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Project-Team DEMAR

DEambulation et Mouvement ARtificiel

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THEME BIO

Activity Report

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2. Overall Objectives

2.1. Overall Objectives

Functional Electrical Stimulation (FES) has been used for about 30 years in order to restore movements. At the beginning, only surface stimulation was possible and thus only used in a clinical context due to the low reliability of electrode placements. In the early eighties, implanted FES appeared through well known applications (pacemaker, Brindley bowel control, cochlear implant, and more recently Deep Brain Stimulation). The complexity of the system for movement restoration is such that no commercial application really arise. Even though the original idea of FES is still the same, activating the moto-neurone axons with impulse current generator, the stimulus waveform and its parameters have drastically evolved and the electrode placements became various: epimysial stimulation at the muscle's motor point, neural stimulation on the nerve,

Sacral roots stimulation near the spinal cord. These changes came from fundamental research, not yet achieved, in neurophysiology. This knowledge can efficiently be included in the next implanted neuroprosthetic devices allowing a wide variety of features. Moreover, currently, FES is the only way to restore motor function even though biological solutions are studied, because the research are not yet successfully tested on humans. Few teams carry out researches on implanted FES (http://www.ifess.org) and the functional results remain poor. Nevertheless, the technique has proved to be useable and needs enhancements that will be addressed by DEMAR. In particular, complex electrode geometries associated with complex stimulus waveforms provide a way to perform fibre type selectivity and spatial localisation of the stimuli in the nerves. These features are not yet implemented and demand new hardware and software architectures. Some teams in Denmark (Thomas Sinkjaer, SMI U. Aalborg), Germany (Klaus Peter Koch, IBMT Franhaufer Institute), England (Nick Donaldson, U. College of London), Belgium (Claude Veraart, U. Catholique de Louvain), United States (Thomas Mortimer, Cleveland FES centre), and Canada (Mohammad Sawan, Ecole Polytechnique de Montréal), work on multi-polar neural stimulation but mainly on the electrode aspect.
Such a complex system needs advanced control theory tools coupled with a deep understanding of the underlying neurophysiological processes. This major area of research will be also an important part of the DEMAR objectives. Very few teams (for instance Robert Riener, ETH in Zurich, Switzerland) work on this topic because it needs a great amount of interactions between completely different disciplines such as neurophysiology, biomechanics, automatic control theory, and advanced signal processing. Besides, animal experiments performed in order to validate and identify models are particularly difficult to manage. Control schemes on such a complex non linear, under-actuated system, not completely observed and perturbed by the voluntary movements of the patient are quite difficult to study due to the lack of precise simulations platforms (for practical evaluation before experimentation) and the lack of theoretical results on such systems.
DEMAR is a joint project between INRIA, CNRS, Universities of Montpellier I and II. DEMAR is located at LIRMM (joint CNRS and University laboratory working on Computer sciences, Micro electronics, and Robotics) in Montpellier. DEMAR works in close relationship with rehabilitation centres among them the Centre Bouffard Vercelli in Cerbère and Propara in Montpellier. International collaborations exist since 2003 with the Sensory Motor Interaction Lab at the University of Aalborg in Denmark (Professors Thomas Sinkjaer, Dejan Popovic, Ken Yoshida). DEMAR research interests are centered on the human sensory motor system, including muscles, sensory feedbacks, and neural motor networks. Indeed, DEMAR focuses on two global axes of research:

- Modeling and controlling the human sensory motor system.
- Interfacing artificial and natural parts through implanted neuroprosthetic devices.

The main applied research fields are then:

- Quantitative characterization of the human sensory motor system firstly for motor disorders diagnosis and objective quantification, and secondly in order to help the design of neuroprosthetic devices.
- Restoring motor and sensitive functions through implanted functional electrical stimulation (FES) and neural signals sensing.
- Improving surface stimulation for therapy (verticalization of paraplegic patients, reduction of tremor, reeducation of hemiplegic post-stroke patients...)

3. Scientific Foundations

3.1. Modeling and controlling the human sensory-motor system

Our global approach is based on the theoretical tools of the automatic control theory.

3.1.1. Modeling

Designing efficient control schemes and performing realistic simulations need for modeling. The scientific approach is to develop multi scale models based on the physiological microscopic reality up to a macroscopic behavior of the main parts of the sensory motor system: muscles, natural sensors and neural structures. We also aim at describing multi scale time models to determine impulse synchronized responses that occur in a reflex or with FES, up to a long term fatigue phenomenon. All these models have a control input that allows them to be linked as different blocks of the sensory motor system.

Besides, we have to deal with problems related to the identification protocols. Identification is then based on the observation of signals such as EMG, output forces, and movement kinematics, while medical imaging gives the geometrical parameters and mass distributions. The success of the identification process is highly sensitive to the quality of the experimental protocols on animals and humans.

3.1.2. Synthesis & simulation

Simulation platforms have been largely developed for biped systems, including advanced impact models (using non regular equation, work carried out in collaboration with BIPOP). Given that kinematics and dynamics are described using Denavit-Hartenberg parameters and the Lagrangian formulae, such tools can be used. Nevertheless, important differences rely on the actuators and their associated model. Thus, based on this platform, a new one can be developed including the complex muscle dynamics. In particular, muscle dynamics contain discontinuous switching modes (contraction - relaxation, extension - shortening), strong non linearities, length and shortening speed dependencies that imply complex numerical resolutions.

As regards synthesis, generating a useful and efficient movement means that criteria can be defined and evaluated through an accurate numeric simulation. Optimization methods are then used to process the data in order to obtain stimulation patterns for a given movement. Two problems occur, firstly the complexity of the models may provoke the failure of the optimization process, secondly the criteria that have to be optimized are not always known. For instance, we have to define what is a "normal" gait for a paraplegic patient under FES; are the global energy, the joint torques, the estimated fatigue for each muscle the appropriate criteria ?

3.1.3. Closed loop control

Some tasks cannot be performed using open loop strategies. Keeping standing position with a balance control can be improved as regard the fatigue effect using ankle / knee / hip angle sensors feedback. Muscle's contraction is then controlled to ensure the minimum of fatigue with the maximum stability. Cycling, walking on long distance pathways, need some control to be achieved with a higher level of performance. Modeling and simulation will be used to design control strategies while theoretical studies of performances (robustness, stability, accuracy) will be carried out. The system is highly non linear and not completely observable. New problems arise so that new strategies have to be designed. Finally a compromise between complexity, efficiency, robustness, and easy usage of the system has to be found. Thus, the success of a control strategy design will be evaluated not only through its intrinsic performances but also regarding its ergonomic.

Advanced control strategy such as high order sliding modes for the low level control of the co-contraction will be studied because of its robustness towards model uncertainty. Trajectory free predictive control will be also investigated for a movement phase such as swing phase during gait, because the movement can be described as intuitive constraints such as the center of mass need not to fall. Finally high level hybrid approaches based on continuous control and event triggered commutation of strategies will be studied using a formal representation of the architecture.

3.2. Interfacing artificial and natural parts through neuroprosthetic devices

To overcome the limitations of the present FES centralized architecture, a new FES architecture was proposed according to the SENIS (Stimulation Electrique Neurale dIStribuée) concept: the distribution of i) the stimulation unit with its control near its activator, i.e. its associated neural electrode ii) the implanted sensor with its embedded signal processing.

FES will be thus performed by means of distributed small stimulation units which are driven by an external controller in charge of the coordination of stimulation sequences. Each stimulation unit (called DSU, Distributed Stimulation Unit) will be in charge of the execution of the stimulation pattern, applied to the muscle by means of a neural multipolar electrode. A DSU is composed of analogue and digital parts (§6.2.1).
The SENIS architecture therefore relies on a set of DSU which communicates with an external controller. We therefore studied the communication architecture and defined an adequate protocol, assuming firstly that the communication should be performed on a wireless medium and secondly that this architecture can also contain distributed measurement units (DMU for sensors).
The external supervisory controller will probably be designed and implemented according to a software component based approach, like that we developed for instance for robot controllers [21], [24], [20], [22], [23], [29].

3.2.1. Stimulators

We mainly focus on implanted devices interfaced with neural structures. Both the knowledge about how to accurately activate neural structures (neurophysiology), and technology including both electrode manufacturing and micro electronics will be studied. Complex electrode geometries, complex stimulus waveforms, and the multiplicity of the implantation sites are the subjects we deal with in order to obtain a selective, progressive and flexible activation of neural structures. Our theoretical approaches are based on:

- Design and test in micro electronics with ASIC developments.
- Formal Petri Nets representation of the numeric control parts.
- 3D electrostatic theory to model interactions between electrodes and neural structures.
- Electrophysiology modeling such as Hodgkin-Huxley model.

3.2.2. Sensors

The development of a closed-loop controller implies the use of sensors whose choice and number are highly constrained by practical, psychological and cosmetic considerations: the stimulation system has to be implanted in order to simplify its use by the patient; it is therefore not possible to cover the person with various external apparatuses. An alternative to artificial sensors is the use of natural sensors already present, which are intact and active below the lesion in the spinal cord of the injured patients. DEMAR is then interested in implanted sensors in order to design complete implanted solutions (stimulation and sensing). As regards sensing, two kinds of sensors will be studied:

- Physical sensors such as micro attitude centrales.
- Natural sensors that means interfacing with afferent nerves and ENG recordings. The same theoretical tools and technology as for implanted stimulators could be used.

In both cases, advanced signal processing applied to biosignals is needed to extract relevant pieces of information.

3.2.3. Patient interface

The patient interacts with the system in three ways:

- He decides which movement he wants to achieve and informs the system.
- He performs voluntary movements in a cooperative way, to turn right or left for instance, but he could also disturb the system when a closed loop control is running.
- Passive actions like arm supports through the walker for the paraplegic patient are used to control balance and posture.

It's not trivial to integrate all these events in the system. This field of research can learn from tele-operation and Human Machine Interfaces research fields. The patient needs also to get pieces of information of the current state of the system. Sensory feedback have to be implemented in the system such as screen, sound, tactile vibrations, electrical stimulation, etc... Choosing meaningful pieces of information such as heel contact, and the way to encode it, will be addressed.

3.2.4. Supervision & networking

Activating the system through stimulators, sensors, and analyzing patient behaviors need multiple devices that communicate and demand energy. Interfacing natural and artificial parts imply to address problems such as networking, data transfer, energy storage and transfer through wireless links. On such a complex system, supervision is necessary to ensure security at the different involved levels. Fault tolerance and reflex behavior of the system will be studied to improve system reliability particularly when the patient uses it at home without any medical person support. The theoretical approach is based on Petri Nets to design and then analyse the behavior of the entire distributed system. More technological aspects related to RF transmission will be studied.

4. Application Domains

4.1. Objective quantification and understanding of movement disorders

Modeling based on a physical description of the system lets appear meaningful parameters that, when identified on a person, give objective and quantitative data that characterize the system. Thus, they can be used for diagnosis.

Modeling provides a way to simulate movements for a given patient so that through an identification process it becomes possible to analyse and then understand his pathology. But to describe complex pathology such as spasticity that appears on paraplegic patients, you need not only to model the biomechanics parts - including muscles -, but also parts of the peripheral nervous system - including natural sensors - to assess reflex problems. One important application is then to explore deficiencies globally due to both muscles and peripheral neural nets disorders.

4.2. Palliative solutions for movement deficiencies

Functional electrical stimulation is one possibility to restore or control motor functions in an evolutive and reversible way. Pacemaker, Cochlear implants, Deep Brain Stimulation are successful examples. DEMAR focuses on movement disorder restoration in paraplegic and quadriplegic patients, enhancements in hemiplegic patients, and some other motor disorders such as bladder and bowel control.

The possibility to interface the sensory motor system, both activating neural structure with implanted FES, and sensing through implanted neural signal recordings open a wide application area:

- Restoring motor function such as grasping for quadriplegic patient, standing and walking for paraplegic patient, foot drop for hemiplegic patients. These applications can be firstly used in a clinical environment to provide to physiotherapist a new efficient FES based therapy (using mainly surface electrodes) in the rehabilitation process. Secondly, with a more sophisticated technology such as implanted neuroprostheses, systems can be used at home by the patient himself without a clinical staff.
- Modulating motor function such as tremors in Parkinsonian patient using DBS (Deep Brain Stimulation). Techniques are very similar but for the moment, modeling is not achieved because it implies the central nervous system modeling in which we are not implied.
- Sensing the afferent pathways such as muscle's spindles, will be used to provide a closed loop control of FES through natural sensing and then a complete implanted solution. Sensing the neural system is a necessity in some complex motor controls such as the bladder control. Indeed, antagonist muscle's contractions, and sensory feedbacks interfere with FES when applied directly on the sacral root nerve concerned. Thus, enhanced activation waveforms and sensing feedback or feedforward signals are needed to perform a highly selective stimulation.

In any case, experimentations on animals and humans are necessary so that this research needs a long time to go from theoretical results to applications. This process is a key issue in biomedical research, it needs: i) design of complex experimental setups both for animals and humans, ii) ethical attitude both for humans and animals, with ethical committee approval for human experiments iii) volunteers and selected, both disabled and healthy, persons to perform experiments with the adequate medical staff.

5. Software

5.1. RdP to VHDL tool

Participant: David Andreu.

The architectural design underlying the SENIS concept leads to embed a complex system within each distributed FES unit (§6.2.1); a DSU (Distributed Stimulation Unit) embeds for instance a micro-machine, a RAM manager, reference models, a protocol interpreter, the analogue subsystem and its interface with the digital part. For the design of the digital part of this complex system with a relatively high level of abstraction, we use Petri nets. Its formalism and associated tools ease the description and verification (analysis) phases; we thus designed a tool allowing the implementation to be directly performed from this model. In this purpose, we proposed an approach based on components for the automatic translation into VHDL, of interpreted Petri nets with time [6]. We thus developed a prototype (beta version) allowing this automatic VHDL code generation (producing a VHDL synchronous component) from a graphical description of a Petri net based model.
This software, named HILECOP (HIgh LEvel hardware COmponent Programming), has been registered as a new software application (APP Registration).

6. New Results

6.1. Modeling and controlling the human sensory-motor system

6.1.1. Skeletal muscle modeling and identification

Participants: Hassan ElMakssoud, David Guiraud, Philippe Poignet.

Based on the initial work [14], [7] developed in the team, we analyzed the data obtained from 3 rabbits and corrected slightly the model to get a good accordance with experimental data. In particular the dependence between shortening speed and the muscle dynamics has been modified to be conformed not only to the Hill law - concentric contraction - but also to the Van Leeuwen law - eccentric contraction-. Besides, the force-length relation has been introduced at the microscopic level inducing a modification in the global dynamics at the macroscopic scale. This involved a new identification protocols as regards data processing but also data acquisition. Publication on the modified model and the numeric implementation of it is under writing.

6.1.2. Modeling interface between electrode and nerve

Participants: Maureen Clerc, David Guiraud, Joan Fruitet.

We have initiate the collaboration with ODYSSEE through the GENESYS project. The GENESYS project (STIC-Sante) focusses on restoring bladder control, the function for which there is one of the highest demand from patients suffering from spinal chord injury. For optimal bladder control, one must stimulate, within the same nerve, two muscles whose characteristics and actions are very different, and hence, one must perform selective recruitment of the two different types of nerve fibers. By using multipolar neural electrodes, and multiphasic waveforms, the response of the axons can be made to depend on their characteristics, their diameters, propagation direction, and positioning within the nerve. In order to conceive such electrodes, and the waveforms to apply, one must model the electrode-nerve electrical interaction, in three dimensions. This project aims at studying the interaction between stimulation electrodes and nerve fibers, in a three-dimensional model. The goal is to simulate the electrical field in a nerve resulting from a current injection profile on the electrodes and to investigate its action, both in terms of simulations, and in vivo, on the nerve fibers. At the scale of the nerve, the simulation is based on a Boundary Element Method developed at INRIA Odyssee, which must be adapted to the nerve conductivity model, which is highly anisotropic. The implementation of this project was initiated by Joan Fruitet during his internship in summer 2006, and will be continued by Sabir Jaquir as a postdoc between Demar and Odyssée as of November 2006.

6.1.3. Joint trajectory synthesis and control

Participants: Samer Mohammed, Philippe Poignet, David Guiraud.

6.1.3.1. Closed loop control applied on knee joint (MPC)

Closed loop control of a muscle actuating the knee joint of a paraplegic patient constitutes a prerequisite step for further assisted movements such as standing up, standing and walking. Currently most clinics still adopt an open loop control strategy although this later induces excessive stimulation of the main muscles and thus fast muscular fatigue and poor return to the patient. We have used a mathematical muscle model which has been described previously, representing the most dynamic phenomenon that occurred during contraction. The number of recruited motor units increases as a function of intensity and pulse width stimulation patterns. This phenomenon is modeled by an activation model representing the ratio of recruited fibers α and a mechanical model (muscle contraction) expressed by a set of nonlinear differential equations. The ability to handle nonlinear multi-variable systems that are constrained in states and/or control variables motivates the use of Model Predictive Control (MPC) [17]. The MPC problem is usually stated as an optimization one subject to physical coherent constraints, and is solved with classical optimization algorithms. In our particular case the nonlinearities of the muscle model, the constraints on the input stimulation current and on the output knee joint position lead us to adopt a controller relying on the MPC (fig.1).

6.1.3.2. Optimal stimulation sequences generated in open loop control (task dependent)

The goal is to provide pulse width PW or stimulation current sequence to be applied to the skeletal muscles involved in the standing up, walking... (quadriceps) in a forward dynamic problem formulation. The sequence is obtained through an optimisation procedure that consists in minimizing muscular activities and the tracking error between desired and current kinematic trajectories. The muscular and joint dynamics (fig.2) were taken into account as constraints while solving the optimisation. Figure 3 illustrates the tracking of a desired trajectory representing the flexion-extension of the knee, the corresponding pulse width sequence and the optimisation time required to perform the optimisation process.

6.1.4. Posture estimation and modeling

Participants: Gaël Pages, Nacim Ramdani, Philippe Fraisse, David Guiraud.

Posture estimation during standing

The feasibility of posture estimation from forces exerted on the handles of a walker during standing is investigated [19], [18], [26]. The problem is stated as a constraint satisfaction one and is solved with an algorithm based on interval analysis. The methodology is capable of taking account of any uncertainty in either assumed known or measured quantities. At the end, uncertainty bounds are computed for the estimated posture.

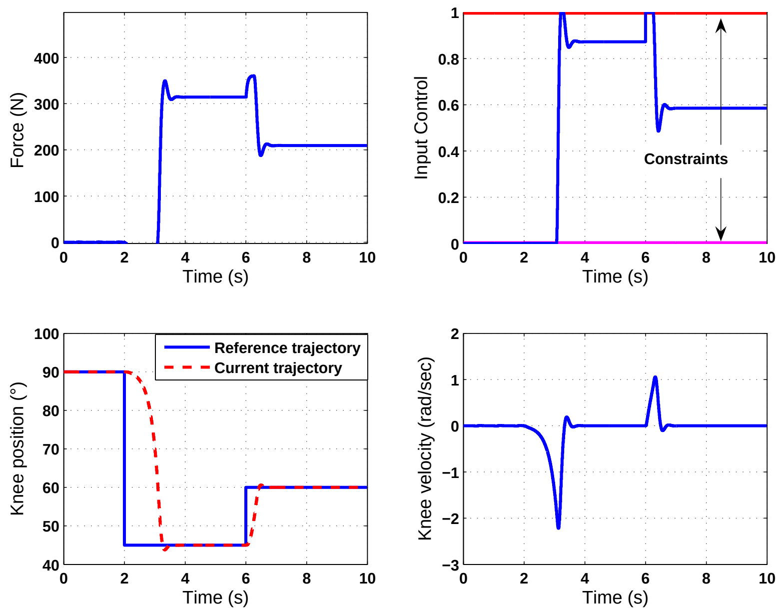


Figure 1. Response of the controller to step positions of the knee joint. Figures show that MPC finds a solution that satisfies the constraints and gives acceptable performances

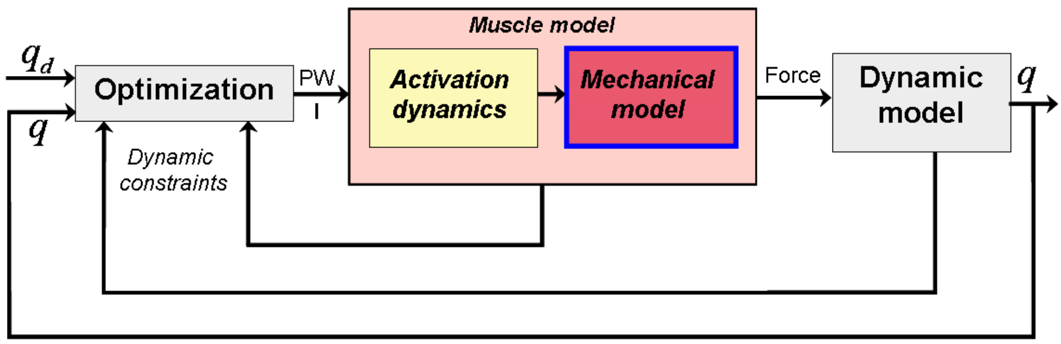


Figure 2. Synthesis method

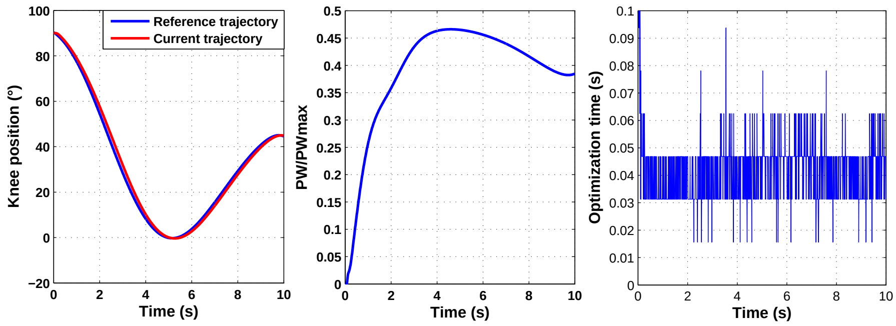
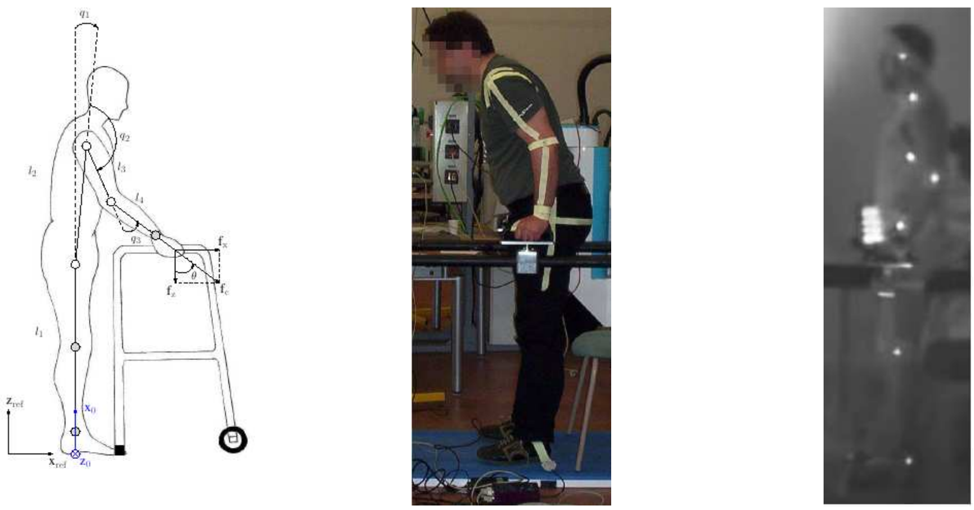


Figure 3. Results obtained on the synthesis of the stimulation PW parameter in order to follow a desired trajectory

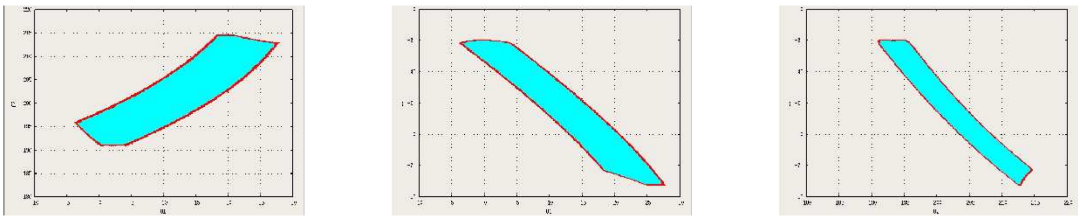
The constraints are derived from a kinematic model of the human body regarded as a biomechanical system and written in the sagittal plane (figure 4-a). The posture is defined by the hip, shoulder and elbow joints (respectively q_1, q_2 and q_3). In addition, an extra constraint is obtained by assuming that the orientation of the forearm is collinear to the resultant forces measured on the handles. The methodology has been first validated with experimental data obtained with healthy subjects. In a first series of tests, the two 6-axis force-torque transducers were attached onto the handles of a walker. In order to test the methodology with paraplegic patients under FES, it was necessary to install the transducers on adjustable parallel bars. This is a classical apparatus used in rehabilitation centers and more suitable for patients. The methodology was again validated with healthy persons (figure 4-b) and finally used and validated with paraplegic patients under FES (figure 4-c).



(a) (b) (c)

Figure 4. (a) The four bar linkage human model ; (b) Experiments with healthy subject ; (b) Experiments with paraplegic patient

The solution sets obtained with a paraplegic patient are shown by figures 5. They represent projections of the computed inner (i.e. set containing only solutions but not all) and outer (i.e. set containing all solutions as well as inconsistent values) solution sets onto planes $q_i \times q_j$. The real posture was measured during the experiment and was given by: $q_1 = 1.7°$, $q_2 = 194°$ and $q_3 = -34°$. The results contain the real measured posture. Figure 6 illustrates an example of feasible postures taken in the solution sets.



(a) (b) (c)

Figure 5. Paraplegic patient: inner and outer approximation of posterior feasible set onto (a) $q_1 \times q_2$, (b) $q_1 \times q_3$, (c) $q_2 \times q_3$.

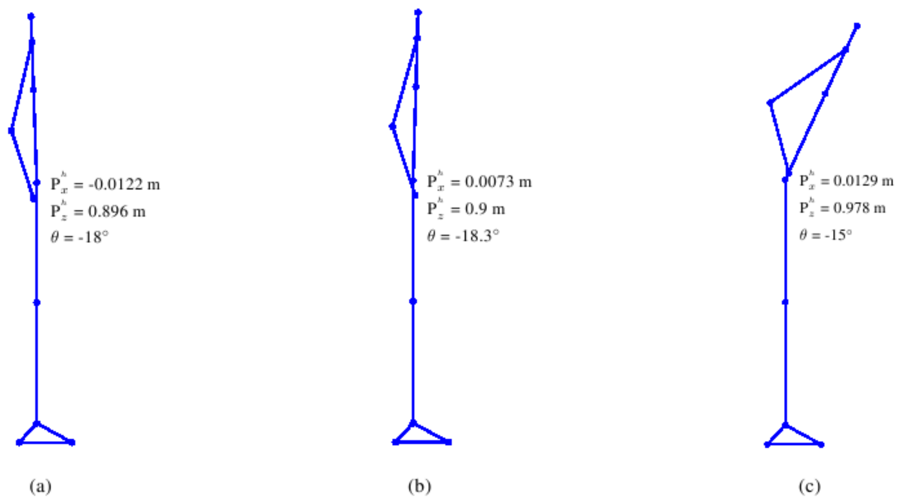


Figure 6. Paraplegic patient: examples of feasible postures (a) Leaning back, (b) Real Posture and (c) Leaning forward.

Posture estimation during walking

The issue of posture estimation during walking by only measuring forces exerted on handles is addressed in a bounded-error context with interval analysis. The problem under study can be regarded as nonlinear state estimation in presence of unknown inputs and model uncertainty.

Since state-of-the-art set-membership estimation techniques can only deal with nonlinear continuous-time systems of small dimension, new approaches are introduced in order to extend these techniques to the actual models used in biomechanics. The first approach uses contraint propagation in order to tighten computed sets for state vector [27]. The second one uses interval Taylor models, comparison theorems and hybrid automata in order to bracket the uncertain dynamical system between an upper and a lower deterministic hybrid dynamic system with no uncertainty [25], [16], [15].

Posture classification

Online posture estimation can be performed also using neural network and sensors such as accelerometers, when the purpose is only to detect phases of movements. It has been successfully applied to ageing person to detect falling and to perform global activity monitoring [13]. This technique could be applied to design discrete event based controller whereas the state estimation of the different angle could be used for continuous controlling system. Both may be used in an hybrid controller where the best control strategy could be selected depending on the movement to be achieved.

6.1.5. Postural strategies emerging in complete paraplegic patients verticalized with functional electrical stimulation

Participants: Claire Simon, David Guiraud, Didier Delignères, Charles Fattal, Christine Azevedo.

Figure 7. Experimental setup with the VICON, force sensors on both handles and sensitive insoles.

Functional electrical stimulation allows performing an active standing in complete paraplegic patients. This verticalization has benefits in both psychological and physiological aspects. In this study, patients suffering

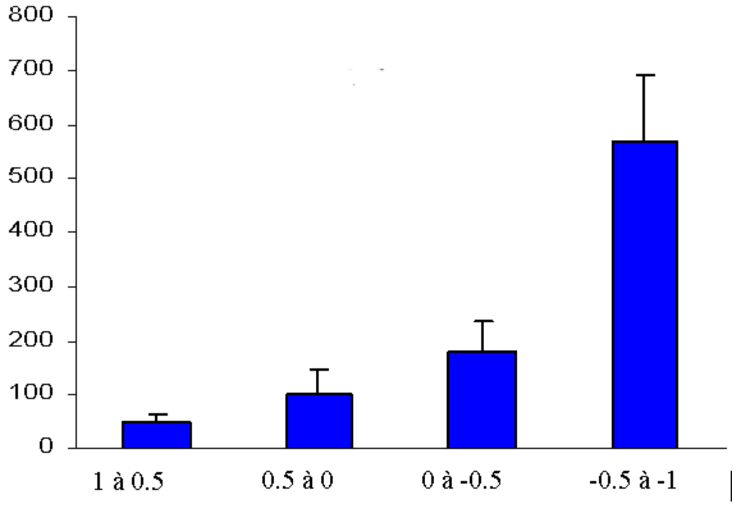


Figure 8. An anti-phase strategy seems to emerge during active verticalization FES-based in complete paraplegic patients. The graph is obtained from the correlation between ankle and hip angles (-1 stands for anti-phase strategy).

from complete spinal cord lesion were equipped with surface electrodes delivering electrical stimulation to 4 muscular groups in each leg, ensuring that 1) lateral movements of pelvis were stabilized; 2) knee joint was locked; 3) ankle was free to rotate. The stimulation sequences were parameterized offline and pre-programmed for each patient. This configuration creates a split-body situation where the body is partly externally controlled, the rest of the body (head, trunk, arms) remaining under the voluntary influence of the central nervous system. Nevertheless, the patient has an indirect action on his lower body through the closed mechanical chain going from hand supports to feet (ankles being free). This study aims at understanding the coordination patterns existing between upper and lower body in order to ensure postural balance. In valid subjects, whatever the perturbations are, 2 stable postural patterns seem to emerge: a "phase mode" where hips and ankles angles vary in a same direction and an "anti-phase mode" where hips and ankles angles vary in opposite directions. These 2 modes define 2 distinct attractor basins for the postural system states. The protocol consisted for the patients, FES aided, to stand in between parallel bars and maintain postural balance by aligning head, pelvis and ankles. In order to compensate their sensorial deficiencies and help them in adopting a correct posture, a visual feedback was assisting them; a screen was placed in front of the patients where they could see their own profile (left side). A video motion analysis system VICON recorded positions of 16 passive markers. 6 degrees of freedom force sensors where fixed on the handles to record efforts of the upper limbs on the parallel bars. NOVEL Pedar insoles were placed inside the patient's shoes to record pressure distribution (fig.7). Patients were trained to FES technique in lying position during 1 week followed by 2 resting days. The first day after this conditioning, the patient was familiarized with the protocol of verticalization. We started recording data from the second day. 5 trials of 1mn standing were executed by each patient. The data analysis focused on (windowed) crosscorrelations between absolute angles (from horizontal) of upper and lower segments (fig.8). The observed coordination modes were evaluated through their occurrence frequency and their efficiency. Efficiency was estimated from the normalized efforts applied by the patients on the handles. The more the patients were supporting their weight on their arms the less the posture was efficient. Despite the patient group was heterogeneous (lesion level and seniority) and despite the significantly different efforts they applied on the handles, it seems that the "anti-phase" mode is the most frequently adopted by the patients, and also the most efficient. Nevertheless, this mode remains unstable as it is not maintained over the trials.

6.1.6. Observing valid limbs to control deficient ones

Participants: Rodolphe Héliot (INRIA/CEA-LETI), Christine Azevedo, Dominique David (CEA-LETI), Bernard Espiau (INRIA RA).

This work is based on a collaboration with CEA-LETI (Grenoble, France) and INRIA-Rhône-Alpes around R. Héliot PhD thesis.
When controlling postural movements through Functional Electrical Stimulation (FES), an important issue is the enhancement of the interaction of the patient with the artificial system through his valid limb motions. We believe that a clever observation of valid limbs could improve the global postural task by giving to the patient an active role in the control of his deficient limbs. We developed an approach to identify a postural task by observing one limb. Our objectives are to: 1) detect and identify subject voluntary actions as early as possible after a movement decision is taken, and 2) to monitor the current motion in order to estimate the task state variables. We employed a set of micro sensors (CEA-LETI TRIDENT system) providing us with accelerations and absolute 3D orientations, then implemented specific signal processing methods.
An experimental campaign on 20 hemiplegic stroke patients has been ran in June 2006 in Zotovic Rehabilitation Center, Belgrade, Serbia. The data are being analyzed presently.

6.1.6.1. 1- Online generation of cyclic trajectories synchronized with sensory input - Application to Rehabilitation

When controlling postural movements through artificial prosthetic limbs or muscle Functional Electrical Stimulation (FES), an important issue is the enhancement of the interaction of the patient with the artificial system through his valid limb motions. Dealing with gait rehabilitation in stroke patients, we developed a method to monitor the ongoing movement and generate the desired trajectory on the affected leg. To achieve this, we place a sensor on the valid leg, and build a model of the sensor measurement during gait. Since the movement is cyclical, we used a non-linear oscillator model, which can autonomously (i.e. without input) produce a cyclical output. We fit the model parameters by optimization, and build an observer of it. Then, we can “filter” the sensor measurements with our observer: since the observer is adapted to its input, we can be sure that the it will well synchronize. Finally, since the observer is also an oscillator, it is possible to reconstruct the oscillator phase, and generate a desired trajectory according to this phase.
Applied to the rehabilitation issue, this method can be used in different ways:

- provide the stimulation system with discrete inputs that will trigger the muscle.
- generate a desired trajectory for the paretic leg, and synthesize the stimulation sequence with a musculo-skeletal model.

6.1.6.2. 2- Gait evaluation system

During a given rehabilitation protocol for stroke patients reeducation, it is of great interest to assess the gait of the patient, to monitor the improvement of the gait. Such evaluation can be achieved through standard tests (Barthel Index, Ashwoth scale, ...) held by the clinicians, or by measuring some gait variables: locomotion speed, symmetry. However, such variables need specific equipment to be measured, and require more people around the patient. Our aim is to provide with a gait analysis system which could easily give an objective criteria of gait quality. By placing an accelerometer on the healthy shank, we can measure some helpful variables, as stride gait frequency. We perform a frequency analysis of the accelerometric signal, and exhibit a frequency ratio that shows good correlation with gait speed and symmetry. Such an analysis only requires a simple system (an accelerometer; today, such sensor can be completely wireless, thus not disturbing the patients’ gait); we developed an analysis software that gives a quantitative result right after the measurement. We believe that such a tool could be of great help in rehabilitation centers.

6.1.7. Towards a model-based estimator of muscle length and force using muscle afferent signals for real time FES control

Participants: Milan Djilas, Christine Azevedo, Guy Cathébras, Ken Yoshida (SMI).

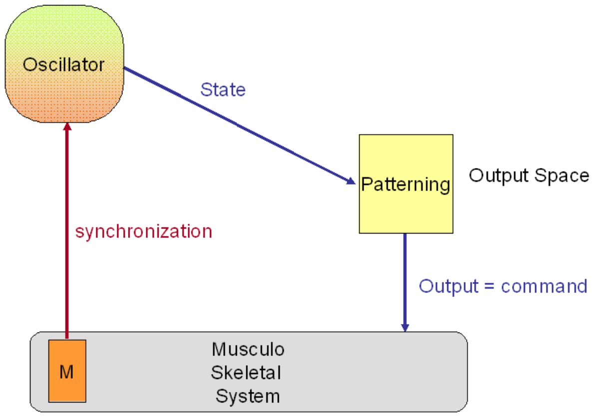


Figure 9. The oscillator is “filtering” the sensor input; its states variables will be used to generate the command

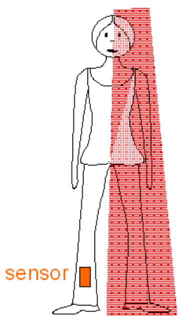
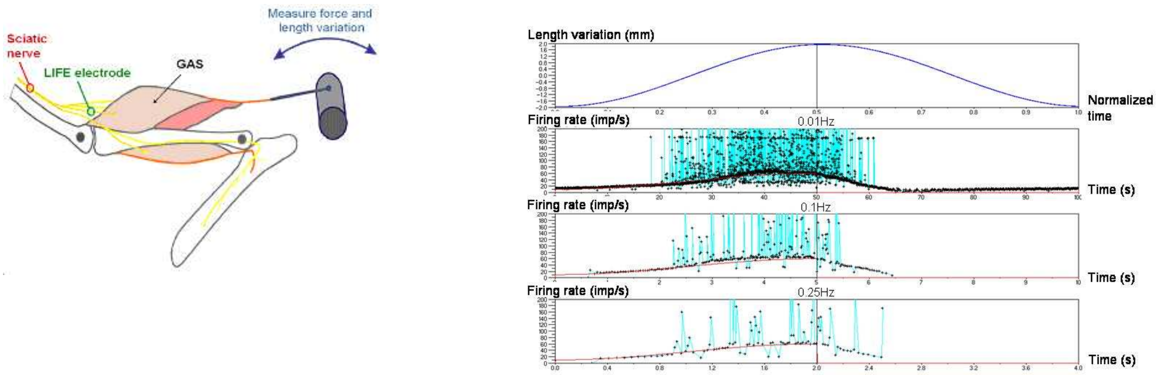


Figure 10. Gait evaluation principle: a single sensor is needed

This work is given in the context of motor function rehabilitation via implanted Functional Electro-Stimulation (FES) and is based on a collaboration with SMI (Aalborg, Denmark) started in 2004. Our ultimate objective is to use natural muscle sensitive fiber information as feedback for the FES artificial controller. This implies online extraction of information from neural activity in a form usable by a closed-loop controller. Two experimental campaigns were ran at Aalborg Hospital, Department of Pathology. A new Longitudinal Intrafascicular Electrode (LIFE) was implanted: the thinfilm longitudinal intrafascicular electrode (TF-LIFE). This electrode has 8 recording sites. A total of 20 rabbits were involved in the study. The TF-LIFE was implanted in the tibial branch innervating the MG muscle. Muscle length and force variation, as well as multi-channel ENG were recorded while applying external mechanical stretches to the muscle (fig.11). ENG signals were analyzed in terms of the single unit responses using a simple threshold detection algorithm. The method manages to provide a rough estimate of ENG firing rate. The results obtained are consistent and the next step is to validate the model experimentally. This simplified approach is appropriate for implementation for on-line application. Effects of muscle fatigue were also investigated, showing a decreased firing rate of muscle afferent neural activity after the muscle is fatigued [12]. The data analysis is still on process.

Note: *This work is supported by an EADS foundation contract with INRIA for M. Djilas PhD thesis (October 2005-September 2008). A EURON financial support starting in November 2005 has also been obtained for this project involving DEMAR and SMI.*



a) Muscle stretching protocol b) Spike classification

Figure 11. Towards a model-based estimator of muscle length and force using muscle afferent signals for real time FES control

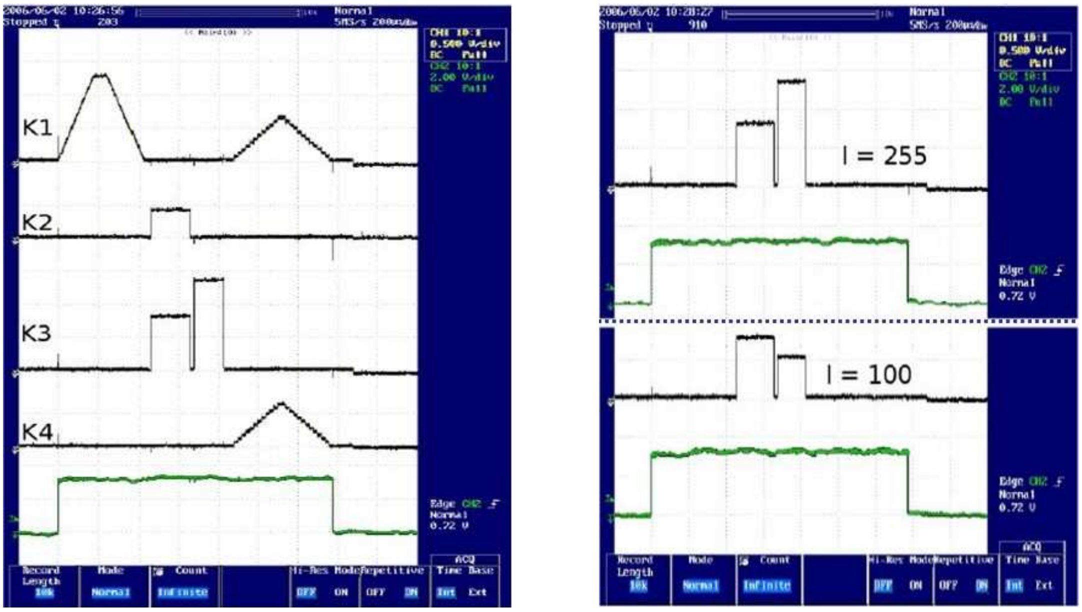
6.2. Interfacing artificial and natural parts through neuroprosthetic devices

6.2.1. Activating the neural system

Participants: David Andreu, Guy Cathebras, Jean-Baptiste Lerat, Jean-Denis Techer, Serge Bernard, David Guiraud, Guillaume Souquet.

Distributed Stimulation Unit (DSU)

Security aspects have been integrated within the DSU, by means of embedded reference models in charge of monitoring the respect of neurophysiology constraints. Moreover, we extended the instruction set of the micro-machine in order to generate more complex stimulus waveforms (fig.12-a). Reference models have thus been modified to also monitor the execution of those new instructions. The micro-machine can currently generate complex stimulus waveforms, containing ramp-like phases for example as well as dynamically modifiable instructions (fig.12-b). These latter allow to set (modify) the parameters of a stimulus waveform (as its magnitude, its duration, etc.) during its execution, offering so the possibility to implement (network-based) closed-loop control.



a) illustrative example of complex stimulation profile

b) network based modification of a stimulus amplitude

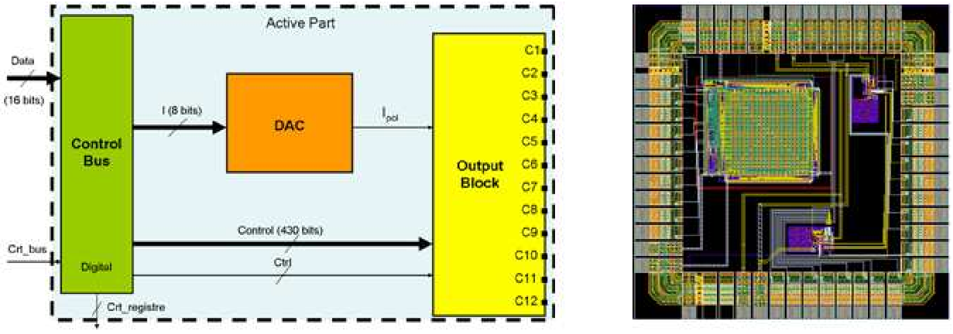
Figure 12. Illustrative stimulation profiles (generated by the Stim-3D prototype)

Active part of the implantable neural stimulator

The active part of the implantable stimulator consists of three main systems: the bus control, the Digital to Analog Converter (DAC and the output block). The bus control is a fully digital system that controls at the same time the DAC and the output block. First of all, the converter supplies an enough current for stimulation. This current is then distributed to the electrodes by the output block. Presently, the twelve outputs of this block allow us to use a twelve pole stimulating electrode. Our work has been divided into two main steps; the design of the DAC and the output block development.

We can notice in figure 13-a that the converter generates a current named I_{pol} to the output block. This bias current is then duplicated by the output block and distributed to the electrodes we wish to activate. I_{pol} is defined by the value of the 8-bit vector "I" (fig.14-b). The converter can deliver a current that ranges from 0 to $1.28\,\text{mA}$ by $5\,\mu\text{A}$ steps. This DAC is a "steering-current DAC" with the same number of current sources as the number of different levels. It consists of 256 elementary current sources, each one could generate $5\,\mu\text{A}$. These sources are switched on or off according to the digital value to be converted. This thermometer architecture allows us to assure the monotonicity of the DAC (any increase of the digital value always corresponds to an increase of the output current) whatever the parameter spread. Moreover, in order to improve the linearity, the sources are switched in such a way that all the suitable configurations share the same barycenter on the layout. A prototype was developed on silicon at the beginning of the year and was successfully validated.

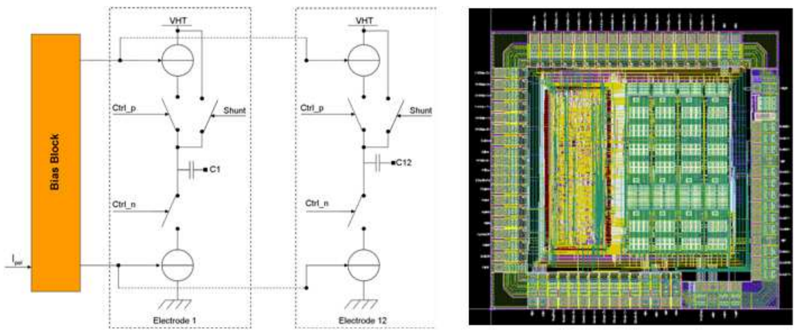
On the other hand, we have developed the output block and the control bus. It's a link to the logic block which will be put together upstream the structure. Indeed, without this unit, we would need 430 bits to check the output block whereas with a series circuit only 16 bits would be necessary. Moreover, for more security, certain layouts for the output block are forbidden by the control bus. An output block diagram is shown in figure 13-b. The current I_{pol} comes in the bias block which enables to bias every current sources from the output block. The distinctive feature of this circuit lies in the fact that each electrode may work like a cathode



a- Structure of the active part of the simulator ***b- Layout of DAC***

Figure 13. Active part of the stimulator

(switch $Ctrl_p$ off) or an anode (switch $Ctrl_n$ off). The switch shunt is used to delete every residual charge on nerve at the end of the stimulation. In figure 14-b, we can see a circuit's layout which has been sent to the foundry during the month of November. As soon as possible, we plan to realize a stimulating prototype to begin tests on animals.



a- Diagram of the output block ***b- layout of the output block.***

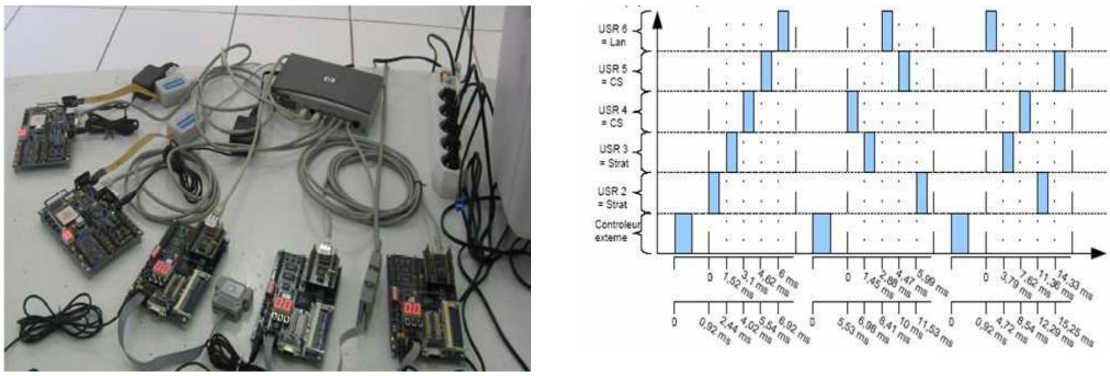
Figure 14. Output Block

6.2.2. Communicating between units

Participants: David Andreu, Jérome Galy.

An experimental platform has been developed (fig.15-a), based on a set of FPGA devices (DSUs) connected by means of an ethernet bus (that will soon be replaced by a specific wire medium, and a wireless medium in the future). Tests have been performed on this platform and the MAC protocol (patented) has been validated(fig.15-b). We are validating the global distributed stimulation unit based architecture behavior, and prototyping a specific (implantable) wire medium.

The MAC protocol could be used for testing System-In-Package wirelessly. This study is performed, outside the DEMAR project, through a collaboration between LIRMM's Microectronics department and NXP (formerly Philips-Semiconductors) in the framework of a CIFRE PhD thesis (student : Ziad Noun) [10], [11].



a) ethernet based DSU network **b)** results of sliding time intervals based trafic

Figure 15. FPGA based experimental plateform

6.2.3. Recording from the neural system

Participants: Lionel Gouyet, Guy Cathebras, Serge Bernard.

In order to use the natural sensors to implement efficient closed loop stimulation, we need to be able to "read" nervous signals. But these signals are complex signals Because nerve is, in fact, "bundle" of axons connected to different organs. The objective of this study is to sort out these signals to extract the expected nervous signal. The physiological signals to be used are the ENG (electroneurogram) which are very low level (μV) and noisy signals. The recording chain consists of the electrode to give an image of the action potentials circulating inside the nerve, the integrated circuit for signal conditioning and signal amplification, and a signal processing stage to extract useful data from the nerve in real time.

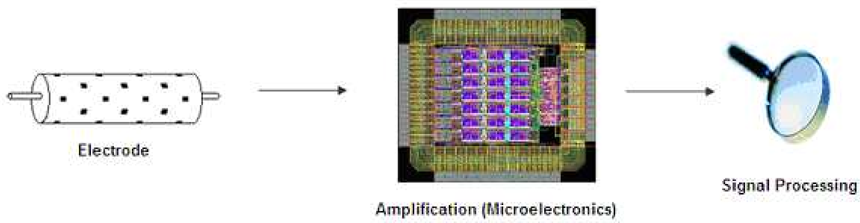


Figure 16. The three stages of a classical recording and processing chain for ENG

The chosen signal processing is the Independent Component Analysis (ICA). This technique requires a large number of parallel recordings to be efficient. In order to provide these recordings, we define a new multipolar cuff electrode with a maximum number of contacts on the nerve, and with a specific geometry allowing efficient attenuation of muscular signals (EMG (mV)) that are parasitic signals in our context. We validated the suitability of this kind of electrode thanks to several experiments on sciatic nerve of rats. The function of the integrated circuit is to amplify the target signals (ENG) together with attenuating the EMG ones. The

EMG rejection requires an averaging of signal obtained from the different poles. Thus, the first stage of our amplifier was developed to calculate the potential difference between a pole and the average of six others poles. In order to reduce both the area overhead and the noise induced by the circuit, we have developed an architecture using only several transistors as illustrated in figure 17. This pre-amplifier has a gain of 40dB, a Band-width of $100kHz$ and an input referred noise of $0.773\mu V$.

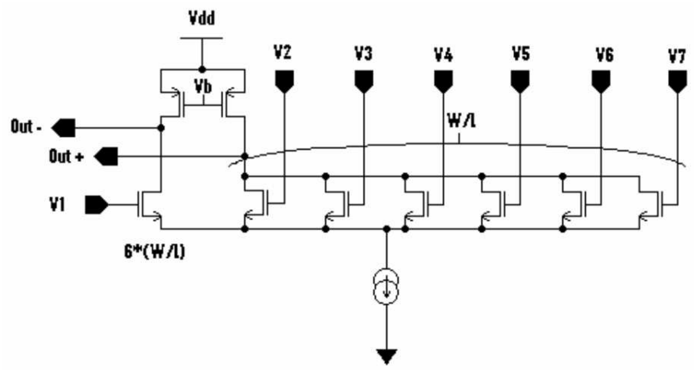


Figure 17. Schematic of the pre-amplifier

This first stage amplifies sufficiently the signal to extract it from the noise and to be able to use a conventional instrumentation amplifier in order to continue the amplification of our signals. A first prototype consisting of seven whole amplifiers was designed in $0.35\mu m$ technology. The silicon area of this first circuit (figure 18) is $1200{,}5\mu m \times 967\mu m = 1.16\mu m^2$

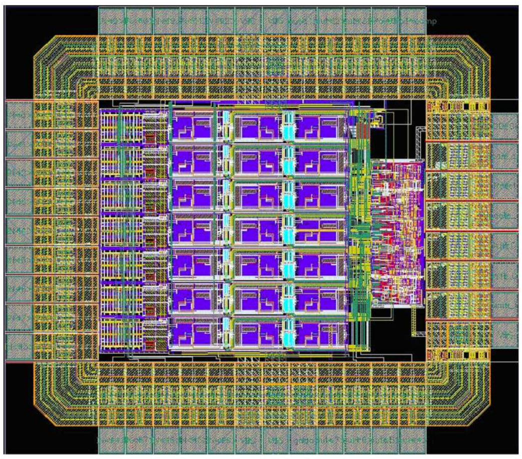


Figure 18. Layout of the microcircuit consisting of seven amplifiers

Concerning perspectives, we plan to validate an ICA algorithm (FastICA), and perform in vivo experiments of the entire processing stage in chronic context (several days at several weeks) in a rat.

6.3. Experimental Campaigns

We would like to emphasize in an hidden part of the work carried out by our team: the experimental campaigns.

6.3.1. Human experiments

We have been running several experiments on human subjects along the year. We have always to deal with security, patient will and sometimes they stop the experiment on themselves. Ethical considerations and security are the most important things to keep in mind and to pay attention with. We have, for each experiment, to write down a detailed proposal that is submitted to the local ethical committee to be allowed to perform experiment. It could take more than one year from the idea to the process of the data, including protocol design, ethical committee approval, and data pre processing. All these experiments must be performed under clinician supervision in a medical center. **Complete paraplegic patients at PROPARA center (Montpellier):** 4 patients have accepted to participate in a study concerning postural strategies evoked during verticalization performed through FES in complete paraplegic patients with agreement of the ethical committee [28]. The experimental setup includes a 3D Motion Capture, an external FES stimulator, foot pressure insoles, two six axes force measurement on each handles and video feedback. The patient preparation needs for 5 days and the measurements themselves take about half a day per patient. The data preprocessing needs for detailed analysis of the data with problem of synchronization and 3D reconstruction before the data can be really used. Data are still under processing for some part of the study. **Complete paraplegic patient at Clémenceau center (Strasbourg):** an implanted patient has accepted to participate in 2 day evaluation experiments [8], [9]. It needs to install the complete setup away from the lab with the only remaining patient using an implanted system. Data collection are unique and needs a careful analysis. **Post-stroke hemiplegic patients at Zotovic center (Belgrade):** 20 stroke patients have accepted to participate in a study concerning evaluation of walking gait through accelerometric signals. 10 stroke patients participated to a campaign in December 2006 within a protocol concerning drop foot correction through FET (Functional Electrotherapy).

6.3.2. Animal experiments

Animal experiments are very important when testing neuroprostheses and studying basics of electrophysiology, but we limit these investigations to minimum needed. The experimental setup is partly designed by the team as regards electronic and software developments. For these protocols we collaborate with the Animal center in Aalborg and UMII Department of Biochemistry and Physiology.

7. Contracts and Grants with Industry

7.1. Contracts and Grants with Industry

An industrial technological transfer contract has been signed with the MXM company that develop cochlear implant and artificial lens implant. MXM can perform also Ethylene Oxyde sterilization necessary for all our experimental setups used during surgery. A DSU prototype (named Stim-3D) and programming environment (MedStim) has been developed within this frame; it allows to graphically describe and to directly download stimulation sequences (pattern of stimulation) into the DSU component (FPGA). Then stimulation can be started/stopped from the environment. Jean Denis Techer helps to transfer this technology. A copy of the system has been sold to ODYSSEE team for use with brain conduction identification protocols.

8. Other Grants and Activities

8.1. International grants

- EURON Prospective Research Project (European Research Network FP6-NOE-507728 sponsored by the CEC- IST Future and Emerging Technologies unit) (2005-2006) "*Lower-extremity movement restoration through muscle closed-loop FES control using natural sensor feedback*". 90keuros. Consortium: INRIA SA and SMI Aalborg Denmark.
- France-Stanford Center for Interdisciplinary Studies: prospective project (Visits and exchanges) in collaboration with Professor O. Khatib from robotics lab (Stanford University) focused on Artificial Walking. 14000$US. Duration: 1 year, 2006-2007. (see: http://ica.stanford.edu/?q=francestanford/projects/2006-2007).
- European Project, HEBE, "Mobile Monitoring and Automatic Fall Detection Device for Ederly People living alone", CRAFT, 6th IST Call, COOP-005935-HEBE, duration: 18 months. (2005-2006). Consortium : Fatronik (Spain), Lirmm, CNRS (France), Zenon (Greece), Icavi bikain (Spain), Wany Robotics (France), Com&Media (Greece). Responsible (Lirmm): P. Fraisse. 123keuros.
- PsiRob ANR Project TREMOR on pathological tremor compensation using FES, 243 kE. Partners: MXM, Propara, CHU Montpellier (Oct. 2006 - Oct. 2009)
- National Medical Reasearch Council - Nayang Technological University. Project on Pathological tremor. LIRMM scientific leader: P. Poignet. Funding for exchange (Oct. 2006 - Oct. 2009)

8.2. National grants

- STIC-Santé GENESYS, (2006-2007), 80keuros, "*GEneric NEuroprosthetic SYStem*"the project focuses on: i) the modeling of electrode-nerve interaction for stimulation in order to provide model based design of electrode, ii) the integration of the first DSU, iii) animals experiments to validate the concept... Partners: ODYSSEE INRIA Sophia-Antipolis, MXM Company Sophia Antipolis, and St Therese Hosp. (Cologne, Germany).
- RNTS, MIMES project, (2004-2006), 60.4keuros, the project focuses on the complete modeling of the body, developing dedicated simulation software tools, advanced external stimulators, and instrumented walker. Partners: BIPOP INRIA Rhône-Alpes, Centre de rééducation Bouffard Vercelli Cerbère, MXM Company Sophia Antipolis.
- ACI neurosciences intégratives et computationnelles (2004-2007), 15keuros, "*Functional electrical stimulation: a specific model of neuro-artificial cooperation for vertical conquest in paraplegic patients*". Leader DPA (FRS) Marseille.
- EADS contract phd thesis grant support of M. Djilas (2005-2008) "*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*". 105keuros

9. Dissemination

9.1. Services to scientific community

- Philippe Poignet is Member of the IFAC technical committee on Nonlinear Systems and Control.
- Philippe Poignet was co-chair of the session "Biomedical Systems Control" at the 6th IFAC Workshop on Modeling and Control in Biomedical Systems, Reims (France), September 2006.
- Philippe Poignet was co-chair of the session "Applications of Nonlinear Model Predictive Control for Fast Systems" at the 1st IFAC Workshop on Nonlinear Model Predictive Control for Fast Systems, Grenoble (France), October 2006.
- Philippe Poignet was IPC Member of the 6th IFAC Workshop on Modelling and Control in Biomedical Systems, Reims (France), September 2006.
- Philippe Poignet was IPC Member of the 1st IFAC Workshop on Nonlinear Model Predictive Control for Fast Systems, Grenoble (France), October 2006.

- Philippe Poignet is co-responsible for the Working Group "CPNL" - GdR MACS http://www.lag.ensieg.inpg.fr/gt-commandepredictive/.
- Philippe Fraisse was co-chair of the session Rehabilitation Robotics, International Conference on Intelligent Robots and Systems, IROS'06, October, 9-15, 2006, Beiijing, China.
- Philippe Fraisse is Member of the IFAC technical committee Networked Systems and member of the IEEE technical committee Networked Robots.
- Philippe Poignet, David Andreu and David Guiraud are members of the local scientific commission number 61.
- Philippe Fraisse is member of the national scientific commission CNU 61.
- Nacim Ramdani is member of the national scientific commission CNU 61.
- Yves Bertrand is a member of the national scientific commission CNU 63
- Serge Bernard is the director of the Institute for System Testing (ISyTest), a joint institute between the LIRMM and NXP semiconductor (the former Philips semiconductors)
- Guy Cathebras is member of the local scientific commission 63
- D. Guiraud particpates to the writing of the special issue in Pour la Science [31]

9.2. Teaching

- Gaël Pages was in charge of the Matlab/Simulink teaching for 2nd year SAEI Master degree students (40h).
- Hassan El Makssoud was ATER teaching automatic control
- Guy Cathébras, associate professor at Polytech'Montpellier (Micro-Electronics and Automation (MEA) Department), teaches: Mathematics and Signal theory for 1st year MEA students; Analog integrated circuits: "An introduction to electronics: designing with Bipolar and MOS transistors", a tutorial for 1st year MEA students; "CMOS Analog integrated circuits design" 28h CAD practical works for 2nd year MEA students; "CMOS standard cells design" 20h CAD practical works for 2nd year MEA students.
- Philippe Poignet Associate-Professor at IUT Montpellier Applied Physics teaching automatic control and signal processing.
- Philippe, Fraisse, Associate-Professor at Polytech'Montpellier (MEA) teaching automatic control and networks.

9.3. Organization of seminars

- D. Andreu organizes CAR06 "Control Architectures of Robots" workshop http://www.lirmm.fr/CAR06/
- M. Grey (SMI, Denmark) "Neuromuscular control and rehabilitation of human walking". December 7th 2005.
- J.-R. Cazalets (UMR5543, Bordeaux) "Les réseaux spinaux de la locomotion". September 26th 2006.
- Philippe Poignet co-organizes 2 days meeting focused on "Robust Control for Robotics" of the Working Group "MOSAR" - GdR MACS, November 2006. http://personnel.supaero.fr/alazard-daniel/gtmosar/novembre2006/programme.pdf

9.4. Research fellow visits

- Visit of K. Yoshida (SMI, Denmark)) and Klaus Peter Koch (IBMt, Germany)

- Visit of M. Grey (SMI, Denmark)) 6th-9th December. 2005.

9.5. Participation in seminars and workshops

- **N. Ramdani (2005)**, "Integrating differential equations", groupe MEA GdR MACS, Oct. 2005.
- **N. Ramdani (2006)**, "Calcul d'atteignabilité pour des systèmes dynamiques hybrides à dynamique continue non linéaire par arithmétique d'intervalles", groupe SDH GdR MACS, Oct. 2006.
- **C. Azevedo (2006)**, Suppléance fonctionnelle et thérapie par la stimulation électrique fonctionnelle." Laboratoire Physiologie et physiopathologie du mouvement (Bordeaux), Oct. 2006.
- **C. Azevedo (2006)**, "Des capteurs artificiels aux capteurs biologiques pour la réhabilitation du mouvement. " Équipe Efficience et déficience motrices UFR STAPS(Montpellier), Oct. 2006.
- **D. Andreu (2006)** gave a lecture on "control architectures of robots", at the Summer School on Image & Robotics (SSIR'06), in July 2006.
- **D. Guiraud (2006)** gave a lecture on "sensing and activating the peripheral nervous system", at the Summer School on Image & Robotics (SSIR'06), in July 2006.
- **D. Guiraud (2006)**, Approche automatique de l'étude du système sensori moteur humain" Laboratoire Physiologie et physiopathologie du mouvement (Bordeaux), Nov. 2006.
- **P. Fraisse (2006)** gave a lecture on " Networked Robots", at the summer school on Image & robotics (SSIR06)
- **P. Philippe Poignet (2006)** gave a lecture on "Robotized Beating Heart Surgery" at the FORUM IB-Sud, Marseille, October 2006.
- **P. Philippe Poignet (2006)**, "Image-based Visual Servoing through Nonlinear Predictive Control", Working Group CPNL - GdR MACS, June 2006

9.6. Theses and Internships

9.6.1. Thesis Defenses

1. Nacim Ramdani defended his HDR,"Méthodes Ensemblistes pour l'Estimation", on 9th December 2005 [30].
2. Samer Mohammed defended his PhD-thesis,"Contribution à la synthèse de mouvement et à la commande des muscles squelettiques sous stimulation électrique fonctionnelle. ", on 23rd November 2006.
3. Gaël Pages defended his PhD-thesis entitled "Estimation de la posture d'un sujet paraplégique en vue d'une rééducation des membres inférieurs sous stimulation électrique fonctionnelle". December, 8, 2006.

9.6.2. Ongoing theses

1. Philippe Fraisse, David Guiraud, and Nacim Ramdani co-supervise **Gaël Pagès**, "*Vers une estimation de posture fiable d'un sujet paraplégique en vue de la réhabilitation fonctionnelle des membres inférieurs pour la station debout.*", Thesis CIFRE MXM, 2004-2007.
2. Étienne Dombre, Philippe Fraisse, David Guiraud and Philippe Poignet co-supervise **Samer Mohammed**, "*Contribution à la synthèse de mouvement et à la commande des muscles squelettiques sous Stimulation Electrique Fonctionnelle*",Thesis LIRMM, 2003-2006.
3. Christine Azevedo co-supervises **Rodolphe Héliot**, "*Modélisation sensori-motrice du contrôle des membres inférieurs chez l'homme et son application à la réhabilitation fonctionnelle*", Thesis from INPG (Grenoble), in collaboration with Bernard Espiau (INRIA RA) and Dominique David (LETI/CEA), 2004-2007.

4. Guy Cathébras and Christine Azevedo co-supervise **Milan Djilas**, “*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*", Thesis INRIA/EADS, 2005-2008.
5. Guy Cathébras and Serge Bernard co-supervise **Lionel Gouyet**, “*Traitements analogiques et numériques des signaux ENG*", Thesis LIRMM MENRT, 2005-2008.

9.6.3. Starting theses

1. David Guiraud and David Andreu co-supervise **Guillaume Souquet**, “*Conception et réalisation d'une architecture de stimulation électro-fonctionnelle neurale implantable pour le contrôle de la vessie*", Thesis CIFRE MXM, 2006-2009.
2. David Guiraud, David Andreu and Christine Azevedo co-supervise **Jérémy Laforêt**, “*Modélisation du recrutement sélectif en neurostimulation multipolaire multiphasique, application à la stimulation neuromotrice sélective*", Thesis LIRMM MENRT, 2006-2009.
3. Christine Azevedo and J.-R. Cazalets (UMR 5543-Bordeaux), co-supervise **Jean-Charles Ceccato**, “*Étude des systèmes posturaux dynamiques.*", Thesis BDI DGA-CNRS, 2006-2009 (Bordeaux/Montpellier).
4. Philippe Poignet supervises **Mourad Benoussaad**, “*Locomotion sous contraintes. Application à la commande d'articulations sous SEF.*", Thesis BDI INRIA / Région LR, 2006-2009.
5. Philippe Fraisse and Nacim Ramdani supervise **Sébastien Langagne**, “*Génération de mouvement adaptative sous contraintes pour la déambulation d'un patient paraplégique par la prise en compte des mouvements volontaires de ses membres supérieurs.*", Thesis BDI INRIA / Région LR, 2006-2009.

9.6.4. Internships

- **2005-2006**
  1. David Guiraud, Didier Delignères and Charles Fattal have supervised **Claire Simon**, "*Emergence de stratégies posturales de coordination*", Projet Master II (SMH), from September 2005 to September 2006.
  2. David Andreu has tutored **Guillaume Souquet**,"*Réalisation d'une unité de stimulation répartie de deuxième génération*", Projet Industriel de Fin d'Études (MEA 3rd year), from September 2005 to January 2006.
  3. David Andreu has supervised **Guillaume Souquet**, "*Développement d'une architecture de stimulation externe multi-unité basée sur un réseau déterministe*", Engineer final internship, from February 2006 to June 2006. This project was carried out within a technological transfer frame with MXM lab. Company. G. Souquet now begins a PhD Thesis (CIFRE MXM-LIRMM).
  4. Christine Azevedo, David Guiraud and David Andreu co-supervised **Jéremy Laforêt** "*Etude du contrôle de la vessie par stimulation neurale implantée*", 2nd year Master STPI intenship (University Montpellier II), from November 2005 to June 2006.
  5. Philippe Fraisse, Martine Eckert, Gaël Pages and Nacim Ramdani have supervised **Sébastien Bottecchia** "Estimation de posture: vers la prise en compte de la 3ème dimension sur le modèle biomécanique", 2nd year Master STPI (University Montpellier II), from April to September 2006.
  6. David Guiraud and Maureen Clerc have supervised **Joan Fruitet** "Mise en oeuvre d'un logiciel de calcul des champs de potentiels et des densités de courant en vue de la modélisation de l'interface nerf-électrode", Ecole Noramle Supérieure d'Ulm première année informatique, from June to July 2006.
- **2006-2007**

1. David Andreu supervises **Nicolas Hebert** and **Pierre Chety**, "*Conception d'une micro-machine dédiée à la stimulation implantée de la cochlée*", Projet Industriel de Fin d'Études (MEA 3rd year), from September 2006 to January 2007.
2. David Andreu supervises **Lionel Duthoo**, "*Conception d'une unité de stimulation électro-fonctionnelle externe autonome à base de coeur de processeur logiciel*", Projet Industriel de Fin d'Études (MEA 3rd year), from September 2006 to January 2007.

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