency, temporal, and spatial (Fig. 4).

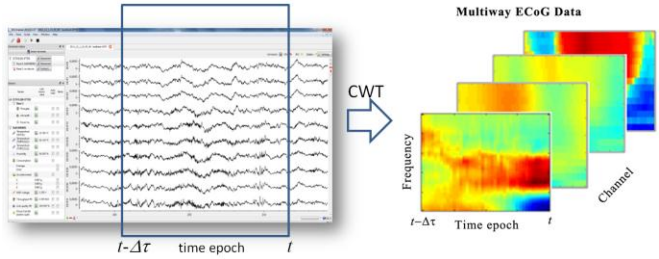

Figure 4: Time epochs of the multi-channel ECoG recording mapped to the temporal-frequency-spatial feature space

The algorithm consists in two stages. During the first stage (calibration), the control model is adjusted to a particular subject. During the second stage (execution), the model allows controlling an external effector (e.g., exoskeleton) through the subject's neuronal activity. For calibration, the high dimensional tensor-value explanatory variables are extracted from the signal by means of continuous wavelet transform (CWT). A decoding model is identified using the tensor-decomposition methods. The

block-wise algorithms [6, 7] allow calibration of the BCI system in the case of high resolution of the data tensor. The single-pass block-wise algorithm [7] provides an adaptive learning, whereas the sparse approach [6] improves the decoding performance. The calibrated model is integrated to the BCI software environment.

The volatility of the wireless connection introduces temporal loss of the signals, i.e., gaps in the data stream. To define and to evaluate the stability of the decoding algorithm to the loss of data, a set of computational experiments were carried out. The goal of the experiments was to compare the decoding performance of the algorithm using the signal without gaps and using the same signal, contaminated by the gaps. In particular, a known epidural-ECoG signal from the Japanese macaques [8] was corrupted with artificial sequences of the gaps. The sequences were generated according to the gaps' distribution in the wirelessly transmitted signals and then imposed on the gaps-free data. The empirical distribution of the gaps was approximated by a mixture of three gaussians with the expectations 3 ms (39%), 14 ms (24%), and 60 ms (37%), respectively. In order to have a sufficient population and to prevent any instability from the signal processing, the number of the gaps was increased 100 times. The decoding performance was studied for the cases of application of different methods of gaps' filling, namely, Zero-Order Hold, First-Order Hold, Autoregressive Model (8^{th} Order), Spline Cubic Interpolation, Piecewise Polynomial Interpolation, Sinusoidal Amplitude L1 Estimation, and Sinusoidal Amplitude and Phase L1 Estimation [9]. In all the cases, the algorithm has demonstrated significant robustness. The biases of prediction (normalized averaged root mean squares) were, correspondently, 1.4%, 1.4%, 1.4%, 3.6%, 1.4%, 1.8%, 1.3%, and 1.3%. Thus, even in the simplest case of the filling, namely, Zero-Order Hold, the influence of the data loss on prediction was negligible.

A particular requirement for the BCI system is stability and robustness in the case of real-time operation. The control system, developed by the CLINATEC® team, successfully meets BCI requirements.

D. EMY Exoskeleton

EMY is a full-body exoskeleton, dedicated to medical purposes and developed by the interactive robotics unit of CEA LIST [10-12] (Fig. 2C). The current EMY architecture features four limbs, two legs with three degrees of freedom each, and two ABLE® anthropomorphic arm exoskeletons with seven degrees of freedom. EMY is powered by an external electrical source and has a deported control electronics. The particular design of EMY's limbs allows accurate torque control which is achieved using a patented, streamlined, mechanical transmission (screw-cable system) that minimizes friction and inertia. This architecture ensures that the current in the motor is an accurate image of the joint torque, so there is no need for a torque/force sensor. This is both simple and reliable while remaining energy-efficient and cost-effective. The interface between the BCI and the robot is achieved by the physics-simulation framework XDE® [13]. The simulation layer allows EMY to be controlled at different levels of complexity, like joint motions, Cartesian motions, or Cartesian programmed trajectories.

E. Preclinical experiments

The preclinical experiments in a monkey were carried out in a male Macaque Rhesus. Ethical approval for them was obtained from ComEth (IRB of the University of Grenoble, France) in accordance with the European Communities Council Directive of 1986 (86/609/EEC) for care of laboratory animals.

The implant WIMAGINE® cannot be implanted on primate's skull since it was designed to be compatible with human's skull dimensions. Thus, a silicone/platinum-iridium cortical electrode array (PMT® Corporation, Chanhassen, USA) was implanted in the region of monkey's left motor cortex. It was connected to the recording electrodes of the implant WIMAGINE® by means of a transcutaneous connector and a specially designed test assembly. The electrode array of the WIMAGINE® and the one used for monkey have exactly the same pitch (4.25 mm), the same material: platinum iridium (silicone rubber for insulation) and the same contact area (3.14 mm^2).

The setup of the experiment is represented in Fig. 5. The monkey was trained to reach an exposed target using the right hand. The hand movements were recorded by an optical motion capture system Vicon (Motion Systems, Oxford, UK). During the calibration stage, the monkey's ECoG data were used together with information about the hand position to identify a prediction model. This model was applied to the ECoG data on the second stage to generate control commands for the arm prosthesis. Fig. 6 illustrates the relative weights of the linear model coefficients in the spatial and frequency domains. In the spatial domain, the weights of different electrodes significantly vary. Application of the sparse model identification approach [6], leads to selection of a small subset of the most informative electrodes, namely 2, 3, 4, 8, 13. In the frequency domain, high frequencies (from 80 Hz up to 150 Hz) have the highest contribution. At the same time, the frequencies in the band [30, 40] Hz as well as around 10 Hz also have a significant contribution. The results of the motion prediction are demonstrated in Fig. 7. The quality of the obtained prediction allows application of the proposed approaches in humans. Moreover, the high performance of decoding authorizes reproducing the arm movement by the exoskeleton arm in real-time.

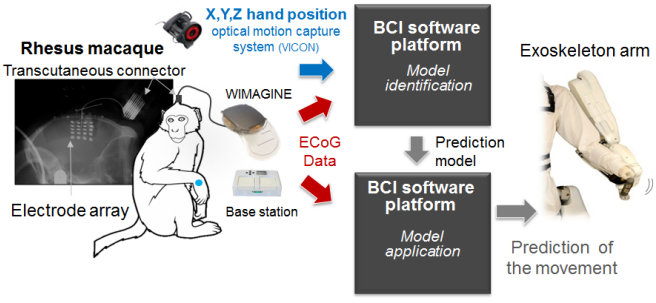

Figure 5: Preclinical experiments' setup in monkey

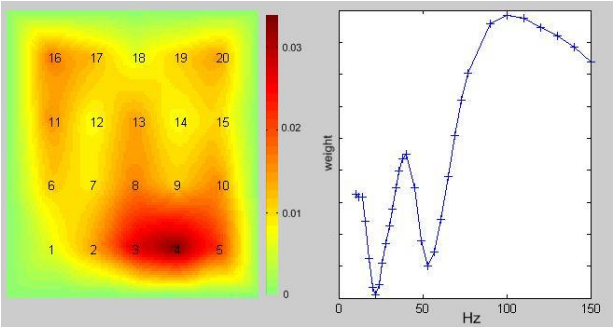

Figure 6: The relative contribution of the elements of the spatial and frequency domains in the identified model

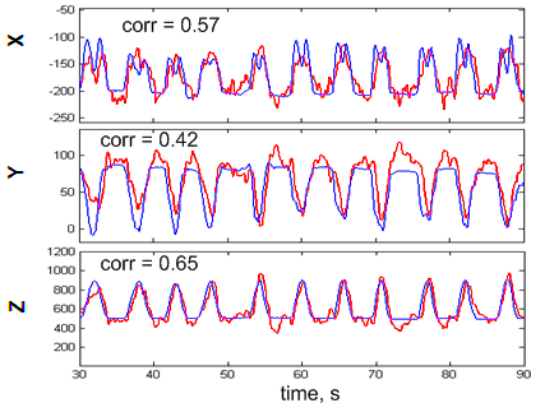

Figure 7: An example of the observed (blue) and predicted (red) X-, Y-, and Z-coordinates of the monkey's right hand

III. Discussion

CLINATEC® BCI platform is an implementation of an innovative project aiming at the rehabilitation of persons with severe motor handicap. It includes two ECoG WIMAGINE® implants and the base station, BCI software environment, ECoG signal decoding algorithms and software, as well as the full-body exoskeleton EMY, dedicated to medical purposes. The whole BCI platform was tested in preclinical experiments carried out in a nonhuman primate (Macaque Rhesus). The control model was calibrated offline using a set of training recordings. The performance of the decoding on a validation set provided high correlation level between the observed and predicted signals, varying from 0.4 to 0.8. Moreover, the application of the informative electrodes selection method could additionally improve the correlation level by up to 10%.

During the online experiments, a fragment of the exoskeleton (the arm) was controlled in real-time by means of decoded neuronal activity (decision rate DR=10 Hz). The delay due to the signal processing, including the signal acquisition, transmission, as well as the commands generation, was approximately equal to 300 ms.

For clinical using, the system should be resilient to loss of data caused by the wireless transmission of the signal. Since the multimodal approach simultaneously processes information from different modalities (frequency, temporal, and spatial), it is not susceptible to the negative effects of a temporary (up to 200 ms) absence of the signal.

The next step of the CLINATEC® project is optimization and adjusting of all the components of the BCI system. Additional tests in animals will be carried out for the evaluation of BCI's performance, as well as identification and elimination of the possible drawbacks. For this purpose, additional animals are scheduled to be implanted.

Acknowledgment

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