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Project-Team DEMAR

DEambulation et Mouvement ARtificiel

Sophia Antipolis - Méditerranée

THEME BIO

Activity Report

2007

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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 (SMI U. Aalborg), Germany (IBMT Franhaufer Institute), England (U. College of London), Belgium (U. Catholique de Louvain), United States (Cleveland FES centre), and Canada (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 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 1 and 2. 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 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 (§6.1.4.2).

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

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.

To go further in the modularity and the reusability of sub-parts of complex hardware systems, we defined HILECOP components. An HILECOP component has : a Petri net-based behavior, a set of functions whose execution is controlled by the PN (Petri Net), and a set of variables and signals. Its interface contains places and transitions from which its PN model can be inter-connected as well as signals it exports or imports. The interconnexion of those components, from a behavioral point out view, consists in the interconnexion of places and/or transitions according to well-defined mechanisms : interconnexion by means of oriented arcs or by means of the "merging" operator (existing for both places and transitions).
We start the development of an Eclipse-based version of HILECOP with the aim at making it accessible to the academic community.

6. New Results

6.1. Modeling and identification

6.1.1. *Modeling and identification of muscles under FES*

Participants: Mitsuhiro Hayashibe, David Guiraud, Philippe Poignet, Christine Azevedo-Coste.

A model-based FES system would be very helpful for the adaptive movement synthesis and control of spinal-cord-injured patients [36], [8]. To fulfill this goal, we need a precise skeletal muscle model to predict the force of each muscle elicited by FES. Thus, we have to estimate many unknown parameters in the nonlinear muscle model. The identification process is essential for the realistic force prediction. We previously proposed a mathematical muscle model of skeletal muscle which describes the complex physiological system of skeletal muscle based on the macroscopic Hill-Maxwell and microscopic Huxley concepts. Here, we present an experimental identification method of biomechanical parameters using Sigma-Point Kalman Filter applied to the nonlinear skeletal muscle model [30].

6.1.1.1. Modification of skeletal muscle model

The measured tensile force during stimulation does not directly represent the force of the contractile element in skeletal muscle. The generated force from the edge of skeletal muscle is the filtered by a mass, spring and damping serial element. The macroscopic skeletal model is shown as in Fig.1. The force F_e at the end of this muscle model is the sum of the spring force F_s and the damping force F_d. When we measure the tension of skeletal muscle during *in-vivo* conditions, the experimental force corresponds to F_e. We newly introduced F_e to deal with the dynamics of the skeletal muscle in a strict sense.
Especially, in case of isometric contraction, we can write $2L_{s0}\varepsilon_s + L_{c0}\varepsilon_c = 0$. The dynamical equation of one of the masses is given by (1). F_c and k_c express the force and the stiffness of E_c respectively. When we take the ratio of F_c and F_e, L_{s0} is offset and it can be written as (3). (4) shows the relational equation in Laplace transform. From the relationship, the differential equation (5) can be obtained.

$$mL_{s0}\ddot{\varepsilon}_s = F_c - k_s L_{s0}\varepsilon_s - \lambda L_{s0}\dot{\varepsilon}_s \tag{1}$$

$$F_e = F_s + F_d = k_s L_{s0}\varepsilon_s + \lambda L_{s0}\dot{\varepsilon}_s \tag{2}$$

$$\frac{F_c}{F_e} = \frac{m\ddot{\varepsilon}_s + \lambda\dot{\varepsilon}_s + k_s\varepsilon_s}{\lambda\dot{\varepsilon}_s + k_s\varepsilon_s} \tag{3}$$

$$\frac{\mathcal{L}[F_c]}{\mathcal{L}[F_e]} = \frac{ms^2 + \lambda s + k_s}{\lambda s + k_s} \tag{4}$$

$$m\ddot{F}_e + \lambda\dot{F}_e + k_s F_e = \lambda\dot{F}_c + k_s F_c \tag{5}$$

Finally, for an isometric contraction, differential equations of this model can be described as follows:

$$\dot{k}_c = -k_c|u| + \alpha k_m|u|_+ - k_c|\dot{\varepsilon}_c| \tag{6}$$

$$\dot{F}_c = -F_c|u| + \alpha F_m|u|_+ - F_c|\dot{\varepsilon}_c| + L_{c0}k_c\dot{\varepsilon}_c \tag{7}$$

$$\ddot{F}_e = -\frac{\lambda}{m}\dot{F}_e - \frac{k_s}{m}F_e + \frac{\lambda}{m}\dot{F}_c + \frac{k_s}{m}F_c$$

$$\ddot{\varepsilon}_c = -\frac{2F_c}{mL_{c0}} - \frac{k_s}{m}\varepsilon_c - \frac{\lambda}{m}\dot{\varepsilon}_c \tag{8}$$

The dynamics of the contractile element correspond to (6) and (7). k_m and F_m are the maximum values for k_c and F_c respectively. From (1) and an isometric length constraint, the differential equation of ε_c is obtained as in (8). The internal state vector of this system should be set as $X = \begin{bmatrix} k_c & F_c & F_e & \dot{F}_e & \varepsilon_c & \dot{\varepsilon}_c \end{bmatrix}$

6.1.1.2. Identification with Sigma-Point Kalman Filter

For the identification of this model, K_c F_c F_e ϵ_c are unknown time-varying values and m λ_s L_{c0} are unknown static parameters to be estimated. Thus, it is a nonlinear state-space model, and many state-variables are not measurable. Moreover, *in-vivo* experimental data include some noise. That is why we need an efficient recursive filter that estimates the state of a dynamic system from a series of noisy measurements. Extended Kalman Filter (EKF) was well-known as standard method. In EKF, the nonlinear equation should be linearized to the first order with partial derivatives (Jacobian matrix) around a mean of the state. When the model is highly non-linear, EKF may give a particularly poor performance and an easy divergence. In skeletal muscle dynamics, its state-space is dramatically changed between contraction and relaxation phases. Then, partial derivatives will be incorrect due to the discontinuity. Therefore, we introduced Sigma-Point Kalman Filter (SPKF). SPKF uses a deterministic sampling technique known as the unscented transform to pick a minimal set of sample points (called sigma points) around the mean. These sigma points are propagated through the true nonlinearity. This approach results in approximations that are accurate to at least the second order in Taylor series expansion. In contrast, EKF results only in first order accuracy.

For the parameter estimation, the force information corresponding to isometric contractions was used along with the electrical input. SPKF was applied to the *in-vivo* experimental data from two rabbits to identify the internal states in the nonlinear dynamics of the skeletal muscle. The experimental muscle force against the doublet stimulation (20Hz, 105μA, pulse width 300μs) is plotted in Fig.2 with red line. It was used for parameter estimation as measurement updates for F_e in SPKF. The blue curve is the estimated muscle force of F_e. The part surrounded by the rectangle was magnified at the upper right side to indicate that the resultant estimated F_e was well filtered against the noisy experimental data. Figs. 3a) and 3b) show the estimated parameter L_{c0} and the error covariance. Both figures show the convergence of the estimation. The transitions of internal state values for ε_c and F_c are obtained as in Figs 3c) and 3s). From these transitions, we can confirm that the contractile element of the model is successfully shrunken following the dynamics of differential equations under the estimation process. As seen from resulted computational transition in graphs, the internal state vectors of skeletal model converged well to stationary values. We tested the estimation from 4 different values for initial states, same results could be obtained in stable conditions. The estimated length of contractile element showed close value to its measured length 6.5cm of the isolated skeletal muscle.

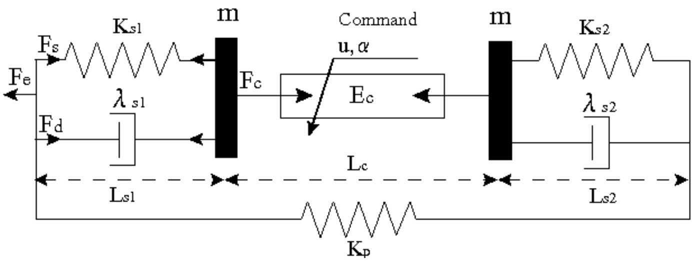


Figure 1. Macroscopic skeletal muscle model.

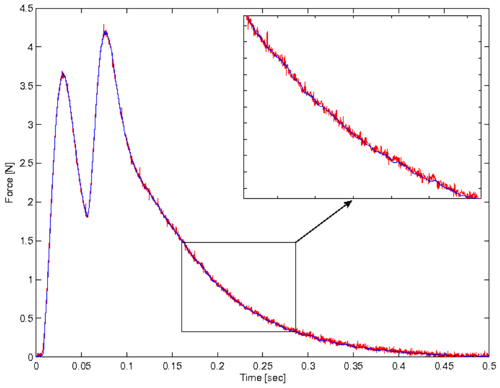
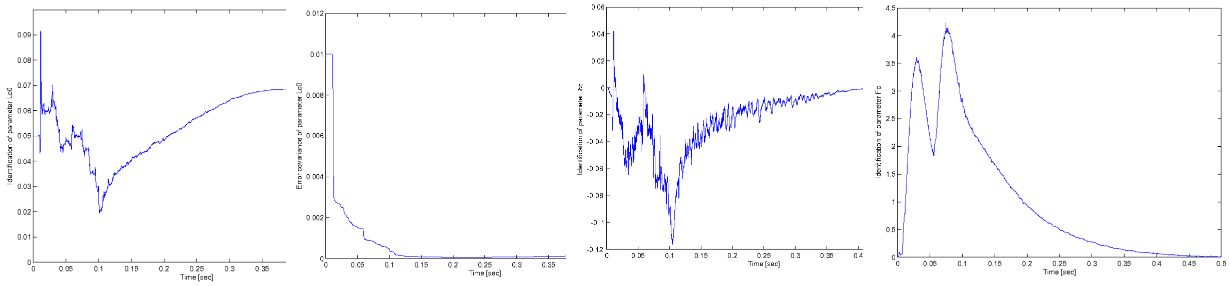


Figure 2. Measured and estimated forces of F_e (N).

6.1.2. Bladder function modeling



(a) Estimated parameter of L_{c0} (m) (b) Error covariance of L_{c0} (c) Estimated strain of contractile element (d) Estimated force of contractile element

Figure 3.

We focus on restoring bladder control, the function for which there is one of the highest demand from patients suffering from lesion of the central nervous system. For optimal bladder control, one must stimulate, within the same nerve, two muscles whose characteristics and actions are very different (the Detrusor which contracts the bladder is a smooth muscle, and the external sphincter which closes the output contains a striated muscle), and hence, one must perform selective recruitment of the two different types of nerve fibers.

6.1.2.1. Smooth muscle modeling

Participants: Jérémy Laforet, David Guiraud, Christine Azevedo-Coste, David Andreu.

Smooth muscles show many differencies compared to skeletal muscles which makes models of the later unable to describe correctly their behavior. We developed a new model of smooth muscle that can be used to simulate the effect of FES [34]. It is composed of a set of differential equations based on the physiological reality so that parameter's values are meaningful and can be used for quantitative and objective evaluation of the muscle state. Moreover, the model has an input controlled by a FES signal so that it can simulate the behavior of the bladder contraction under detrusor stimulation. The model itself can be divided into two blocks:

- Molecular scale model: It describes calcium's dynamics upon the activation of the muscle and the evolution of the different states of actin and myosin. It is built upon Hai & Murphy's work on the molecular mechanics of smooth muscle contraction. We expanded it to take into account our constraints (9): non-isometric contraction, FES driven activation ...

$$\begin{aligned}
[\dot{M}] &= -\mathrm{k}_1\left([Ca^{2+}]\right)\cdot[M] + k_2\cdot[M^*] + \mathrm{k}_7(\dot{\epsilon_c})\cdot[AM] \\
[\dot{M^*}] &= \mathrm{k}_4(\dot{\epsilon_c})\cdot[AM^*] + \mathrm{k}_1\left([Ca^{2+}]\right)\cdot[M] - (k_2+k_3)\cdot[M^*] \\
[\dot{AM^*}] &= k_3\cdot[M^*] + k_6\cdot[AM] - (\mathrm{k}_4(\dot{\epsilon_c}) + k_5)\cdot[AM^*] \\
[\dot{AM}] &= k_5\cdot[AM^*] - (\mathrm{k}_7(\dot{\epsilon_c}) + k_6)\cdot[AM]
\end{aligned} \tag{9}$$

- Cellular scale model: Using the methods developed for skeletal muscles, we expressed the dynamical equations of force and stiffness for the contractile element (11)(12). To that end we redefined attachment and detachment functions from Huxley's cross-bridge model (10). This way we can take into account the molecular scale model and obtain computable equations.

$$\begin{aligned} f(\xi,t) &= \begin{cases} \frac{[M^*]}{[M]+[M^*]}\cdot f_1, & 0<\xi<1,\\ \\ 0, & \xi\notin[0;1] \end{cases} \\ g(\xi,t) &= \left\{ \frac{[AM^*]}{[AM]+[AM^*]}\cdot g_1+\frac{[AM]}{[AM]+[AM^*]}\cdot g_2-f(\xi),\quad \forall\xi \right. \end{aligned} \tag{10}$$

with : $f_1 \propto k_3$, $g_1 \propto k_4$, $g_2 \propto k_7$.

$$\dot{k_c} = \alpha(\epsilon_c)\cdot f(\xi,t) - g'(\xi,t)\cdot k_c \tag{11}$$

$$\dot{F_c} = \frac{\alpha(\epsilon_c)\cdot f(\xi,t)}{2} - g'(\xi,t)\cdot F_c + \dot{\epsilon_c}\cdot k_c \tag{12}$$

with $g'(\xi,t) = \frac{[AM^*]}{[AM]+[AM^*]}\cdot g_1 + \frac{[AM]}{[AM]+[AM^*]}\cdot g_2$

- Geometrical and mechanical model: this block is specific to our application, the bladder. Its task is to describe the particular geometry of this muscle and to translate the computed quantities into meaningful observable ones at macroscopic scale.

Simulations show consistent results with the literature data, both at the molecular and macroscopic scale. Figure 4 shows the results of the simulation of a Brindley implant.

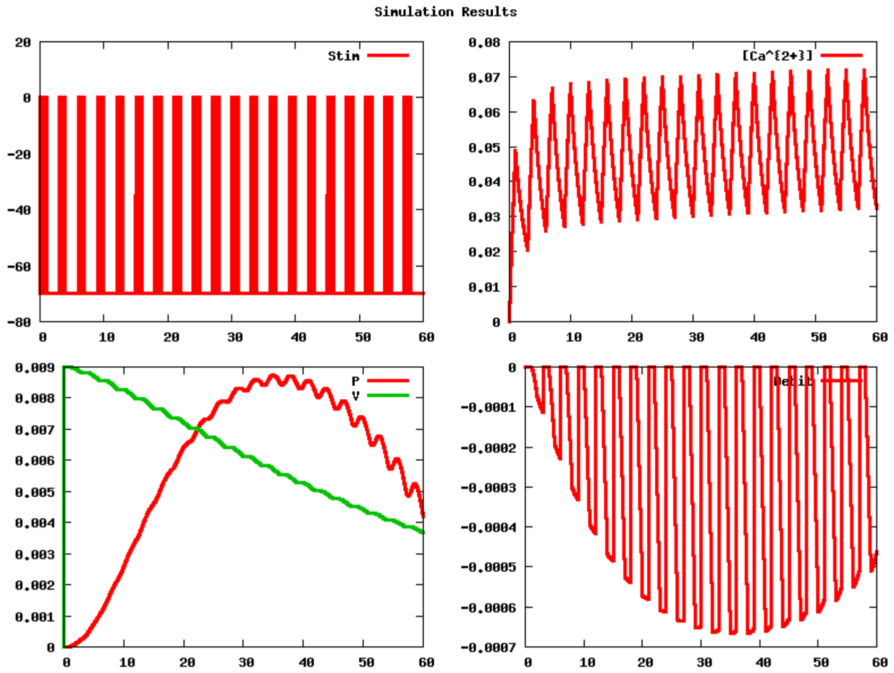


Figure 4. Simulation of a Brindley implant based bladder control.

These preliminary results, after *in-vivo* validations, will be used to characterize bladders that need to be stimulated, for instance for paraplegics, and then to optimize the needed stimulation parameters when neuroprosthesis are used to restore the emptying function.

6.1.2.2. Modeling interface between electrode and nerve

Participants: Maureen Clerc [Odyssee, INRIA Sophia], David Guiraud, Sabir Jacquir.

By using multipolar neural electrodes, and multiphasic waveforms, the response of the axons can be made dependent on their characteristics, their diameters, the propagation direction, and the positioning within the nerve. In order to design 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. At the scale of the nerve, the simulation is based on a Boundary Element Method developed in INRIA Odyssee, which have been 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 has been continued by Sabir Jaquir as a postdoc between Demar and Odyssée [33].

6.1.3. Movement synthesis & control

Part of this work is described in [38].

6.1.3.1. Synthesis of optimal Functional Electrical Stimulation patterns for knee joint control

Participants: Mourad Benoussaad, Philippe Poignet, David Guiraud.

Knee joint control of paraplegics patient constitutes a prerequisite step for further assisted movements such as standing up, standing and walking. In the rehabilitation context, the application of Functional Electrical Stimulation for movement restoration poses some problems in practice. The applied stimulation patterns are often empirically chosen, increasing the muscular fatigue. The goal is to synthesize the stimulation patterns for efficient and accurate functional movement. These patterns, synthesized off-line, should be applied on a real musculoskeletal system.

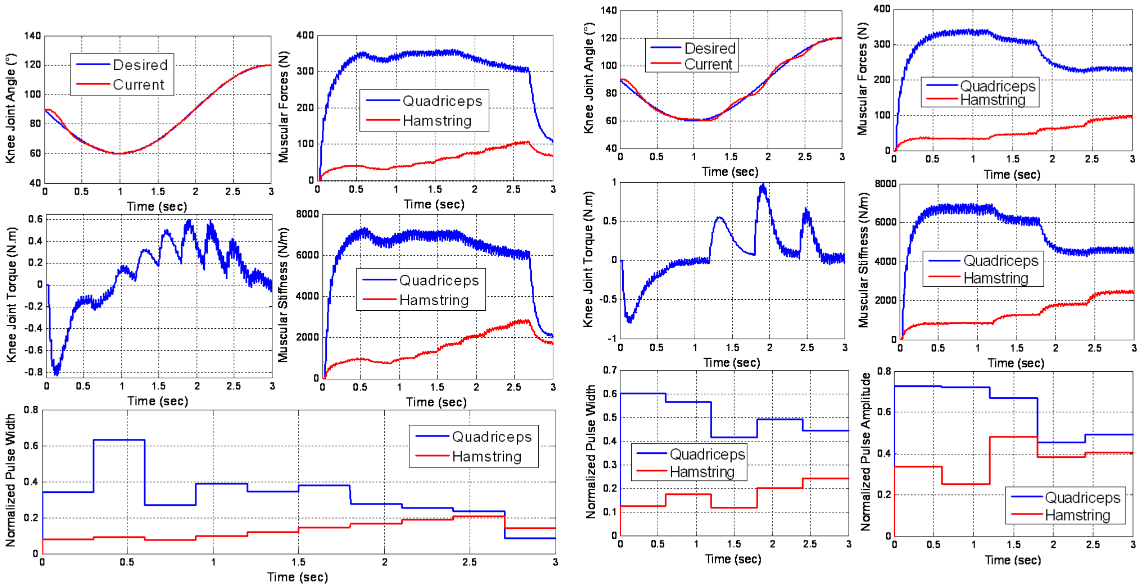
The optimal pattern synthesis is based on a nonlinear constraint optimization approach by considering a biomechanical knee model and the associated agonist/antagonist muscles. The constraint optimization is based on a cost function minimization reducing the muscular activities during the whole movement. The approach was tested in simulation: 1) following several desired knee joint trajectories. The results are reported in [19] [20] as shown on figure 5. 2) generating and following the optimal reference knee joint trajectory and 3) without an explicit reference knee joint trajectory, where only the final knee angle, velocity and acceleration were used as constraints. The results have been compared using the energetic balance sheet. An autorisation was applied for practical experiment validation on paraplegics. The steps of validation protocol are as following:

- Firstly, non-invasive identification protocol of knee model parameters based on real data of patient will be used to customize the model.
- Secondly, the personalized model will be used in optimization procedure in order to synthesis a stimulation patterns.
- finally, the obtained optimal stimulation must be applied using open-loop or closed-loop strategy.

Although, the co-contraction of antagonistic muscles increases the energetic consumption, it is useful for stability movement during walking and ground contact. Future works concern the joint stiffness modeling in order to explicitly control the co-contraction ratio.

6.1.3.2. Activity of the trunk at gait initiation and during locomotion

Participants: JeanCharles Ceccato, Christine Azevedo-Coste, Jean René Cazalets [UMR 5227, Bordeaux], Mathieu De Sèze [UMR 5227, Bordeaux].



(a) Pulse widths optimization (b) Pulse widths and intensities optimization

Figure 5. optimization of input stimulation parameters.

The trunk, due to its central position in body and its mass plays an important role in maintaining balance and thus optimize energetic cost and propulsion. This study aims at better understanding the trunk activity at gait initiation and during locomotion. We propose a protocol to record kinematics and EMG (electromyography) activities of the trunk during gait initiation and walking.

We use a motion capture system (BTS), wireless EMGs (Kine) and force plates (AMTI) to add some dynamic information to the data collected (fig.6).

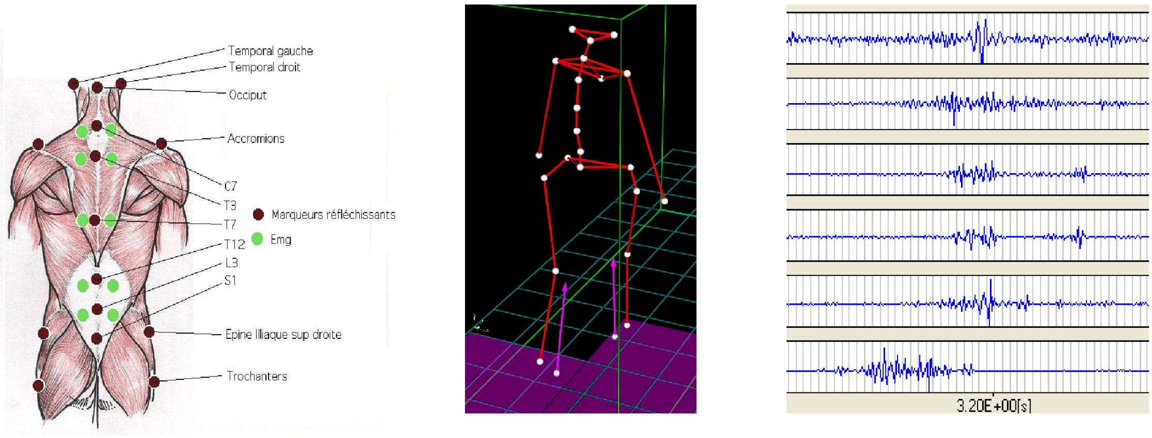


*Figure 6. **A.** Sensor positions, **B.** Kinematics and dynamic data, **C.** EMG data*

First results on EMGs confirm and extend results previously obtained by M. De Sèze about the existence of a descendent metachronal (segment by segment) activation wave of spinal muscles during gait on the side corresponding to the next swing-leg.
Our first finding are that this wave is also present but with lesser amplitude before the first step initiating gait (fig.7 A&B).
The second finding is that this descendant activation is correlated with trunk kinematics which movements occur in a top-down organization (fig.7 C) [23], [24].

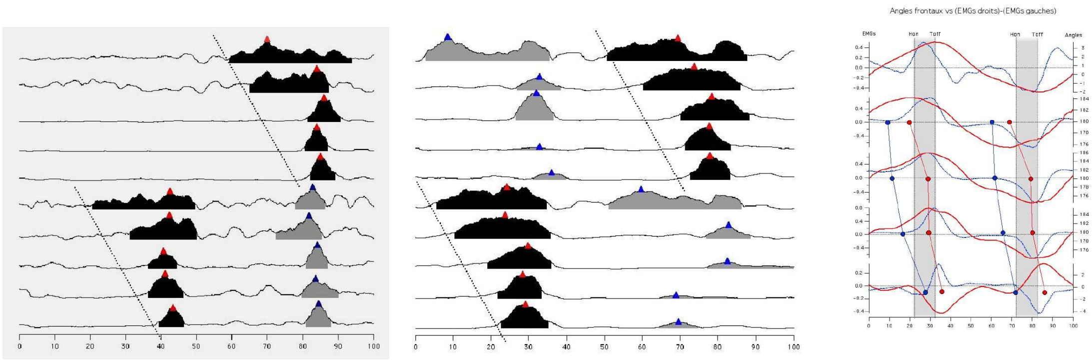


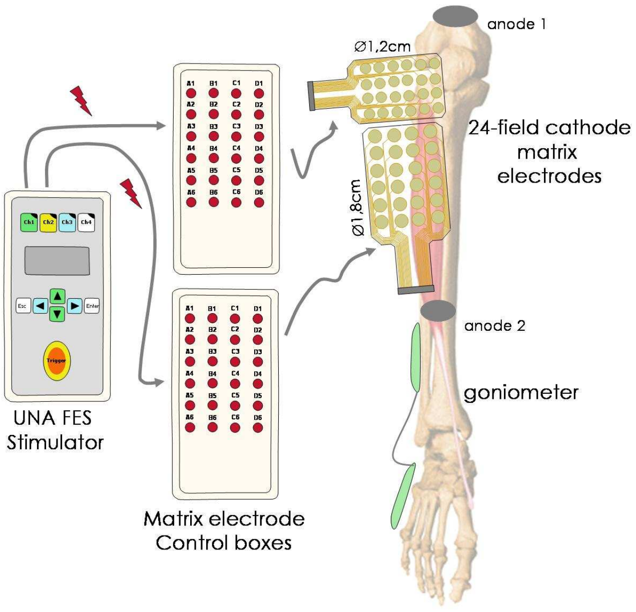
*Figure 7. **A.** Spinal EMG during gait initiation (descendant metachronal wave in black on each side), **B.** Spinal EMG during gait, **C.** EMG (blue) vs. kinematics (red) descendant wave*

6.1.3.3. Treating drop-foot in hemiplegics: the role of matrix electrode

Participants: Christine Azevedo-Coste, Dejan Popovic [Fac. Elect. Engineering, Belgrade], Laslo Schwirtlich [Zotovic Rehab.Center, Belgrade].

One of the main consequences of hemiplegia is the drop-foot syndrome. Due to lack of controllability of muscles involved in flexing the ankle and toes, the foot drops downward and impedes the normal walking motion. Today, there are available assistive systems using surface electrodes. One main drawback of these systems is the difficulty to properly position the electrodes. Furthermore, when standing up, walking, or rotating the leg the relative position of the electrode moves with respect the sensory-motor systems that are responsible for activation of the desired muscle.
A plausible solution for achieving selective stimulation is the application of matrix electrodes. The idea behind the use of surface matrix electrodes is that one can select size, shape, and position of the electrode without physical reallocation or use of multiple electrodes. The matrix electrode allows selection of small fields to be conductive; thereby, definition of size, shape and position of the electrode.

Nine volunteer hemiplegic individuals from the Institute of Rehabilitation "Dr Miroslav Zotovic", Belgrade participated in the study.
In a first part of the experiment, called mapping, the patient was sitting and each of the fields was successively activated and the current amplitude was increased up the apparition of a movement at the ankle. Stimulation intensity was then increased until maximal dorsiflexion was observed. For each field the signal from the goniometer was recorded. In a second phase of the experiment, from the observations made during the mapping stage, multi-field stimulation was performed, involving the fields which were shown to induce dorsiflexion, different shapes were tested and the corresponding goniometer values were recorded (fig.8).
An important result is that the response to the stimulation is very sensitive when using the electrode placed over the peroneal nerve (fig.9-1). It is also found that small variation of pulse charge easily leads to undesired movements that could compromise the walking. The size of the electrode when positioned over the nerve is small, as already demonstrated and applied in most drop-foot stimulators.



(a)

Figure 8. Protocol description.

As expected from the basic anatomy the shape of the electrode that led to the optimal contraction and functional dorsiflexion in most case was a tree like branched structure; not a regular form of ellipse or rectangle (fig.9). The size of the electrode varies greatly from one to the next hemiplegic individuals. This all suggests that making electrode in custom shaped is not a realistic approach for optimal dorsiflexion when stimulating over the muscle [16].

6.1.3.4. FES-assisted standing in complete paraplegia

Participants: Christine Azevedo-Coste, Gael Pages, Charles Fattal [Centre clinique PROPARA, Montpellier], David Guiraud.

We investigate the issues appearing when using FES for sit to stand and standing in complete paraplegic patients.
The protocol was to stand under FES in between parallel bars and to maintain postural balance by aligning head, pelvis and ankles with minimum arm support [37]. In order to help patients to adopt the correct posture, visual feedback assistance was provided: a screen was set up in front of the patients where they could see their own profile. A video motion analysis system recorded the positions of reflective markers placed on relevant body points. Force sensors mounted to handles fixed on the parallel bars recorded arm support efforts. Insoles, fitted in the patient's shoes, recorded plantar pressure distribution (fig.10).

15 complete paraplegic patients (T5-T12) were initially selected to participate in our study. All the patients went through a muscle mapping session during which compatibility with surface electrical stimulation was tested. Muscles involved in standing were investigated: (1) quadriceps vastus medialis, (2) hamstring biceps femoris, (3) gluteus maximus and (4) tibialis anterior (fig.10.
9 patients were finally admitted to perform the next phases of the study. A muscular reinforcement consisting in 4 training sessions was performed. Each session consisted, for each muscle, in 3mn stimulation sequence application followed by 3mn rest, 4 times. The maximum current amplitude was increased over the sessions to improve joint locking.

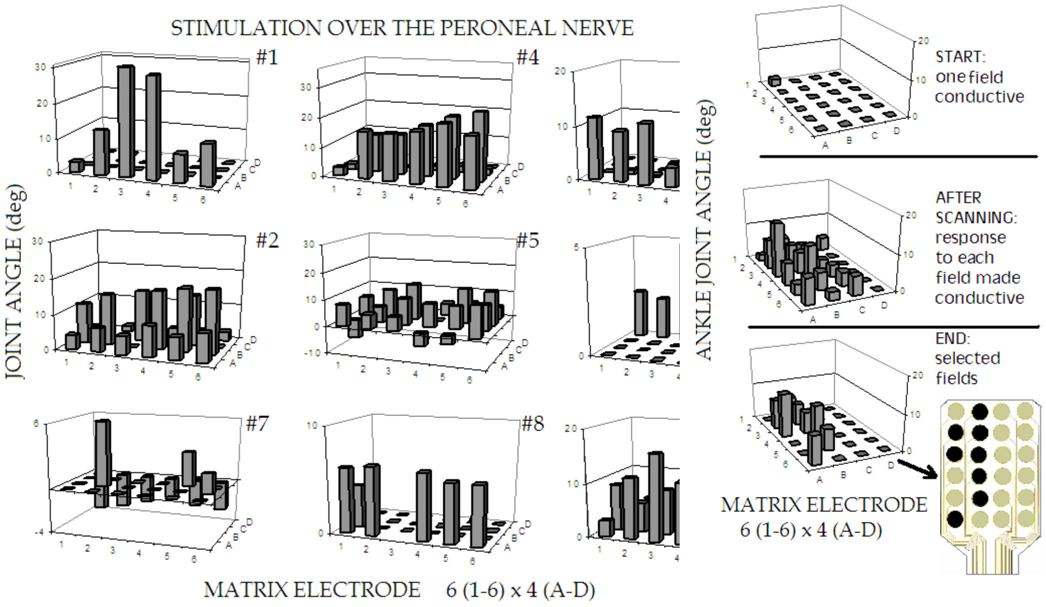


*Figure 9. (**Left**) 1- Result of the mapping session. (**Left**) 2-Multi-field stimulation over the muscle: optimal configuration of the matrix electrode in terms of maximum ankle flexion.*

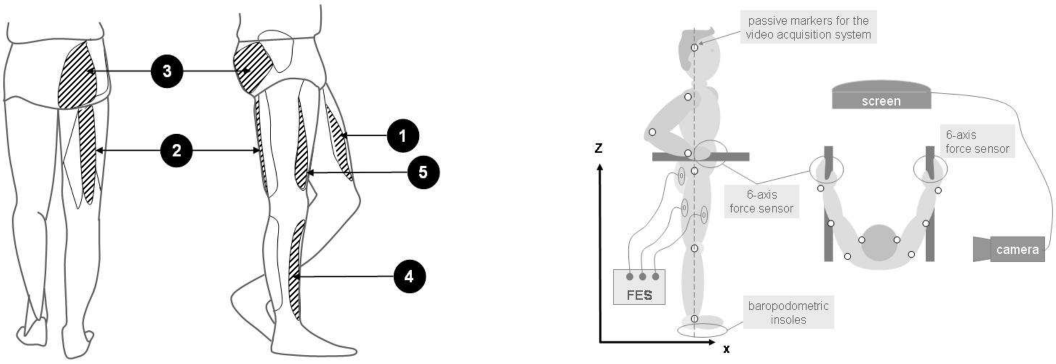
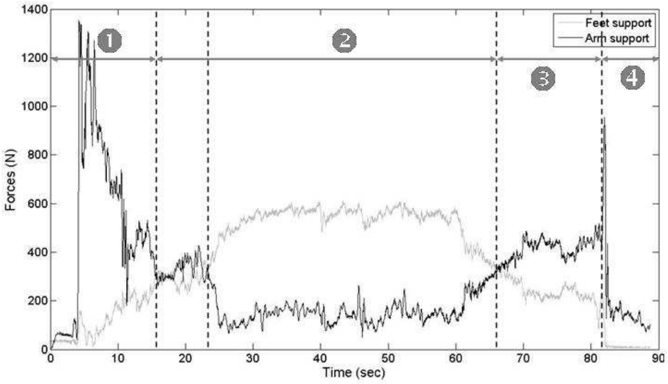


Figure 10. Description of the FES-assisted verticalization protocol

Two verticalization sessions of five trials were performed: a first session to adjust the stimulation parameters and for the patient to get familiarized with the protocol, a second session where kinematics and dynamics information were recorded.
8 patients out of 9 were able to achieve a correct vertical posture. We measured the total efforts applied to the handles and the ground during sit-to-stand transfer and standing. As expected in all the patients, transfer is mainly ensured by arm support. When fatigue occurs the contribution of foot support decreases in favor of arm support.



(a)

Figure 11. Total efforts applied to the handles and the ground during sit-to-stand transfer and standing

The aim of this study was to better understand FES-assisted sit-to-stand and standing and the possibility to get pertinent information with minimum set of sensors. It appears that arm forces measured on the handles could be a good indicator to trigger leg stimulation. The effect would be to decrease the needs of current amplitudes and consequently decrease fatigue [17], [39], [9].

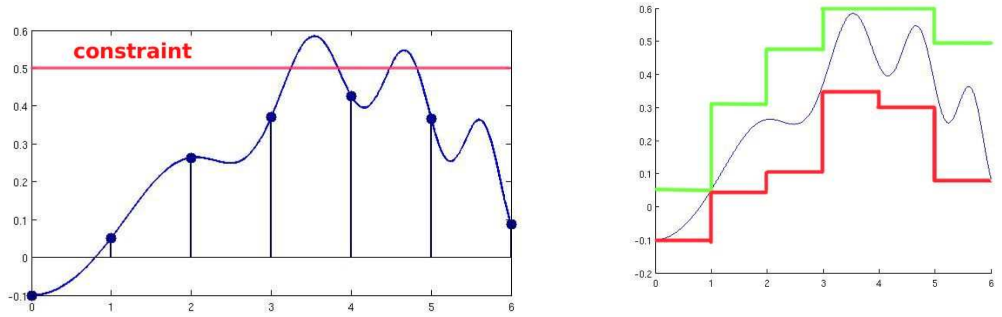
6.1.3.5. Guaranteed constraints computation for a safe path planning (application to paraplegic patients and humanoid robots)

Participants: Sébastien Lengagne, Nacim Ramdani, Philippe Fraisse.

The goal of this study is to find joint trajectories for paraplegic patient deambulation under FES. We suppose that the patient can be modeled as legs of humanoid robots in the sagittal plane, with six degrees of freedom (ankles, knees and hip). Constrained optimization problem is often used to solve this path planning problem. We proposed a new method for the guaranteed computation of the constraints. Indeed, most people use a time-point discretization to fill in the constraints value to an optimization algorithm. This method is hazardous, the optimization algorithm can generate an optimal solution which violates some constraints. Therefore we propose a guaranteed constraint computation which uses interval arithmetics.

To generate a motion, the usual solution is to solve a constrained optimization problem which takes into account several constraints, and an objective function which depends on the application. The optimization algorithm needs a discrete evaluations of the constraints : these constraints must be discretized.

The discretization concerns the process of transferring continuous models and equations into discrete counterparts. The usual way for discretization is to pin out a number k of discretes values during the motion (cf. Fig:12). Once the optimization is finished with optimal results, the motion satisfies all the constraints for the discrete instants, but this does not ensure that the constraints are satisfied between two time-points (cf. Fig:12).



(a) example of a function discretization (b) example of time-interval function discretization

Figure 12.

The main idea of the time-interval discretization is to bound a function $g_{j(t)}$ with a minimum and maximum value during a time interval $[t] = [t_{min}, t_{max}]$ instead of compute a single value as shown in Fig:12. In this case the optimization algorithm is aware about the constraints violation. This work has been published in [35].

6.1.3.6. Modeling human postural coordination to improve the control of balance

Participants: Vincent Bonnet, Philippe Fraisse, Nacim Ramdani, Julien Lagarde [EDM-UM1], Denis Mottet [EDM-UM1], Benoit Bardy [EDM-UM1].

We aim at modeling recent data in the field of postural coordination showing the existence of self-organized postural states, and transitions between them, underlying supra-postural tracking movements. The proposed biomechanical model, capitalizing on stability and optimization criteria, captures the complex postural behaviors observed in humans and can be used to implement efficient balance control principles in patient having disabilities (hemiplegia, paraplegia) humanoids. The first theoretical and experimental results on human beings and humanoid robots in the sagittal plane (fig. 13) show the relevance of this work [22].

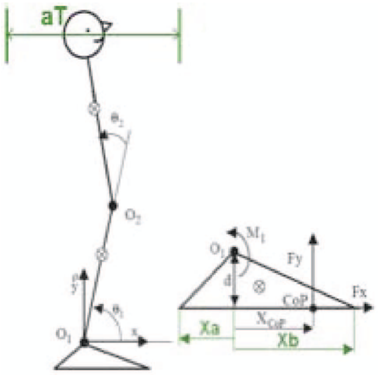


Figure 13. 2D model used to simulate the postural control.

6.1.3.7. Rehabilitation of posture and walking: coordination of valid and deficient limbs

Participants: Rodolphe Héliot, Christine Azevedo-Coste, Dominique David [CEA-LETI], Bernard Espiau [INRIA RA].

When controlling postural movements through artificial prosthetic limbs or Functional Electrical Stimulation, an important issue is the enhancement of the interaction of the patient with the artificial system through his valid limb motions. We address the problem of the coexistence of voluntary controlled with artificially controlled movements (see Fig. 14). We propose to observe the valid limbs through movement sensors in order to optimize the interaction at two levels: a strategic level, where we aim at identifying as soon as possible the postural task the patient intends to execute, and a tactic level, where we aim at monitoring the ongoing task in order to estimate some movement parameters. Particularly, to ensure legs coordination during walking, the CPG (Central Pattern Generator) concept is introduced, and we propose a robust phase estimation method based on the observer of a non-linear oscillator. This framework mixes discrete and continuous behaviors; this duality raises some integration issues and implies to setup a hybrid command architecture. Two additional constraints are the required number of sensors, as well as the complexity of the algorithms, that both have to be kept as low as possible. The proposed solutions are based on movement models, and have been validated through real time experiments [18], [12], [7], [31], [32], [11], [14], [13], [44].

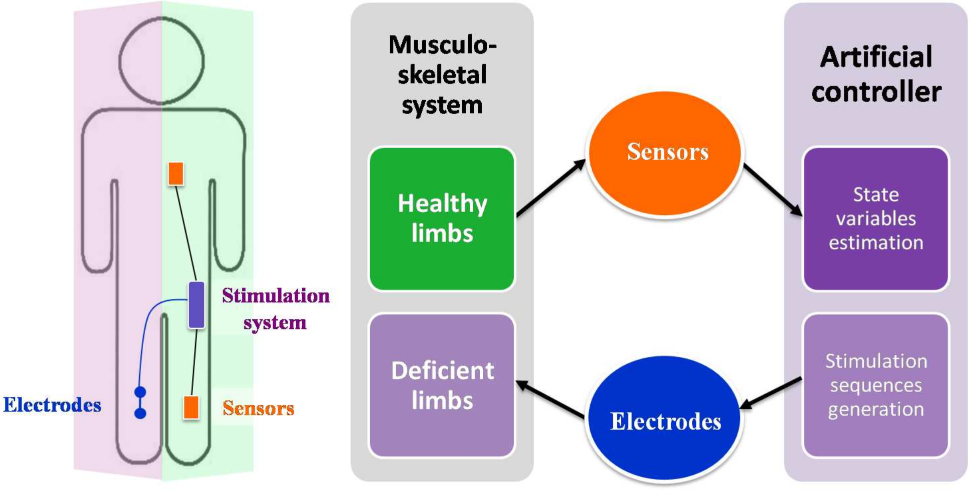


Figure 14. Observing valid limbs to improve deficient limbs artificial control

6.1.4. Activating the natural parts through neuroprosthetic devices

The functional electrical stimulation (FES) consists in activating motor nerves thanks to implantable electrodes inducing controlled muscles contractions. In the context of the DEMAR project we are developing a new generation of distributed neural prostheses [10].

Recent advances in FES show the efficiency of multichannel devices, especially for cuff electrodes. This type of electrode is wrapped around the nerve and can stimulate a large number of fibers. Increasing the number of poles offers the ability to control the spatial distribution of currents and thus the selectivity of the stimuli.

The device presented here is designed to drive twelve independent poles. More precisely, it allows each electrode to be used as an anode (stimulation) or as a cathode (active recovery) independently and can process either in synchronous or in asynchronous mode.

The stimulator integrated circuit consists in two main blocks. The first part is a full-digital block dedicated to the control of the device; it deals with the communication tasks and manages the interpretation and the sequencing of the stimuli. The purpose of the second part, (fig. 15) called the active part, is to generate the stimulation current and to distribute it to the poles of the electrode.

6.1.4.1. Output stage of the neural stimulator

Participants: Guy Cathébras, Jean-Baptiste Lerat, David Guiraud, Serge Bernard.

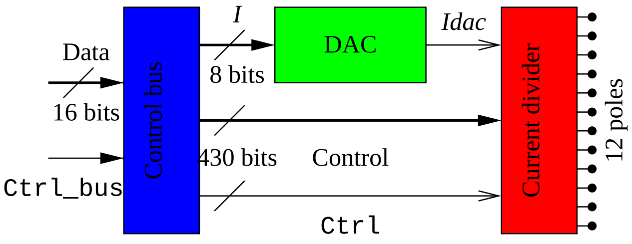


Figure 15. Structure of the active part of the stimulation device.

The active part of the stimulation device is made up of:

- a control bus that acts as the interface with the digital (control) block,
- a digital to analog converter (DAC) generating the required current for the stimulation,
- a reversible current divider allowing the duplication and the distribution of the current between the 12 poles of a multipolar cuff electrode.

The overall shape of the current waveform is defined by the DAC output. The *current divider* block is in charge of the replication and the distribution of this current within the 12 poles of the electrode.The DAC input is 8 bit-coded. To take benefit of this 48 dB dynamic range we use a wide swing cascode current mirror structure (fig. 16). Moreover, the cascode enhances the current gain.

6.1.4.2. Distributed Stimulation Unit (DSU)

Participants: David Andreu, David Guiraud, Guillaume Souquet.

Security aspects have been soon integrated within the DSU, as for instance by means of embedded reference models ensuring the respect of physiological constraints [43]. To allow for remote monitoring of the DSU, we have added the possibility to remotely access to the (internal) DSU state, in addition to already possible access to downloaded micro-programs, network configuration, etc. This gives now access to: the abstract state vector (state of the two micro-program zones and state of the micro-machine), the actual value of parameters of dynamically modifiable instructions, details of the error vector, etc. Doing so, we favor remote diagnosis; for example, this DSU state remote-access allows to understand why an embedded reference model has stopped the stimulus execution. By means of this "large scope" remote-access we can have a precise view of each component of the distributed FES architecture.

6.1.5. Recording afferent signals through neuroprosthetic devices

6.1.5.1. Intrafascicular electro-neurography

Participants: Milan Djilas, Christine Azevedo-Coste, Ken Yoshida [IUPIU, Indianapolis], Guy Cathébras.

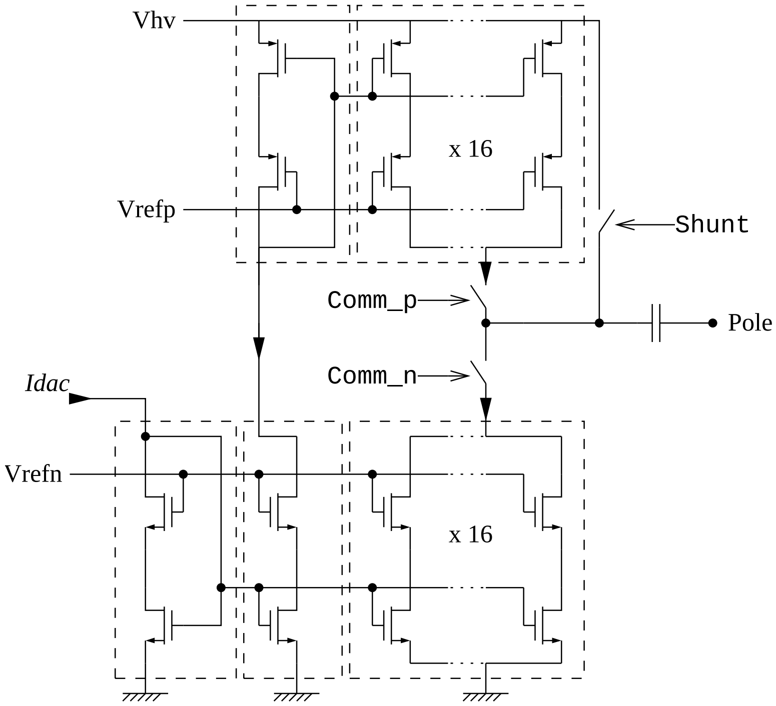


Figure 16. Simplified scheme of the structure driving a single pole.

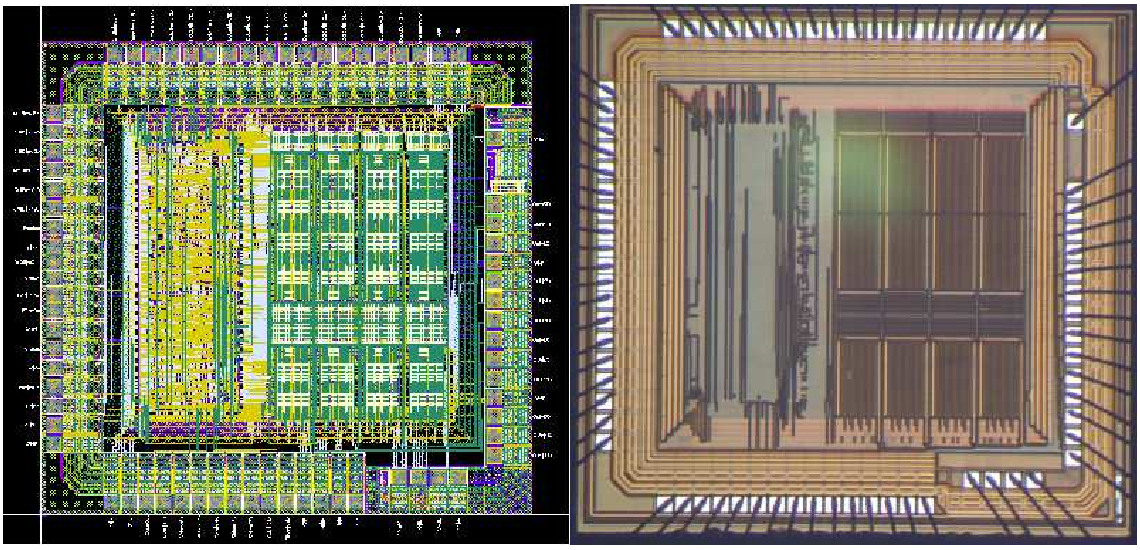
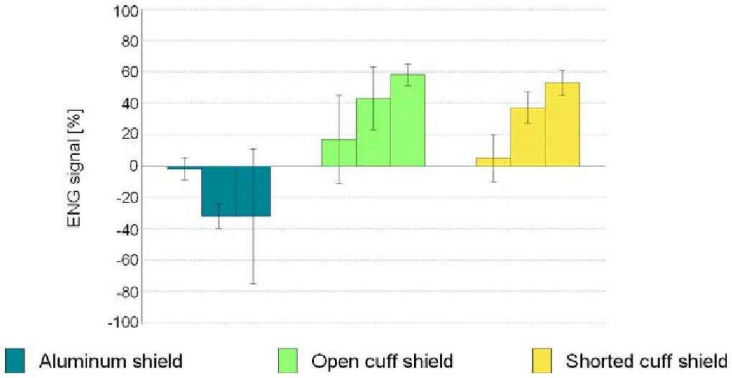


Figure 17. Layout and micro-photograph of the stimulation device.

6.1.5.1.1. Improving the SNR in intrafascicular recordings

Shielding the implant site in intrafascicular recordings could be used as a means to improve the signal-to-noise ratio. Three shield configurations were compared to the no shield case: 1) Aluminum shield, 2) Open circuit shielding cuff, and 3) Shorted shielding cuff electrode. They were compared in terms of their effect on the levels of nerve response, stimulation artefact and EMG artefact. These preliminary results show an indication that putting a cuff electrode around the LIFE implantation site increases the recorded ENG levels (Fig. 18), while wrapping just a conductive foil decreases both the ENG signal and EMG artefact levels. This is still an ongoing study and more experiments are needed to draw definite conclusions.



(a)

Figure 18. Comparison of ENG levels. The bar graph shows the ENG levels for 3 trials, relative to the no shielding case.

6.1.5.1.2. Modeling the muscle spindle neural response to passive stretch

A new model of the neural firing rate is proposed. It outperforms the earlier proposed linear model, as it manages to capture the non-linear properties of the relationship between afferent neural firing rate and muscle length (Fig. 19). Estimation of muscle length from the recorded multi-channel ENG provides more robust results compared to using single-channel recordings. In order to further improve the estimation, classification of action potentials is needed. Any potential effects of muscle fatigue on afferent nerve response would also prove to be invaluable for closed-loop FES. These issues are in the focus of our ongoing study [25].

6.1.5.2. Multipolar-cuff recording

Participants: Lionel Gouyet, Guy Cathébras, Jean-Baptiste Lerat, Fabien Soulier, Serge Bernard.

Concerning signal acquisition from the neural system, our main objective is the development of an electro-neurogram (ENG) recording device. We designed an electrode and the associated micro-electronics to improve the sensitivity and the selectivity compared to the available devices, together with a better rejection of parasitic signals such as electro-myogram (EMG).

The first step of this study was to choose the way the signal would be processed and thus, to define the specifications of our device. To increase the amount of information recorded from a nerve, we decided to apply an Independent Component Analysis (ICA) to the recorded data. This signal processing requires a large number of parallel recordings to be efficient. In order to provide these recordings, we define a new hexagonal multipolar cuff electrode (fig. 20) with a large number of contacts on the nerve [29]. Numerical simulations have shown that this specific geometry provides an efficient attenuation of muscular signals (EMG) that are parasitic signals in our context [28], [21]. This attenuation is a major concern in our research because of the level of the neural signals (μV) compared to those of parasitic signals (mV). A first study using a commercial array of electrodes has validated the suitability of the multipolar approach on sciatic nerves of rats.

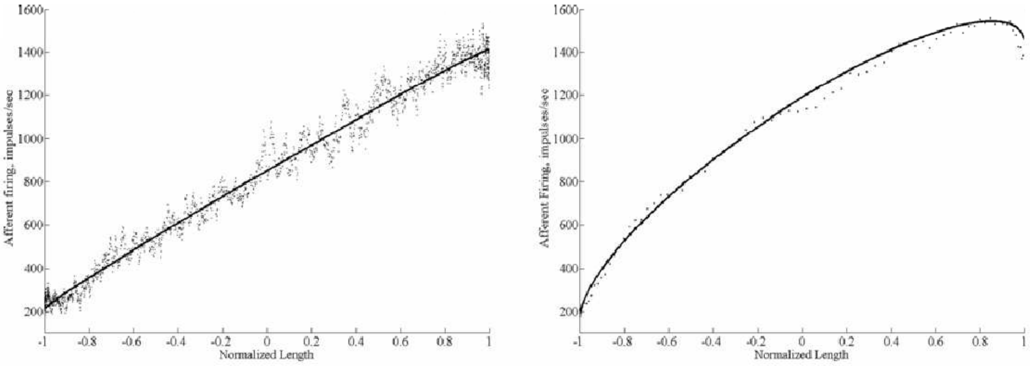


Figure 19. Result of fit for one channel of the tfLIFE for stretch frequencies of 10 mHz (left) and 250 mHz (right). The abscissa shows the normalized muscle length and the ordinate shows the neural firing rate. The full lines are the fitted curves

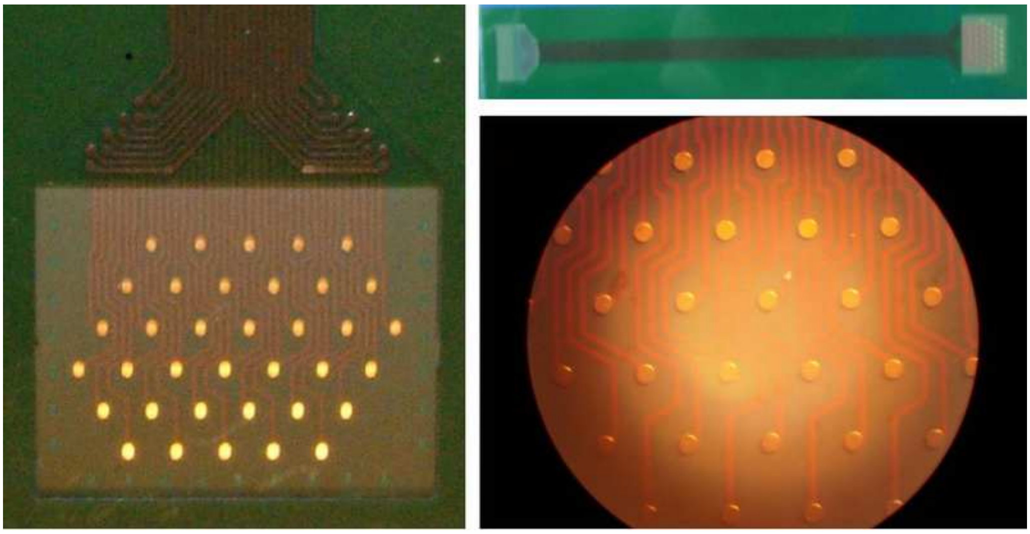


Figure 20. Views of the multipolar electrode.

A specific low-noise amplifier was designed in 0.35 μm technology (fig. 21) aimed to amplify the targeted signals (ENG) while attenuating the EMG. 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 the six surrounding poles. In order to reduce both the area overhead and the noise induced by the circuit, we have developed an architecture using as few transistors as possible.

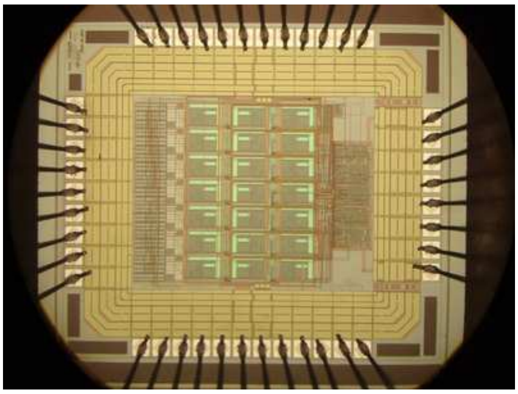


Figure 21. Micro-photograph of the amplifier circuit.

Our perspectives for this year are several *in vivo* experiments to evaluate the improvement of our recording chain compared to the existing devices. The electrode and the amplifier are the two first elements of the recording chain, the third part being the processing block that will be developed next year.

6.1.6. Communicating between units

Participants: David Andreu, Jérome Galy, Guillaume Souquet, David Guiraud.

A DSU embeds a protocol-stack based on three layers: Application [41], MAC [42] and physical layers.

The MAC protocol, called STIMAP (Sliding Time Interval based Medium Access Protocol), has been formally validated [27]. The functional electrical stimulation is a critical and real time application domain: communications have to be safe (no collision, no loss, neither long nor unexpected delay). Therefore, an important part of this system from an efficiency point of view is the medium access mechanism. The validation of our protocol permits to ensure that it fits with the specific constraints of our context ensuring determinism and favoring reactivity (within the stimulation architecture).

We presently work on improvments of the MAC protocol. We are studying mecanisms, based on the listening of the trafic, to improve DSU time-intervals synchronization (on our asynchronous network); the aim is to ensure that intervals overlapping can not occur.
The first experimental platform which has been developed was based on a set of FPGA devices (DSUs) connected by means of an ethernet bus. Tests have been performed on this platform and the MAC protocol (international patent) has been validated.

We also developed two other experimental plateforms respectively based on an implantable 2-wire bus and a wireless technology. Due the modularity of our protocol-stack, only the physical layer needed to be adapted for these plateforms. Those plateforms are:

- The SENIS bus [40] is a single 2-wire implantable (medical) cable that provides data and will provide energy. This architecture needs only for a 2-wire bus to communicate whatever the number of poles or the number of DSU is. This structure is then easy to implant in the way that a single 2-wire cable needs to be linked from one unit to the next (according to a bus topology). The configuration can evolve adding new stimulation units in further surgical sessions.

- The wireless plateform we developed is based on 2.4 GHz RF low-power technology from Freescale; it has been developed as an extrabody network (this technology being not adequate for intrabody communication) allowing to deploy a stimulation architecture in the context of external FES based functional reeducation.

The MAC protocol can be used in other domains than FES, as for instance to develop a wireless architecture 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). The design being realized, we are developping an experimental plateform. This proposition of a specific wireless architectures for testing System-In-Package wirelessly is in the patent process (with NXP) [45].

6.2. Experimental Campaigns

We would like to emphasize a transversal part of the work carried out by our team: the experimental campaigns.

6.2.1. 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):** in 2007, 5 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. 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. **Post-stroke hemiplegic patients at Zotovic center (Belgrade):** 4 stroke patients participated to a campaign in November 2007 within a protocol concerning drop foot correction through FET (Functional Electrotherapy) using matrix electrode. **Parkinson Disease (PD) Patients at the Neurological Center in Belgrade:** 9 PD patients participated to a campaign in November 2007 within a protocol concerning evaluation of FES to correct walking gait.

6.2.2. Animal experiments

Animal experiments are very important when testing neuroprostheses and studying basics of electrophysiology, but we limit these investigations to minimum needed. In 2007, experiments have been run at Montpellier I University biology institue and at UAB university in Barcelona.

7. Contracts and Grants with Industry

7.1. Contracts and Grants with Industry

An industrial technological transfer contract is ongoing 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).

A new contract has been signed with Vivaltis company that is specialized in the development of external stimulation. We commonly aim at new advanced externel FES system dedicated to clinical rehabilitation.

8. Other Grants and Activities

8.1. International grants

- France-Stanford Center for Interdisciplinary Studies: prospective project (Visits and exchanges) in collaboration with Professor Oussama Khatib from robotics lab (Stanford University) focused on Artificial Walking. 14000$US. Duration: 1 year, 2006-2007. (see:http://ica.stanford.edu/france/projects/2006-2007).
- National Medical Reasearch Council - Nayang Technological University. Project on Pathological tremor. LIRMM scientific leader: P. Poignet. Funding for exchange (Oct. 2006 - Oct. 2009)
- EGIDE ECONET support for travel expenses with Slovenia and Serbia (2007). 15keuros.

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).
- PsiRob ANR Project TREMOR on pathological tremor compensation using FES, 243 kE. Partners: MXM, Propara, CHU Montpellier (Oct. 2006 - Oct. 2009). This project is managed by the DEXTER team at LIRMM.
- RNTS, MIMES project, (2004-2007), 60keuros, 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.
- EADS contract phd thesis grant support of M. Djilas (2005-2008) "*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*". 105keuros
- DGE Neurocom, (2007-2010). 475keuros, "*Implant Cochléaire " tout implanté " pour la restauration des surdités sévères et profondes*". Partners : MXM-Neurelec, ELA-Sorin group, SOMMEPP, APHM Hopitaux de Marseille, CHU Montpellier.

9. Dissemination

9.1. Services to scientific community

- David Guiraud was member of the scientific comitee and chair of a session of the ASSISTH conference held in Toulouse.
- Philippe Poignet is Member of the IFAC technical committee on Nonlinear Systems and Control.
- Philippe Poignet is co-responsible for the Working Group "CPNL"- GdR MACS http://www.lag.ensieg.inpg.fr/gt-commandepredictive/.
- Philippe Fraisse is co-responsible for the working group GT7 - Humanoid Robotics - GDR Robotique

- 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.
- Guy Cathébras is member of the local scientific commission 63
- Christine Azevedo-Coste was invited editor of the JESA Journal special issue in Robotics for Handicap (2007).

9.2. Teaching

- Guy Cathébras, 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 Professor at IUT Montpellier Applied Physics teaching automatic control and signal processing.
- Philippe Fraisse, Professor at Polytech'Montpellier (MEA) teaching automatic control and networks.

9.3. Organization of seminars

- Z. Matjacic (Ljubljana, Slovenia) "Mechatronics and robotics in rehabilitation". September 2007.
- T. Bajd (Ljubljana, Slovenia) "Upper limb reeducation using virtual reality". October 2007.
- D. Durand (Cleveland, USA). June 2007.
- J.L. Puel (UM1, Montpellier). April 2007.

9.4. Research fellow visits

Ken Yoshida, 25th June - 6th July. Experiments on rabbits for intrafascicular recordings experiments.

9.5. Participation in seminars and workshops

- P. Fraisse organized the workshop entitled "Journées Nationales de la Robotique Humanoïde", 2007, March 29, 30. Montpellier, France, (see http://www.lirmm.fr/JNRH/).
- C. Azevedo-Coste (2007), Technical considerations when designing FES applications, Course on FES for physiotherapists FESAIR. (Vancouver, Canada), June 2007 [15].
- P. Fraisse, Invited presentation [26]. Workshop on Motion Planning for Humanoid Robots to be held in conjuction with IEEE-RAS International Conference on Humanoid Robots, 2007, Nov. 29, Dec. 2, Pittsburgh, USA.
- D. Andreu co-organized, with Prof. J. Malenfant (LIP6), the workshop CAR07 "Control Architectures of Robots : from models to execution on distributed control architectures" (http://www-src.lip6.fr/homepages/car2007/index.htm).
- D. Guiraud and D. Andreu presented the architecture and communication issues in the context of implanted FES, as well as the MAC protocol which has been designed. "Réseau implanté médical" presented at the 4th workshop CNRS RECAP - Réseaux de capteurs.
- Philippe Poignet co-organizes the session on "Medical Robotics and Rehabilitation" during the workshop "Journées Nationales de la Recherche en Robotique".

- Philippe Poignet co-organizes the 3rd summer school in "Surgical Robotics" (http://www.lirmm.fr/uee07/).

9.6. Theses and Internships

9.6.1. Thesis Defenses

1. Rodolphe Héliot defended his PhD-thesis entitled "*Modélisation sensori-motrice du contrôle des membres inférieurs chez l'homme et son application à la réhabilitation fonctionnelle*". October, 26, 2007.

9.6.2. Ongoing theses

1. Guy Cathébras and Christine Azevedo-Coste co-supervise **Milan Djilas**, "*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*", Thesis INRIA/EADS, 2005-2008.
2. Guy Cathébras and Serge Bernard co-supervise **Lionel Gouyet**, "*Traitements analogiques et numériques des signaux ENG*", Thesis LIRMM MENRT, 2005-2008.
3. Christine Azevedo-Coste 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. 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.
5. David Guiraud, David Andreu and Christine Azevedo-Coste co-supervise **Jérémy Laforêt**, "*Modélisation du recrutement sélectif en neurostimulation multipolaire multiphasique, application à la stimulation neuromotrice sélective*", Thesis LIRMM MENRT, 2006-2009.
6. Philippe Poignet and David Guiraud co-supervise **Mourad Benoussaad**, "*Synthèse de séquences de stimulation optimales pour la déambulation de patients paraplégiques.*", Thesis BDI INRIA / Région LR, 2006-2009.
7. Philippe Fraisse and Nacim Ramdani co-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.

9.6.3. Starting theses

1. Philippe Poignet supervises **Antônio Bo**, "*Compensation active du tremblement pathologique du membre supérieur via la stimulation électrique fonctionnelle.*"
2. Jérôme Galy supervises **Amine Debhaoui**, *Transmission sans fil de données et d'énergie.*
3. David Guiraud and Alain Varray supervise **Maria Papaiordanidou**,"*Nature périphérique et centrale de la fatigue musculaire.*"

9.6.4. Internships

- **2006-2007**
    1. Christine Azevedo-Coste and Rodolphe Héliot co-supervised Florent Moissenet "*Description accélérométrique de la marche humaine*", final project (PFE) (IFMA engineer school, Clermont-Ferrand), from Feb. to June 2007.
    2. Christine Azevedo-Coste supervised Azzedine Faress "*Développement d'une interface logicielle pour le contrôle d'une plateforme oscillante*", final project (IUT GEII, Montpellier), from April to June 2007.

3. David Andreu supervised Pierre Chety, "Conception d'une micro-machine dédiée la stimulation implantée de la cochlée", Engineer final internship, from February 2007 to June 2007.
4. David Andreu supervised Grégory Angles. "Conception et réalisation d'un environnement d'exploitation de stimulateurs électro-fonctionnels", Master Professional final internship in computer engineering, from April 2007 to September 2007.
5. David Andreu supervised Shichun Deng. "HILECOP : étude d'une approche fondée sur les composants", Master Professional final internship in computer engineering, from April 2007 to September 2007.
6. David Andreu and Philippe Fraisse co-supervised Mickael Toussaint " Etude et expérimentation de l'asservissement de l'articulation du genou sous stimulation électro-fonctionnelle sans fil", 2nd year Master STPI intenship (University Montpellier II), from November 2006 to June 2007.

- **2007-2008**
  1. David Andreu supervises Grégory Angles. "SENIS Manager: an environnent for configuration, deployment and exploitation of a distributed neural FES architecture", 6 month computer engineer contract (XMX). This project is carried out within a technological transfer frame with MXM lab. Company.
  2. David Andreu supervises Robin Passama. "Conception et réalisation d'un environnement de développement d'applications de contrôle basées sur la stimulation électro-fonctionnelle", 12 month computer engineer contract. This project is carried out within the NEUROCOM project.
  3. David Andreu supervises Steve Coustenoble, "Passerelle pour Architecture de Stimulation Electro-Fonctionnelle Per-Opératoire" Projet Industriel de Fin d'Etudes (MEA engineer final year), from September 2007 to January 2008.
  4. David Andreu supervises Roland Tiraboschi and Guillaume Roquet, "Contribution au Test de Production des SiP : Architecture et Protocoles de Communication Embarqués au sein du SiP" . Projet Industriel de Fin d'Etudes (MEA engineer final year), from September 2007 to January 2008.

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[1] C. AZEVEDO-COSTE, P. POIGNET, B. ESPIAU. *Artificial Locomotion Control: from Human to Robots*, in "Robotics and Autonomous Systems (RAS) Elsevier", vol. 47/4, 2004, p. 203–223.

[2] H. EL MAKSSOUD, D. GUIRAUD, P. POIGNET. *Mathematical muscle model for Functional Electrical Stimulation control strategies*, in "International Conference on Robotics and Automation (ICRA), New Orleans, LA, USA", 2004, p. 1282-1287.

[3] D. GUIRAUD, J. GALY, G. CATHÉBRAS, S. BERNARD, D. ANDREU, Y. BERTRAND, J.-D. TECHER. *Device for distributing power between cathodes of a multipolar electode, in particular of an implant*, vol. WO 2006/027473 A1, 2006.

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[5] D. GUIRAUD, T. STIEGLITZ, G. TARONI, J. DIVOUX. *Original electronic design to perform epimysial and neural stimulation in paraplegia*, in "J. Neural Eng.", vol. 3, 2006, p. 276-286.

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[8] S. MOHAMMED, P. POIGNET, P. FRAISSE, D. GUIRAUD. *Rehabilitation of the paralyzed lower limbs using Functional Electrical Stimulation: Robust closed loop control*, ARS Vienna - (Advanced Robotic Systems) Rehabilitation Robotics., I-Tech Education and Publishing, 2007.

[9] N. RAMDANI, C. AZEVEDO-COSTE, D. GUIRAUD, P. FRAISSE, R. HÉLIOT, G. PAGES. *Posture and movement estimation based on reduced information. Application to the context of FES-based control of lower limbs*, ARS (Advanced Robotic Systems) Human-Robot Interaction, 2007.

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[10] D. ANDREU, D. GUIRAUD, G. SOUQUET. *Stimulation Electro-Fonctionnelle : vers une architecture distribuée de stimulation neurale*, in "RS-JESA: Journal Européen des Systèmes Automatisés, Robotique et Handicap", vol. 41, 2007, p. 159-177.

[11] S. BONNET, R. HÉLIOT. *A magnetometer-based approach for studying human movements*, in "IEEE Trans. Biomedical Engineering", vol. 54, 2007, p. 1353-1355.

[12] S. DOSEN, D. POPOVIC, C. AZEVEDO-COSTE. *Optiwalk. Un nouvel outil pour la conception et la simulation de lois de commande pour le controle de la marche de patients atteints de déficits moteurs*, in "Journal Européen des Systèmes Automatisés (JESA). Numéro spécial : Robotique et handicap", 2007.

[13] R. HÉLIOT, B. ESPIAU. *Multi Sensor Input for CPG-based Sensory Motor Coordination*, in "IEEE Transactions on Robotics (Special Issue on Bio-Robotics), accepted", 2007.

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