A RECONFIGURABLE SYSTEM FOR MOVEMENT REHABILITATION AND DIAGNOSTICS WITH FES

Piotr Kaczmarek, Andrzej Kasiński, Marek Kraft and Przemysław Mazurkiewicz
Poznań Univeristy of Technology, Insitute of Control and Information Engeenering, Piotrowo 3a, 60-395 Poznań, Poland
Piotr.Kaczmarek@cie.put.poznan.pl, Andrzej.Kasinski@cie.put.poznan.pl

Keywords: Electrical stimulation, rehabilitation, movement restoration, instrumentation.

Abstract: The architecture of a custom originally designed FES system is described. The system is built from off-the-shelf and cusom components to obtain a target functionality. List of potential applications is provided. Some tasks have been already tested in laboratory and clinical conditions. Hardware specification of proprietary components is given and interfacing issues are addressed.

1 INTRODUCTION

Motion restoration through the appropriate functional electrostimulation (FES) of a neuro-muscular system is an interesting perspective. Still, the investigations are continued at the level of a single joint as well as that of a limb. The most interesting problem is to evaluate how the electrical stimulation program translates into an efficient and controlled elementary motion. Commercially available functional stimulators can be divided in 2 groups: stimulators for clinical research (like the S88 from Grass Teledyne), daily-use electrical stimulators for rehabilitation and functional electrical stimulation systems used in neurophysiological research (like NeuroTrac, Compex Motion, ODFS, Parastep)(Keller et al., 2002; Taylor et al., 1999). In principle all of these stimulators provide the possibility to alter the stimulation pulse frequency, amplitude and duration. In most cases (S88, NeuroTrac, ODFS, Parastep) these parameters are controlled manually by the user. Only the most advanced stimulators, like Compex Motion, allow to control the parameters by means of a closed loop control based on data coming from a number of sensors (switches, force sensors, EMG sensors). Most common approach is a simple event-triggered stimulation for a certain amount of time with the parameters set by the therapist (ie. in ODFS stimulators the stimulation sequence is triggered by a heel-switch). All of the above mentioned stimulators lack the capability of optimizing the shape of the single stimulation pulse, leaving only various square or trapezoid pulse combinations at the therapist disposal.

Many research institutes try to determine the influence of stimulation parameters on the muscle contraction, the fatigue effect, as well as the long-term effects generated in the muscles subjected to persistent stimulation (this refers to the regeneration process as well as to side effects). The experiments are aimed at investigation of physiological properties of the muscles both of healthy and of disabled subjects (Chizeck et al., 1999). An interesting issue is to reveal the optimal stimulation pattern for the application in the FES systems (Breen et al., 2006). So far the optimization process was restricted to the selection of the stimuli train frequency (Chou et al., 2005), or the pulse width and amplitude. The influence of the stimulating pulse shape on the contraction force has not been studied yet. Moreover, research results of the experiments concerning the pulse shape influence on the muscle contraction are not clear (Bennie et al., 2002).

Both movement restoration and rehabilitation processes are evaluated upon apparent effects. Such effects can be used as a feedback for the FES control algorithm, however it is desirable to quantify the effects, which are of different character. First apparent effect is the response of neuro-muscular system under stimulation on its own. The neuro-muscular system excitation level can be judged on the basis of the electromyographic signals (EMG) being the response to the electrostimulation. In movement restoration experiments however, it is necessary to measure and to analyze the EMG of the particular muscles contributing to the movement (Kutch and Buchanan, 2001). Moreover, it might be desirable to use a multi-channel transcutaneus electrode to support the decomposition of the EMG signal for studying the propagation of a single action potentials and motor point localization, or to analyze the signals in more detailed way. In order to get a better image of the stimulation effects there might be also required to partially estimate the state of a biomechanical system from additional physiological signals such as electroneurograms (ENGs)(Sinkjaer et al., 2003) or mechanomyograms (MMGs) (Kaczmarek et al., 2005; Orizio et al., 2003) which better reflect the senso-motor system activity as well as changes of the muscle geometry, respectively.

However, these signals reflect the intermediate effects of electrostimulation, but the target result (the final effect) is the motion of a limb or at a lower level, the motion of a joint under study. There are two interesting aspects of the motion evaluation - the static aspect, related to the force generated by a joint at a certain perceived level of the EMG activity while correlated with joint configuration (angle), and the second, which is related to the resulting motion dynamics. The investigation of the first aspect is performed by the simultaneous recording of EMGs of the appropriate muscle and the resulting force being directly recorded with the tensometric device, while the joint is locked at a particular angle. For the second aspect, it is necessary to acquire simultaneously the signals of the generated force, EMGs, the joint-angle rotation signal and the task-space acceleration signal due to the resulting dynamic motion of the limb.

This would be possible under the condition that one disposes of a fully programable electrostimulator with a necessary number of outputs, of a measurement system running during stimulation (a multichannel EMG signal acquisition and a processing system) and of a measurement system to evaluate the biomechanical effects of the FES (an instrumented exoskeletal device - the orthosis). In this paper we describe such a custom system, which has been built from modules and list examples of applications of that system to the rehabilitation and diagnostics procedures.

2 THE SYSTEM ARCHITECTURE

The schematic outline of the complete system is shown in fig. 1. The main control and sensors readout tasks are performed by the embedded 3,5” PC. The

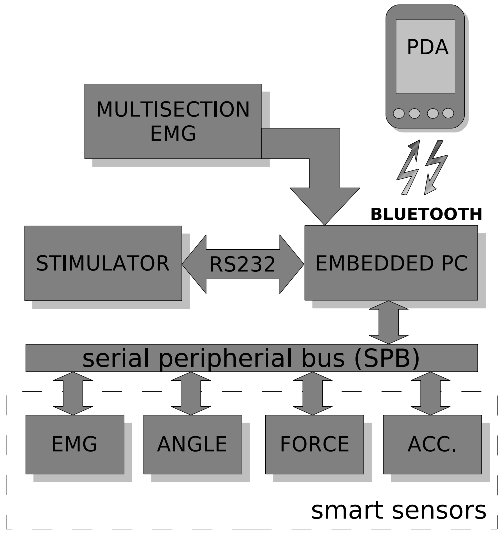

Figure 1: The block diagram of the FES system.

PC is equipped with a Intel Celeron 400MHz processor, 256MB RAM and 4GB CompactFlash card. The configuration of the system involved in a particular task is open in a sense, that the use of a simple serial peripheral bus (SPB) and of a specially designed communication protocol enables the user to connect a number of intelligent sensors (like accelerometers, goniometers, tensometers, point EMG sensors) to form a distributed measurement system, enabling tailoring of the system configuration to the particular task at hand. These distributed sensors perform all the measurement, preprocessing and data forming operations on-site. This allows to reduce the influence of various environmental interferences on measurements. The availability of sensor data enables the system to perform real-time closed loop control of joints by proper muscles stimulation depending on this data. The embedded PC is equipped with a multichannel A/D converter PCM-3718HG. This converter is used to measure the data from a multi-section EMG electrode. The PC is also fitted with the Bluetooth wireless interface. This enables remote control (for example by exchanging stimulation programs during rehabilitation), the visualization of a system state and sensor readouts (usable in biofeedback applications). For simple therapeutic programs at the patient bed it is possible to control the system by a palmtop.

2.1 Electrostimulator

The stimulator unit has the ability to perform stimulation through four independent channels. This enables independent stimulation of different muscle groups. The control circuit consists of a microcontroller and a 4-channel, 8-bit digital to analog converter (DAC).

Such the system setup enables the user to define the pulse shape, frequency, amplitude and other parameters (i.e. number of stimuli, initial delay, pulse train profile and modulation frequency) independently for each stimulation channel. The output stage consists of a voltage controlled current source, which can source a current of up to 60 mA and can work with voltages up to 400 Vpp, which is important in the case of the transcutaneous stimulation. The high voltage stage is galvanically separated from the control circuit. Control and programming of the device can be performed on-line via RS232, SPI or I2C interface. In that way the described device let the therapist to define flexibly the movement-restoration or rehabilitation requirements to each individual patient and to the particular task.

2.2 Orthosis and its Instrumentation

The orthosis is a skeleton enabling the force and position sensors attachment. Fig. 2 presents the exoskeleton of the ankle joint, which is one of the most important joints for balancing and locomotion tasks. The orthosis enables to perform static measurements (during an isometric contractions), as well as dynamical acquisitions during walking or balancing. It is equipped with the angle sensor i.e. an incremental encoder of 0.05 deg resolution and with the force sensor based on a planar-beam force sensor with a full-bridge strain gage. The system is capable of measuring a torque generated by a dorsi as well as a plantar flexion during isometric contractions for variable ankle joint angles in the range between -10 and 10Nm. The mechanical solution of the force sensor allows to obtain the force, that is always perpendicular to the sensor beam and independent on the ankle joint angle. The orthosis controller has a 10-bit AD converter with a variable input gain. This let the user to select appropriate gain depending on the performed test and the torque value. Moreover, the controller performs signal processing tasks such as a signal filtering and sampling with rate up to 4kHz, evaluation of the absolute angle of the joint and data buffering. The communication and data transfer to the Embedded PC is performed via SPB. Moreover, during locomotion or balancing tests, 3D accelerometric sensors can be fixed to the exoskeleton. The accelerometric sensor is equipped with a microcontroller and a 10bit AD converter, moreover it has 3 digital inputs enabling to connect the additional switches (foot switches or limit switches) or other discrete triggering elements. The smart sensor can operate in three modes, selected by the user via SPB. The first one is the data acquisition mode, where raw data is transmitted to the embedded PC. The second is the data processing mode, enabling the estimation of the velocity and of the position and the signal filtering. The third is the events detection or a fuzzification mode, which is used for fuzzy logic control algorithm. The sensor in such a mode evaluates the system state from the accelerometric signals and digital input state according to the given set of fuzzy rules.

The use of registered signals is the following. 3D acceleration signal together with goniometric signal let to reconstruct the position and the motion trajectory independently. This enables to analyze the kinematic effects of the electrostimulation and to discover pathological deficits. The tensometric subsystem gives the opportunity to evaluate the contraction force at a single joint. Thus not only the kinestatic evaluation is possible but also dynamics of the movement can be studied.

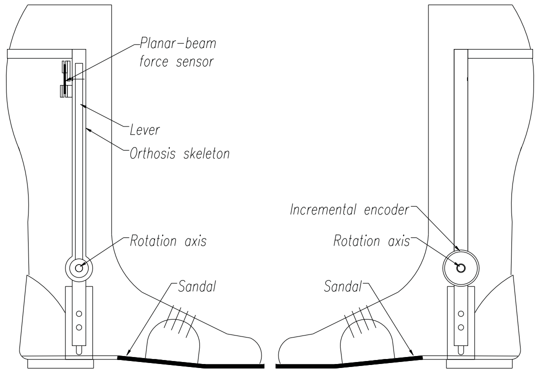

Figure 2: Instrumented Orthosis of the ankle joint.

2.3 EMG Acquisition Subsystem

Multichannel EMG. Important part of the presented system is an EMG electrode (Fig 3). The electrode consists of 9 rectangular AgCl contacts surfaces placed of a distance of 5 mm and with the contact surface size of 10x1[mm]. Multichannel EMG signal acquisition system is modular, where every module is connected to a single acquisition channel. It consists of an instrumental amplifier, analog high-pass Butterworth filter (f3dB=10Hz), low-pass Butterworth filter (f3dB=1000Hz) and a final amplifier stage giving the total gain within the range 1000÷2000. Acquired signals are collected by a PCM-3718HG card connected to the embedded PC.

Point-like EMG Smart Sensor. Smart EMG sensor is a device with analogue and digital parts. The analog part is similar to that described in a previous section. However, the contact surfaces (electrodes) are integrated with the PCB of the analog subsystem.

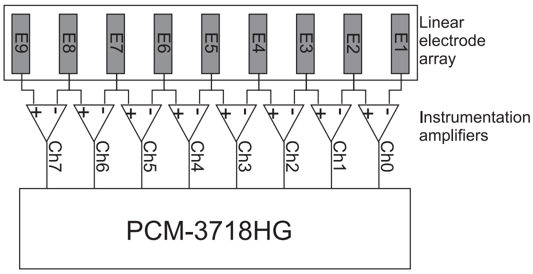

Figure 3: Linear electrode array for multichannel EMG.

The digital part consists of microcontroller with a 10-bits AD converter. Its main role is the acquisition of the analog EMG signal, buffering and basic preprocessing such as evaluation of the RMS value. The sensor can operate in two modes. In the first, the raw data are transmitted via SPB to the master controller, in the second mode only the results of processing are transmitted. The sensor is designed to be placed directly over a tested muscle in order to reduce noise and artefacts. Additionally, all IC chips can work in the shutdown mode for protecting the sensor amplifiers from damage due to the high-voltage stimulation.

3 APPLICATIONS OF THE SYSTEM

3.1 Research Tasks

As far the system has been used in 4 research tasks focused on the FES issues.

Stimulus Waveform Optimization. The system restricted to the stimulator, the force sensor and the EMG sensors has been used to evaluate the influence of the stimuli shape on the muscle contraction dynamics, and comfort level. The experiments were performed on a group of healthy volunteers and subjects with movement deficits. Within this study the biphasic stimuli with inter-phase interval (IPI) have been tested. 24 stimulus waveforms have been taken into account. They are combination of a pulse widths (50, 100, 175, 250us) and the inter phase intervals (0, 50, 250, 500, 1000, 2000us). The preliminary results suggest that the contraction force recorded during stimulation depends not only on the pulse amplitude, width and frequency, but also on the IPI. The contraction force has increased significantly with increase of the IPI. Additionally decrease of the pain sensation side-effects was reported. The results suggest, that the modification of the pulse shape seems to be an alternative for the the commonly used force control techniques such as a pulse-width, amplitude or frequency modulation.

Evaluation of the EMG-force Relationship. Using the instrumented orthosis and exoskeletons one is limited to apply the FES system only in the clinics. Therefore it is essential to built the portable FES with feedback based on measured physiological signals. This is necessary in order to evaluate or estimate the force and the joint configuration. In this study, the maximal voluntary contraction force and the EMG signal have been recorded while varying the ankle joint angle. It was observed, that for a medial gastrocnemius muscle the maximal force increases with increase of the dorsi flexion, however the RMS value of the recorded EMG signal significantly decreases, which may suggest the decrease of the muscle activity level. This phenomenon demonstrates that the for the force estimation at a gastrocnemius muscle from the EMG signal, the simultaneous estimation of the ankle joint orientation is required. This effect did not occurred for tibialis anterior muscle.

Evaluation of the Fuzzy Rules for a Fuzzy Logic Controller for Movement and Balancing Tasks. The efforts are made to create a fuzzy sets describing the phase of gate cycle during locomotion from 5 accelerometric sensors located at lower limbs and the trunk as well as from EMG sensors. This could enable to estimate the mass center position changes during locomotion or balancing tasks. The smart sensors are powerful enough to perform simple classification tasks and enable easy testing and evaluation of the rules.

Developing of the FES Control Algorithms. Using the Embedded PC with Linux on-board as the system supervisor enables an easy development and testing of various control algorithms based on fuzzy logic, neural networks or classical control. Moreover, the standard, well known and powerfull tools and libraries can be used for the application developing and testing. The distributed intelligent sensors may be reconfigured to work in a given control mode delivering a appropriate feedback signals.

3.2 Diagnostics Tasks

The diagnostics tasks refer to the potential application of the system in the clinical field. In the presented system it is possible to perform the electrophysiological as well as kinematics test, which may support the diagnosis. Moreover, such system could be used for

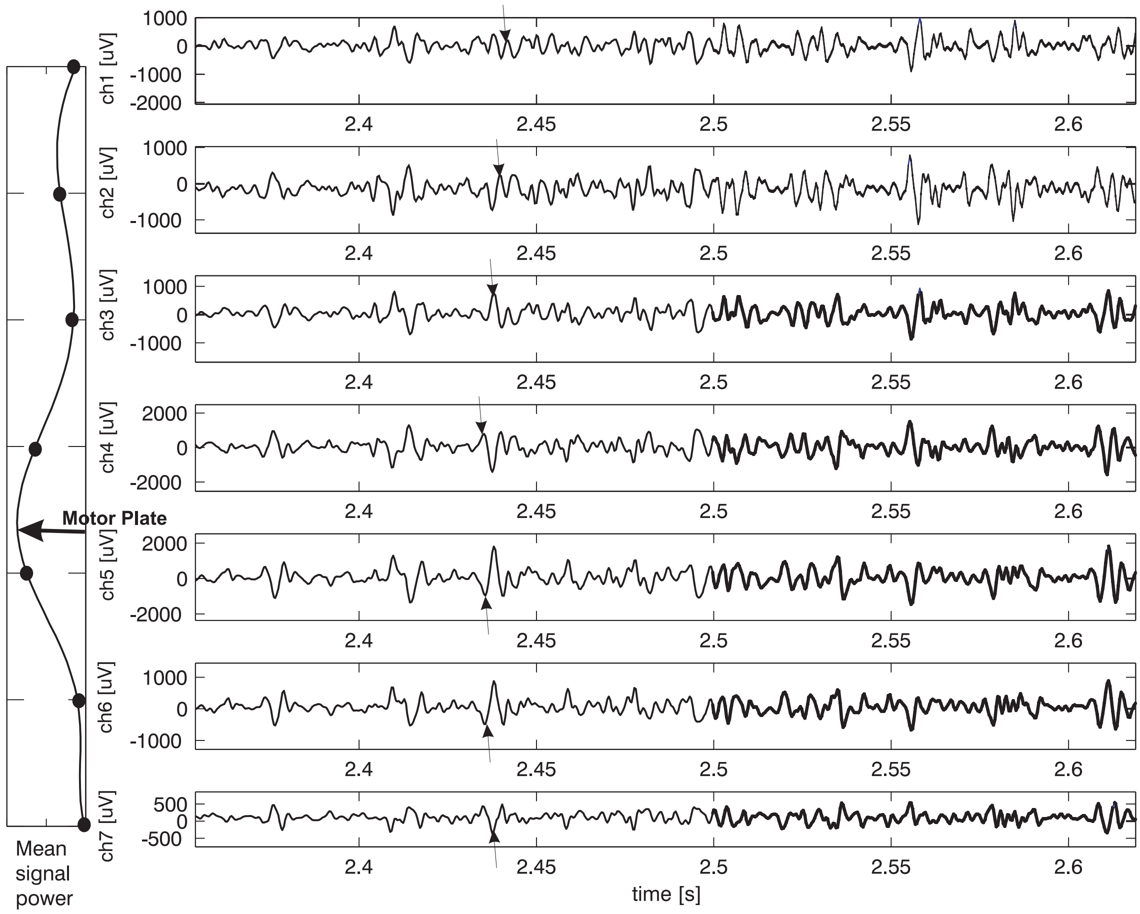

Figure 4: The multichannel EMG signals recorded from a tibialis anterior muscle with 8-point linear electrode array. A selected Action Potential (AP) propagating through the muscle has been marked with the arrows. The mean EMG signal power has also been computed. The black dots denote the mean signal power of the particular EMG channels. The maximum of the mean signal power between the channels ch4 and ch5 denotes the motor point localization.

selecting the individually optimized stimulation treatment.

Multisection EMG. Signals recorded with the multichannel EMG signal acquisition system have been used to estimate the conduction velocity of motor unit's action potentials (AP). This can be achieved by a special technique based on analysis of the APs having similar shape and being recorded in neighbouring channels. Selected AP generated by a single MU has been marked in Fig. 4. The AP propagation velocity can be computed on the basis of measured delay of the AP observed in particular channels and known distance between electrode points. Additionally, the system allows to localize neuromuscular junction in a particular muscle. It has been shown that signal parameters such as AVR or mean frequency (Fmnf) of the signals recorded at given points located along the tested muscle, can indicate the localization of the innervation zone. The motor point can be localized in two ways: the first is localization based upon the maximum signal power and the second is the AP phase inversion. The phase inversion can be seen in Fig 4 where the AP marked with the arrows is inverted in the channels ch5, ch6 and ch7. The motor point localization is important for an appropriate stimulation electrodes placement in FES application as well as a linear array-electrode placement in the signal decomposition task. The main purpose of the decomposition task is to estimate a discharge time of a particular motor unit during a voluntary contraction. In contrary to the decomposition systems of the intracellular EMG signals, decomposition of the multichannel surface EMG signals does not require to use needle electrodes which is an advantage. Multichannel recordings may compensate for the lower selectivity and give a deeper insight into the motor units activity. These information can be used in more sophisticated algorithms to improve the overall performance. The smart EMG sensors can be used during walking tasks in order to analyze the muscles synchronization issues. Two sensors located over 2 antagonistic muscles can discover their synchronization during contractions. Moreover, the information from these sensors can be used in control algorithms.

System Identification. The estimation of the system state only from physiological sensors or the determination of fuzzy sets must be adjusted to the individual subject. Moreover, the optimal control algorithm for the FES controller must be selected. The system is capable to perform tests enabling to work out the force-EMG relationship for each subject. It is possible to prepare a set of tests which enable semi-automatic calibration of the sensors system.

The Stimuli Optimization. The stimulation experiments revealed the variability of the excitability level for the same stimulation procedure. The variability is dependent on the pathology but also on the individual features of the subject. Therefore, the stimulation waveforms and stimulus shapes should be selected individually. It was observed, that the stimulation let to divide the subjects into few groups. The system let to perform tests enabling classification of the subject to the particular group.

3.3 Rehabilitation Tasks

Repetitive Exercises with or without Stimulation Support. The aim of such a treatment is to increase the maximum contraction force, or to increase a range of motion. A subject can observe the actual force level, the EMG amplitude, or the joint angle on the screen, and to try to follow the reference trajectory as set by the therapist. Moreover it is possible to use the stimulation in order to compensate partially for the error between the reference and the actual trajectory.

Restoration of Movement Functions for the Physically Disabled Subject. The main aim of the presented system is to develop a daily-use FES system for the restoration of movement functions with a minimal number of sensors. The system is potentially capable to operate in closed feedback loop mode with sensors and stimulation sequences configured individually by therapist on the basis of the identification tests results. However, to obtain satisfying results with this application further investigations and development of control algorithm is necessary.

ACKNOWLEDGEMENTS

The work was partially supported by the Polish Ministry of Education and Science, project no. 1445/T11/2004/27.

REFERENCES

Bennie, S. D., Petrofsky, J. S., Nisperos, J., Tsurudome, M., and Laymon, M. (2002). Toward the optimal waveform for electrical stimulation of human muscle. *Eur J Appl Physiol*, 88(1-2):13 – 19.

Breen, P. P., O'Keeffe, D. T., Conway, R., and Lyons, G. M. (2006). A system for the delivery of programmable, adaptive stimulation intensity envelopes for drop foot correction applications. *Med Eng Phys*, 28(2):177 – 186.

Chizeck, H. J., Chang, S., Stein, R. B., Scheiner, A., and Ferencz, D. C. (1999). Identification of electrically stimulated quadriceps muscles in paraplegic subjects. *IEEE Trans Biomed Eng*, 46(1):51 – 61.

Chou, L.-W., Ding, J., Wexler, A. S., and Binder-Macleod, S. A. (2005). Predicting optimal electrical stimulation for repetitive human muscle activation. *J Electromyography Kinesiology*, 15:300–309.

Kaczmarek, P., Celichowski, J., and Kasiński, A. (2005). Experimentally verified model of mechanomyograms recorded during single motor unit contractions. *J Electromyogr Kinesiol*, 15(6):617 – 630.

Keller, T., Popovic, M., Pappas, I., and Müller, P. (2002). Transcutaneous functional electrical stimulator "compex motion". *Artificial Organs*, 26(3):219–223.

Kutch, J. J. and Buchanan, T. S. (2001). Human elbow joint torque is linearly encoded in electromyographic signals from multiple muscles. *Neurosci Lett*, 311(2):97 – 100.

Orizio, C., Gobbo, M., Veicsteinas, A., Baratta, R. V., Zhou, B. H., and Solomonow, M. (2003). Transients of the force and surface mechanomyogram during cat gastrocnemius tetanic stimulation. *Eur J Appl Physiol*, 88(6):601–606.

Sinkjaer, T., Haugland, M., Inmann, A., Hansen, M., and Nielsen, K. D. (2003). Biopotentials as command and feedback signals in functional electrical stimulation systems. *Medical Engineering & Physics*, 25(2003):45 – 96.

Taylor, P. N., Burridge, J. H., Wood, D. E., Norton, J., Dunkerly, A., Singleton, C, and Swain, I. D. (1999). Clinical use of the odstock drop foot stimulator - its effect on the speed and effort of walking. *Arch Phys Med Rehabil*, 80:1577 – 1583.