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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

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 researches, 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 these researches 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 (Deambulation Et Mouvement ARtificiel). 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 (Thomas Stieglitz, 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, ZTH in 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 (DEambulation et Mouvement ARtificiel) 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 relations with rehabilitation centres among them the Centre Bouffard Vercelli in Cerbère, and Propara in Montpellier. International collaborations have been initiated with the Sensori 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 sensori motor system, including muscles, sensory feedbacks, and neural motor networks. Indeed, DEMAR focuses on two global axes of research:

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

The main applied research fields are then:

- Quantitative characterization of the human sensori motor system firstly for motor disorders diagnosis and objective quantification, and secondly in order to help the design of neuroprosthetic devices.
- Restoring motor or sensitive functions through implanted functional electrical stimulation (FES) and neural signals sensing.

3. Scientific Foundations

3.1. Modelling and controlling the human sensori-motor system

As regards modelling and control, our global approach is based on the theoretical tools of the automatic control theory ([3],[4]).

3.1.1. Modelling

Designing efficient control schemes and performing realistic simulations need for modelling. 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 sensori motor system : muscles, natural sensors and neural structures. We also aim at describing multi scale time models to figure out 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 sensori 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 the 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 system, 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 and in the global architecture of the high level command. Thus, based on this platform, a new one can be developed including the complex muscle's dynamics. In particular, muscle's dynamics contain discontinuous switching modes (contraction - relaxation, extension - shortening), strong non linearities, length and shortening speed dependencies that imply complex numeric 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 good criteria ?

3.1.3. Closed loop control

Some tasks can not be performed by 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. Modelling 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, 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 studied using a formal representation of the architecture.

3.2. Interfacing artificial and natural parts through neuroprosthetic devices

To overcome the limitations of the actual 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 [26]. Each stimulation unit (called DSU, Distributed Stimulation Unit) is 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. So we studied the communication architecture and defined an adequate protocol (§6.2.4), assuming firstly that the communication should be performed on a wireless medium and secondly that this architecture can also contain distributed measurement units (sensors §6.2.2).

3.2.1. Stimulators

We mainly focus on implanted devices interfaced with neural structures. Both the knowledge about how to activate accurately 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 modelling such as Hodgkin-Huxley model.

3.2.2. Sensors

The development of a closed-loop controller implies the use of sensors which choice and number are highly constrained by psychological and cosmesis 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 accelerometres.
- Natural sensors that means interfacing with afferent nerves and ENG recordings. The same theoretical tools and technology as for implanted stimulators will be used. Nevertheless, advanced signal processing applied to biosignals will be used such time-frequency techniques.

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 the balance and the posture.

The way how the system integrates all these events is not trivial. This field of research can learn from teleoperation 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 onto the system like screen, sound, tactile vibrations, electrical stimulation,... 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 analysing patient behavior need for 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 whole distributed system. More technological aspects related to RF transmission will be studied.

4. Application Domains

4.1. Objective quantification and understanding of movement disorders

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

Modelling 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 of the 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 the 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 sensori 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 quadraplegic 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 physiotherapits a new efficient FES - mainly surface - based therapy 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, modelling is not achieved because it implies the central nervous system modelling. Nevertheless, the application is possible for a daily use by the patient.
- Sensing the afferent pathways such as muscle’s spindles, will be use 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. If we want to avoid neurectomy or complex electrode placements, enhance activation waveforms and sensing feedback or feedforward signals are needed to perform a highly selective stimulation.

5. Software

5.1. Embedded software for FES system

Participants: David Guiraud, Bernard Gilbert.

CPU196 is an embedded software attached to a hardware custom design developed for the low level control of stimulators. It ensures some basic securities for both implanted and surface stimulators and allows them to function in an autonomous way without any PC connections [30].

5.2. 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 [25]. In this purpose, we proposed an approach based on components for the automatic translation into VHDL, of interpreted Petri nets with time. 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.

6. New Results

6.1. Modelling and controlling the human sensori-motor system

The global approach is described in [21][20][6] [5]

6.1.1. Muscle modelling

Participants: Hassan El Makssoud, David Guiraud, Philippe Poignet.

We developed, based on previous modelling from Huxley, Zahalac and Sorine, an original multi scale muscle model based on physiological phenomena. The model is composed of three blocks ([1] [18] [17]) :

- Mechanical modelling. An original multi scale model (from a sarcomere up to the whole muscle) was developed and is expressed in the state space with a set of differential equations. The generated force and the equivalent instantaneous stiffness of the contractile element are the outputs of the model, the chemical activation, the recruitment percentage and the shortening speed are the input of the model. Two models were developed depending on their final use. One includes muscle's masses in order to be accurate enough in isometric contraction without any movement, the other is much simpler without masses and dampers to be used in a complex musculoskeletal model. In this last case, dampers and masses are transferred respectively to the joint and the segments.
- Recruitment modelling. It represents the transfer function between the stimulus parameters (intensity and pulsewidth) and the percentage of activated muscle's fibres. This model is a static one with a sigmoïd like transfer function.
- Electrochemical activation modelling. The Calcium dynamics that appears between the neural signal action potential activation and the muscle's fibres activation is modeled through a linear second order low pass filter followed by a threshold on off activation so that mainly the stimulus frequency (that triggers this dynamics) is involved.

The two last items will evolved because they are actually not based on micro scale physiological phenomena.

6.1.2. Geometrical and dynamical modelling

Participants: Gaël Pages, Samer Mohammed, Philippe Fraisse, Philippe Poignet, David Guiraud.

Different models have been developed depending on to study carried out : i) a three dimensional model of the human body with 24 degrees of freedom (DOF), rotations only, using a tree structure with one attached foot for static standing study with the walker, ii) a complete knee model with agonist antagonist muscle and one DOF for studying the behavior of different controls strategies. We use anthropometric data and robotic rules to express models (Denavit-Hartenberg approach).

6.1.3. Identification and platforms

Participants: Hassan El Makssoud, Philippe Poignet, David Guiraud.

We are currently working on muscle model parameters estimation. The estimation can be quite complex when dealing with living processes (animals or humans). It usually requires to design a very accurate protocol providing sufficient information taking into account the very short time available to perform the *in-vivo* experiments for instance due to fatigue. The model was first simplified by considering the isometric case and thus is written as a state-space model. Classical extended Kalman filtering is then computed to estimate the parameters relating the force output to the current stimulation input measurements. The efficiency of the identification technique depends partly on the generation of sufficiently exciting trajectories in terms of applied currents corresponding to large dynamics changes of the force output. Thanks to the stimulator, we are able to design such a wide range of exciting trajectories and first results are very promising. Experiments have been performed during the summer 2004 at the SMI (Aalborg, Denmark) on six acute rabbits on inserted and isolated muscles. The SMI lab is fully equipped for working on rabbits and benefits from a great experience in such protocols. However an instrumented chair is currently under developments in our lab for performing experiments on humans [19]. It allows to make the muscles work in isometric, isotonic, and isokinetic modes. The chair is equipped with a DC motor, a torque sensor and a position sensor. It can be used with synchronized stimulation patterns and EMG measurements.

6.1.4. Movement control

Controlling the sensori motor system through the FES technique is complex due to the muscle's dynamics, the biomechanical structure, but also the available measurements for feedbacks. The results presented in this section are exploratory results that mainly come from the robotic area. The first three items are related to the biped robotics possible contributions, the fourth item deals with the possibility to achieve low level control using a high order sliding mode control, and finally the fifth item is aiming at understanding the natural multi level control scheme involved in the human sensori motor system.

6.1.4.1. Trajectory generation for biped robots

Participants: Fabien Lydoire, Christine Azevedo, Philippe Poignet.

The first part of the works has been dedicated to develop tools for robotized bipeds [7][12] which are considered as an intermediate step for testing and improving proposed control strategies. The works presented in the PhD thesis of F. Lydoire described the walking pattern generation as the solution of a constrained optimisation problem. The constraints ensuring motion are expressed in the operational space. At the moment, only static case has been considered through numeric simulation.

6.1.4.2. Trajectory Free Nonlinear Model Predictive Control (TF-NMPC) approach

Participants: Christine Azevedo, Philippe Poignet.

[15][14]

Christine Azevedo PhD-thesis (defended in September 2002), co-supervised by both Bernard Espiau (INRIA RA) and Philippe Poignet has been selected among the three nominees for the Georges Giralt EURON (European Robotics Research Network) PhD Thesis Award (2004). The Nonlinear Model Predictive Control (NMPC) ability to take into account constraints in its formulation makes it well adapted to the problem of movement synthesis. But a direct application is very limited in rapid dynamic systems due to the strong hypothesis necessary to ensure stability. Therefore we proposed to adapt and designed TF-NMPC (trajectory-free nonlinear model predictive control), based on a sliding horizon optimization problem. A set of physical constraints is imposed to define implicitly the allowed movements. TF-NMPC consists in optimizing from inputs (torques, state, contact forces...) the future behavior of the system submitted to the constraints and using the dynamic model computed on a finite time interval (horizon). The solution of the optimization algorithm is a sequence of control inputs over the prediction horizon. Only the first input is applied to the system and the procedure starts again.

6.1.4.3. Nonlinear predictive control and interval arithmetic

Participants: Fabien Lydoire, Philippe Poignet.

Following the works achieved during the PhD thesis of C. Azevedo and dedicated to the synthesis of a new approach based on a TF-NMPC, we investigate the problem of optimization involved in the predictive control strategy by using interval arithmetic [12]. Indeed, the NMPC problem is expressed as a Constraints Satisfaction Problem (CSP) which can be solved by interval analysis techniques. First, some modifications and improvements of the classical contractor using propagation-back propagation technique have been proposed in order to adapt interval tools to our specific problem of control. Second, in order to reduce the pessimism introduced by interval state estimation, we proposed a discrete spatial domain leading to an interior approximation of the state. The performance of the proposed strategy have been tested in simulation on an inverted pendulum model [22], [9]. Further works will concern the real-time implementation and the use of systematic software computing and dealing automatically the constraints decomposition.

6.1.4.4. High order sliding mode applied to the control of one joint

Participants: Samer Mohammed, Philippe Fraisse.

We focused on the use of the muscle model in closed loop control schemes for standing up lower body links. Most of the currently FES clinical applications use an open loop control strategy especially during standing up, sitting down and standing which are prerequisite phases before any upward mobility. In order to provide safety knee extension, an excessive stimulation of the quadriceps is usually applied during standing up or standing with an increasing pulse width yielding thus an earlier fatigue. The difficulty arising in the context of the FES is the high complexity of the process with respect to physiological phenomena such as fatigue and non linearities of the dynamics. We then test our muscle's model by applying classical control strategies in standing up situations. The efficiency obtained by using sliding mode controller or a switching curve approach in the state space have been evaluated in simulation [23].

6.1.4.5. Human postural locomotion control

Participant: Christine Azevedo.

When during quiet standing, a subject is briefly accelerated downwards, a short-latency drop in Soleus muscle (SOL) EMG may be observed after 45 ms. This was previously hypothesized to be the result of a sudden decrease in facilitatory feedback mediated by group I afferents. If on the other hand the subject is accelerated upwards, a reflex peak may be observed in the SOL EMG at similar latency. Thirdly, a similar reflex peak may be observed by applying a quick rotational dorsiflexion perturbation. The purpose of the current study was to investigate relative contributions of group Ia and group Ib afferents to these three different responses, by applying vibration to the Achilles tendon. A tendon vibration primarily stimulates spindle receptors. Both human primary and secondary spindle endings respond to vibrations, but activation is more effective in group Ia afferents than in group II or Ib innervating Golgi tendon organs. Long-standing Achilles tendon vibration depresses the short-latency stretch reflex following a toe-up rotation. 11 healthy subjects participated in a study carried out at the center for Sensori-motor Interaction (Aalborg, Denmark) together with J. Van Doornik and T. Sinkjær. The randomised protocol consisted in applying 3 different perturbations to the support platform: downward vertical acceleration, upward vertical acceleration and toe-up rotation. The protocol was carried out without and with Achilles tendon vibration. Vibrations had a significant decreasing effect in SOL response to perturbation amplitude in the 3 conditions ($n=10$, T-Test, $p<0.01$). Ia afferent fibers were therefore likely to play an important role in the soleus EMG responses observed for vertical accelerations of the platform [16]. A locomotion study has also been carried out and data are currently analysed. A synthesis comparing human versus biped robot gait control has been proposed [28].

6.2. Interfacing artificial and natural parts through neuroprosthetic devices

6.2.1. Activating the neural system

Participants: Jean-Denis Techer, Guy Cathebras, Serge Bernard, David Guiraud, David Andreu.

The analogue part of each Application Specific Integrated Circuit (ASIC) is the most critical challenge for microelectronics considerations. Indeed, the medical context involves very stringent constraints in terms of safety and performances. A first prototype has been designed and we are carrying out some experiment validations. This circuit delivers precise calibrated stimulation pulses to specific multi-polar electrode together with a very safety running cycle. In particular, the Digital Analogue Converter has been thought to be fully monotonic and the output stage to ensure a passive and secure discharge of the safety capacitor according to an electrode model evaluation [2]. Also some tricky features have been added in order to improve the classical charge pump that generates on-chip high voltage [24],[10],[29].

During the stimulation sequence, the DSU runs programmes using a dedicated reduced instruction set; this embedded micro-machine drives the analogue subsystem through an interface (LIRMM Research Report n°04067). While performing the stimulation sequence we must ensure that physical constraints are respected, as for examples "the time interval between two stimuli must not be lower than 20 ms", "the stimulus pulse width must not be greater than 1 ms", etc. Such a monitoring of the sequence execution is done through embedded reference models (one reference model for each cathode of the multi-polar electrode). Micro-machine and reference models are designed using Petri Nets formalism and then translated using the PN to VHDL software.

6.2.2. Sensing the neural system

Participants: Christine Azevedo, Ken Yoshida.

A collaboration started with the Centre for Sensori-Motor Interaction (SMI), Aalborg Denmark to explore the possibility of using afferent neural activities from muscle spindle fibers as feedback for controlling position of a joint through muscle FES. Current studies at SMI aims at developing monitoring of biological signals for feedback in a FES system. In a previous study [31], experiments in cats have demonstrated the feasibility of controlling ankle extension by neural stimulation using an estimation of the joint angle from recordings of the two antagonist muscles spindle activities.

Recordings have been performed during animal experiments (rabbits). A cuff electrode has been placed around the sciatic nerve for stimulation and intrafascicular electrodes have been implanted in Medio Gastrocnemius (MG) nerve branch in eight acute rabbits. We have recorded the nerve electrophysiological activity in parallel with MG muscle length and force variation as well as electromyogrammes, for a passive and active muscle recruitment. The data collected are currently submitted to signal processing in order to identify the correlation between muscle variables and neural activity. This model will represent a part of the sensors implied in the muscle's reflexes.

6.2.3. Instrumented walker

Participants: Philippe Fraisse, Gael Pagès.

A preliminary phase before a complete closed loop solution is to let the patient act on the system through an rich interface. In this framework, we aim at achieving an enhancement compared to open loop solutions, which enables the patient to control (teleoperated mode) the lower limbs by means of an instrumented walker. Two 6 axis force sensors are fitted between the handles and walker in order to measure the desired movement and attitude of the patient. The force vectors are processed by using the different models of the patient (kinematic, dynamic and muscles) in order to generate a stimulation pattern allowing the desired movement. Moreover, the attitude of the upper limb information (ex: forward, backward) stemming from force sensors will be integrated within the controller to adapt the motion and stimulation pattern.

6.2.4. Communicating between units

Participant: David Andreu.

The communication architecture of SENIS is based on an asynchronous broadcast network, according to a three-layer model: physical, data link and application layers [27]. The physical layer is not considered in this work.

Addressing of devices can be unicast, multicast and broadcast, as it is required by the application in order to, for instance: configure a DSU (unicast), stop all DSUs (broadcast), start the group of DSU implied in the current movement phase (multicast).

We defined an application protocol allowing to get the following services: download/upload of programs, start/stop/restart the stimulation, configure the network parameters (of a DSU), get the status of a DSU, get an application acknowledgment, notify an event (error detection for instance), etc.

We particularly focused on the data link protocol to provide a reliable communication between devices that share the same (wireless) media link. The aim is to get a deterministic control of the medium access (MAC). The cooperation model between devices (controller and DSU) is based on the master/slave relationship. Most exchanges are issued from the master device, with possible responses from the slave one. Nevertheless each slave (DSU) implied in the current context (e.g. movement phase) must be able to notify events (error detection) without being explicitly polled as usually done in such cooperation model. Thus we must control the access to the medium in order to allow this needed slave access, with a priority based ordering, while preserving a deterministic MAC. We defined a sliding time windows based "access right": each member of a given group (of slaves) has a priority from which it determines its access time window. This time window slides if previous members (i.e. members of greater priority) didn’t use its own time interval. Indeed, each time interval is such that a part of it is reserved for the reaction of the controller if it has to react to the event just notified; so, if the slave device time interval is not used the time interval dedicated to the controller is released (and used for the next slave device). This MAC policy has been modeled by means of Petri Nets and will be soon implemented on FPGA devices [29].

7. Contracts and Grants with Industry

Bear Medical, Oxycor project, (2002-2004), 12.4 keuros, design of the control strategies to be used with patients with oxygen deficiency. A set of sensors (accelerometres, oxygen saturation metres) is used in a closed loop control system to monitor and then adjust the oxygen delivery during changes activities performed by the patient.

8. Other Grants and Activities

8.1. Regional grants

- Région Languedoc Roussillon, (2002-2004), 22.4 keuros financial support for equipments for movement analysis (foot pressure insoles, 3D video, EMG, multi moment chair).
- University of Montpellier II, EEAI Department, (2002), 11.4 keuros, design of the first ASIC dedicated to implanted neural stimulation.

8.2. National grants

- ROBEA CNRS-INRIA national programme, (2002-2003), 67 keuros, equipements for movement analysis and identification platforms. The theoritical part focuses on the muscle modelling. Partners, BIPOP (INRIA Rhône Alpes)
- RNTS, MIMES project, (2004-2006), 60.4 keuros, the project focuses on the complete modelling of the body, developping dedicated simulation software tools, advanced external stimulators, and instrumented walker. Partners, BIPOP Grenoble, Centre de rééducation Bouffard Vercelli Cerbère, MXM Company Sophia Antipolis.
- ACI neurosciences intégratives et computationnelles (2004-2007), 15 keuros, Functional electrical stimulation: a specific model of neuro-artificial cooperation for vertical conquest in paraplegic patients. Leader DPA (CNRS) Marseille.

9. Dissemination

9.1. Services to scientific community

- 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.

9.2. Teaching

- David Andreu, associate professor at Polytech'Montpellier (Department of Micro-Electronics and Automation (MEA)), teaches:

  - Discrete Event Systems : "modelling and analysis with Petri nets" for 2nd year MEA students, "high level Petri nets" for 3rd year MEA students, "Hardware and software Implementation of Petri nets" for DEA SYAM students (corresponding to 2nd year SAEI Master students)
  - Network : "TCP/IP Model" and "Industrial local area networks" for 2nd year MEA students and 1rst year SAEI Master students.
  - Real-Time Systems : "Initiation to real-time systems " for 2nd year MEA students.
- Christine Azevedo has given a lecture (4h) within Robot Kinematic and Dynamic course to 8th Semester students at Health Science and Technology Engineer School of Aalborg University.
- Gaël Pages is in charge of the TP Matlab/Symoro(40h) for DEA SYAM students.
- Philippe Fraisse, assistant professor at IUT de Montpellier, department of Communication and Networking. He has given a lecture to master students (information theory and networked control systems).
- Guy Cathébras, associate professor at Polytech'Montpellier (Micro-Electronics and Automation (MEA) Department), teaches:

  - Signal theory (12h course and 12h tutorial) for 1st year MEA students (corresponding to third year SAEI Licence students).

  - Analog integrated circuits: "An introduction to electronics: designing with Bipolar and MOS transistors" 24h tutorial for 1st year MEA students (SAEI L3) ; "CMOS Analog integrated circuits design" 28h CAD practical works for 2nd year MEA students (SAEI M1); "CMOS standard cells design" 20h CAD practical works for 2nd year MEA students (SAEI M1).
  - Electronic systems: 40h practical works for 2nd year MEA students (SAEI M1).

- Philippe Poignet is lecturer at IUT of Montpellier, Physic's Instrument Department. He co organised the Summer European University (2003) in Surgical Robotics and gave a talk on "Motion control and interacion control in medical robotics". He was invited for a tutorial "From mini-invasive surgery to endocavitary / endoluminal interventions. Part I : Research issues in endoscopic mini-invasive surgery" at the 7th Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI04).

9.3. Participation to seminars and workshops

- Guiraud D. has given a talk: "*La restauration de la fonction motrice par la commande artificielle du système sensorimoteur périphérique*", during the seminar "Mouvement à l'Echelle Humaine" at the Museum d'histoire naturelle, Grenoble, 13th January 2003.
- DEMAR research axes have been presented during a German - French Workshop on Humanoid and Legged Robots. Metz, France, October 2004 [20]
- Serge Bernard presented his works: "*Application Specific Integrated (ASIC) Stimulator*", during a joint seminar between SMI, DEMAR and INRIA RA. Aalborg, Denmark, June 2004.
- Philippe Poignet presented his works: "*Medical Robotics and Biped Systems*", during a joint seminar between SMI, DEMAR and INRIA RA. Aalborg, Denmark, June 2004.
- David Guiraud presented his works: "*Modeling based on robotic theoretical formalism*", during a joint seminar between SMI, DEMAR and INRIA RA. Aalborg, Denmark, June 2004.
- David Guiraud and Christine Azevedo presented their works during a seminar at the Neuroscience Institute of Montpellier. November 2004.
- Christine Azevedo presented her works "*Vertical accelerations of the support: contribution of Ia afferents in soleus EMG variations.*" during the Motor control research symposium Aalborg / Copenhagen. Sandbjerg, Denmark, May 2004.
- Hassan El Makssoud presented his works: "*Modélisation et identification du muscle squelettique*" during a seminar "Séminaire croisé INRIA Sophia-Antipolis" between DEMAR and EPIDAURE projects: "Muscles striés : modélisation, identification et commande sensori-motrice." INRIA Sophia-Antipolis, France, April 2004.
- Christine Azevedo presented her works: "*Le contrôle postural chez l'homme : approches comportementale et neurophysiologique.*" during a seminar "Séminaire croisé INRIA Sophia-Antipolis" between DEMAR and EPIDAURE projects: "Muscles striés : modélisation, identification et commande sensori-motrice." INRIA Sophia-Antipolis, France, April 2004.

9.4. Theses and Internships

9.4.1. Thesis Defenses

- Philippe Fraisse defended his HDR on 3rd December 2004,“*Commande de robots à Architectures Complexes*" [11]
- Philippe Poignet defended his HDR on 10th December 2004,“*Automatique pour le vivant : du modèle à la commande*" [13]
- Fabien Lydoire defended his PhD thesis on 13rd December 2004,“*Génération de trajectoires pour la locomotion artificielle et commande à horizon fuyant avec l'arithmétique d'intervalles*". His work was co-supervised by Philippe Poignet and Etienne Dombre in 2001-2004.

9.4.2. Ongoing thesis

- Philippe Poignet, David Guiraud, and Etienne Dombre co-supervise Hassan El Makssoud, “*Modélisatoin du muscle strié squelettique sous FES*", Thesis LIRMM, 2002-2005.
- Serge Bernard, Yves Bertrand, Guy Cathébras and David Guiraud co-supervise Jean-Denis Techer, “*Conception, vérification et test de circuits integrés analogiques pour application médicales*", Thesis LIRMM, 2002-2005.
- Philippe Fraisse, and David Guiraud, co-supervise Gaël Pagès, “*Contribution à la commande en effort d'un déambulateur instrumenté pour la génération de mouvements des membres inférieurs par stimulation électrique fonctionnelle*",Thesis CIFRE MXM, 2003-2006.
- Philippe Fraisse, David Guiraud, co-supervise Samer Mohammed, “*Synthèse et simulation des séquences de stimulation pour la marche en boucle ouverte à partir de modèles biomécanique et physiologique du membre inférieur*",Thesis LIRMM, 2003-2006.
- 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).

9.4.3. Internships

- **2002-2003**
  - David Guiraud and Philippe Poignet co supervise Hassan El Makksoud (DEA 2002) "*Comparaison et validation des différents modèles de muscles*."
  - David Guiraud supervises Ludovic Brethes (DEA 2002) "*Modèle géométrique du membre inférieur et identification par vidéo 3D*."
  - David Andreu has supervised Gladys Claude, "*Etude d'un protocole de communication pour une architecture de stimulation électro-fonctionnelle répartie : le concept SENIS*", Maitrise EEA, from April 2002 to July 2003.
  - David Andreu has supervised Nicolas Bruchon, "*Etude de la traduction automatique en VHDL d'un réseau de Petri généralisé interprété temporel, selon une réalisation synchrone*", Engineer internship (MEA 2nd year), from June 2002 to September 2003.
  - Guy Cathébras and David Guiraud co supervise Laurent Mounier (Ecole Centrale Lyon, 2002) "*Réalisation du layout de l'ASIC mixte analogique-numérique pour la stimulation neurale implantée, recherche sur les structures multiplicateurs de tension très faible consommation*."

  - Philippe Fraisse, and David Guiraud, co-supervised E. Maherzi (DEA 2003), “*Recherche de solutions de posture à partir de la mesure d’efforts sur un déambulateur instrumenté*".
  - Philippe Fraisse, and David Guiraud, co-supervised N. Albert (DEA 2003), “*Etude d’une interface force/position pour la commande des membres inférieurs par FES*".
- **2003-2004**
  - David Andreu has supervised Nicolas Bruchon,"*Conception et réalisation d’un prototype de traduction automatique d’un réseau de Petri généralisé, interprété, temporel en VHDL*", Projet Intégré de Fin d’Etudes (MEA 3rd year.), from September 2003 to January 2004 [26][25].
  - David Andreu has supervised Guihlem Vavelin,"*Développement d’un environnement de modélisation par Petri généralisé, interprété, temporel et de génération automatique du code VHDL "équivalent"*", Engineer internship (MEA 2nd year), from June 2003 to September 2004.
  - David Andreu has supervised Gladys Claude, "*Formalisation par réseaux de Petri d’un protocole application pour la communication entre unités de stimulation répartie : notion d’Unité de Stimulation Répartie*", DEA, from February 2003 to July 2004 [27].
  - Serge Bernard and Guy Cathebras co-supervise Abdelkrim Khelifa and Amine Mounaim, "*Conception et optimisation d’un convertisseur Numérique/Analogique pour application SEF*", 3rd year for Students of Polytech of Montpellier
  - David Guiraud supervises Vincent Libertiaux (Ecole Supèrieure d’Aéronautique, Toulouse, 2004), "*Méthode de reconstruction 3D basée modèle utilisant la vidéo métrie*."
  - Philippe Fraisse, and David Guiraud co-supervised Francis Linsolas (DEA 2004), “*Proposition d’une loi de commande robuste appliquée à la commande de l’articulation du genou d’un paraplégique*
- **2004-2005**
  - David Andreu has started the supervision of Guihlem Vavelin, "*Développement d’une plateforme de test de l’architecture SENIS, basée ethernet et FPGAs*", Projet Intégré de Fin d’Etudes (MEA 3rd year), from September 2004 to January 2005.

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[2] D. Guiraud, J. Divoux, P. Rabischong. *Identification of a First Order Model of Implanted Electrode on the First SUAW Patient*, in "IFESS'02: International Functional Electrical Stimulation Society, Ljubljana, Slovenia", June 2002.

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[11] P. FRAISSE. *Commande de robots à architecture complexe*, Habilitation à diriger des Recherches, Université Montpellier II, December 2004.

[12] F. LYDOIRE. *Génération de trajectoires pour la locomotion artificielle et commande à horizon fuyant avec l'arithmétique d'intervalles*, Thèse de doctorat, Université Montpellier II, December 2004.

[13] P. POIGNET. *Automatique pour le vivant : du modèle à la commande*, Habilitation à diriger des Recherches, Université Montpellier II, December 2004.

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