COMBINED STIMULATION AND MEASUREMENT SYSTEM FOR ARRAY ELECTRODES

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Abstract: Array electrodes have the potential to significantly advance Functional Electrical Stimulation (FES) performance and patient compliance by optimizing the electrode position. To evaluate the potentials and for research purposes, an universal stimulation system for array electrodes has been developed. The system additionally features volitional EMG recording from the array electrodes during active stimulation. Multiple devices, one stimulator and at least one demultiplexer, are synchronized to deliver up to 10 stimulation pulses per stimulation cycle at a frequency of $\approx$ 420 Hz. A typical stimulation cycle period is 50 ms. The real-time controllable array electrode can include up to 60 elements for the active electrode and up to 4 elements for the indifferent electrode. A small switch module permits placement near the array electrode, eliminating extensive wiring. The stimulation system is fully controllable from a PC via USB interfaces.

1 INTRODUCTION

For selective transcutaneous Functional Electrical Stimulation (FES) it is important to place one smaller active electrode over the motor point of the target muscle to achieve optimal results. Motor points are areas where muscles are most likely to be activated. Finding these motor points requires some expertise and often another placement point achieves better results because of patient specific characteristics (O'Dwyer et al., 2006) (Popovi-Bijeli et al., 2005). In FES, usually biphasic, charge balanced, stimulation pulses are applied. The larger indifferent electrode is placed away from any motor point to avoid that the compensating pulse generates an action potential.

Array electrodes have the potential to simplify the electrode placement because any number of array elements can form a "virtual electrode", which can dynamically change position and size. This, together with intelligent control software, allows automatic optimization towards the distinctive, real motor point of the target muscle, even for imprecise placement of the array electrode (Keller et al., 2006). Array electrodes also allow a much more precise muscle activation in areas like the forearm, where a lot of different muscles are close together.

A number of research projects used array electrodes because of the above mentioned advantages. The presented studies demonstrated that a selective stimulation of the forearm muscles by array electrodes can be realized to induce precise finger and wrist-joint movements (Popovi-Bijeli et al., 2005) (O'Dwyer et al., 2006). A selective correction of a drop-foot in hemiplegics was investigated in (Azevedo-Coste et al., 2007). The largest applied electrode array comprised 60 elements (Keller et al., 2006). Most stimulation systems presented in literature serve only one array electrode and do not provide an open and flexible PC interface for real-time control of the switch configurations.

2 CONCEPT

The developed system utilizes an already existing 8 channel stimulation device and extend it for use of array electrodes. This requires the development of a demultiplexer and the ability to synchronize the different devices.

The stimulation is controlled by a 20 Hz top level control loop, implemented on a designated computer in Scilab/Scicos (http://www.scilab.org) or Matlab/Simulink (http://www.mathworks.com). Every 50 ms, the stimulator will generate a sequence of up

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to 10 stimulation pulses that are distributed to normal stimulation channels or channels with a demultiplexer (arrays). Therefore, the top level control loop transmits a sequence configuration to the stimulator and to the demultiplexer(s) every 50 ms.

The sequence configuration consist of up to 10 individual configurations for the stimulation pulses and switch settings. This way the stimulator receives up to 10 pulse configurations which define the pulse width and stimulation current of each biphasic stimulation pulse as well as the information to which channel the pulse has to be delivered. Each demultiplexer receives a corresponding number of switch configurations for the stimulation pulses as well as one optional EMG switch configuration, if an electromyography (EMG) signal shall be recorded from the array electrode. A switch configuration defines which of the available 64 switches are active.

As soon as stimulator and demultiplexer(s) have received there configurations they synchronize themselves as explained in section 5. The computer on which the top level control loop runs is not involved in the synchronization. If applicable the EMG switch configuration is set after all stimulation pulses of that stimulation cycle have been sent.

Figure 1 shows an example with a stimulation sequence for only one demultiplexer (array) where 4 distinctive muscles are activated.

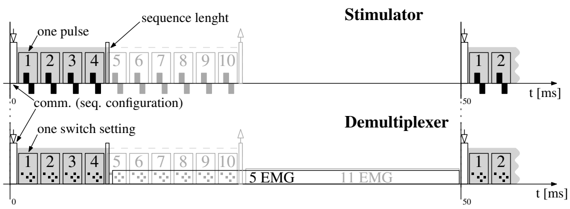

Figure 1: Example for a sequence of 4 pulses for the stimulator device and one demultiplexer. The largest possible sequence is indicated in gray.

3 SYSTEM OVERVIEW

The core system consists of a RehaStim^{TM} stimulator and at least one demultiplexer. A demultiplexer distributes one stimulation channel over an array of small, especially designed electrodes. Up to 8 demultiplexer can be connected to one stimulator but stimulator channels can also be used without the demultiplexer.

Figure 2 depicts the entire system with all possible components. For the sake of simplicity, we assume in the following, that only one demultiplexer is connected to the stimulator.

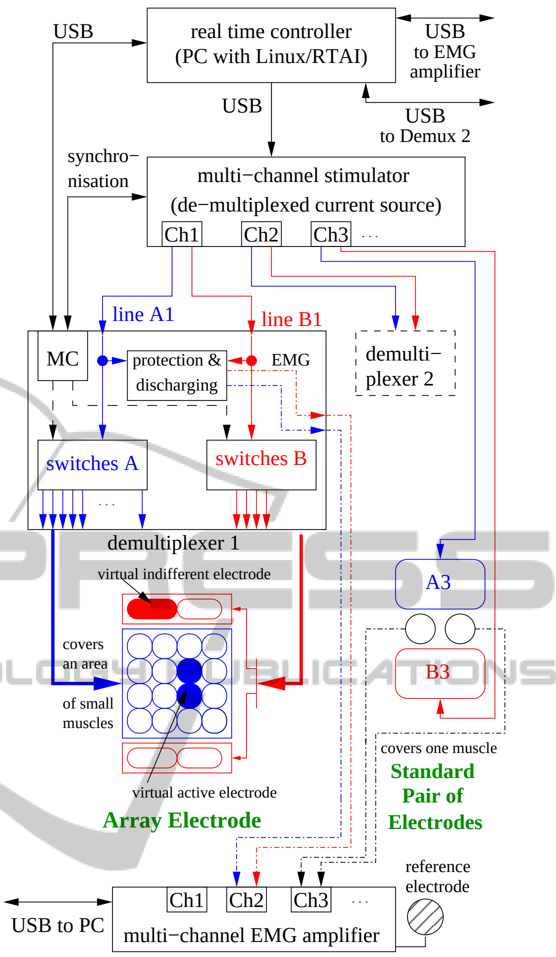

Figure 2: System overview.

A standard PC or laptop controls the entire system by implementing a top level control loop. A real-time operating system like RTAI (https://www.rtai.org) is advised but not crucial since the top level control loop only runs with about 20 Hz, providing the next sequence configuration for the stimulator and all connected demultiplexer(s). The configuration data is sent via an USB link to the respective device. No special safety precaution is needed since all devices have galvanic isolated USB ports.

The system uses the certified, current-controlled 8 channel stimulator RehaStim^{TM} available from the company HASOMED GmbH. The stimulator outputs a biphasic stimulation pulse with a stimulation current from 2 mA to 130 mA and a pulse width from 10 μs to 500 μs. The RehaStim^{TM} device can be directly controlled by an external device, preferable a personal computer. The RehaStim^{TM} implements a special operation mode which accounts for the need of synchronization and pulse sequences.

The hardware design of the demultiplexer, the synchronization process and the EMG measurement including EMG amplifier protection are described in more detail later on.

The demultiplexer can support a width range of array electrodes with two exclusive sets of array elements. The first set is used to build the virtual active electrode and may consist of up to 60 elements. The second set with maximal 4 elements is used to build the virtual indifferent electrode. To minimize losses and to prevent a short circuit due to misconfiguration the array elements related to the virtual indifferent electrode must be placed on a different gel layer than the array elements belonging to the virtual active electrode.

4 DEMULTIPLEXER DESIGN

The demultiplexer is divided into two parts, a *power* module and a *switch* module. This segmentation allows the *switch* module to be placed very close to the array electrode, with a minimum of necessary cables.

Power Module. The demultiplexer is powered from an external 12 V power supply or battery. The *power* module hosts the galvanic isolated USB port and the galvanic isolated SYNC port.

The SYNC port safely connects the demultiplexer to the RehaStim^{TM} stimulator. The signals "Demultiplexer Ready" (DMR) and "Stimulation in Progress" (STIM), which are essential for synchronization, are routed through the SYNC port. The synchronization process is further explained in Section 5.

All demultiplexer functions, including communication, synchronization and switch operation, are controlled by a Cypress programmable system-on-chip (PSoC). The 8-bit MCU core uses a 24 MHz system clock, providing sufficient execution speed to ensure peak performance and minimized stimulation delays.

The *power* module communicates with the *switch* module over a 24 MHz differential data link. This high speed forward channel includes a CRC check to ensure data integrity. Any error on the *switch* module is reported back over a low speed backward channel and is processed by the PSoC MCU.

Switch Module. The *switch* module includes the receiver for the 24 MHz differential data link, the actual switch matrix and the EMG protection circuit. The switch matrix consists of 64 high voltage CMOS analog switches and makes a compact design of the *switch* module possible.

One of the eight stimulator channels is connected to the *switch* module. The stimulation channel's active electrode line is connected to 60 switches, allowing up to 60 array elements to form the virtual active electrode. The stimulation channel's indifferent electrode line is connected to 4 additional switches. A short circuit due to misconfiguration is therefore impossible. The stimulation voltages can rise up to ±150 V. Therefore two 300 V rated 34 pin IDC connectors are used to connect the demultiplexer with the array electrode.

5 SYNCHRONIZATION

Since the system uses independent devices for generating the stimulation pulses and controlling the switches, these devices need to be synchronized. The demultiplexer must set the switches before any stimulation pulse is generated and move on to the next configuration as soon as the stimulation pulse is completed. Therefore the demultiplexer needs to know when a stimulation pulse is generated and the stimulator needs to know when the switch configuration for the next stimulation pulse is established. This information is encoded into the two synchronization signals STIM (Stimulation in Progress) and DMR (Demultiplexer Ready).

Figure 3 shows the handshake and the synchronized execution of a stimulation sequence with two pulses sent via the demultiplexer while no EMG switch configuration is applied. The pulse frequency within a sequence is fixed to 420 Hz.

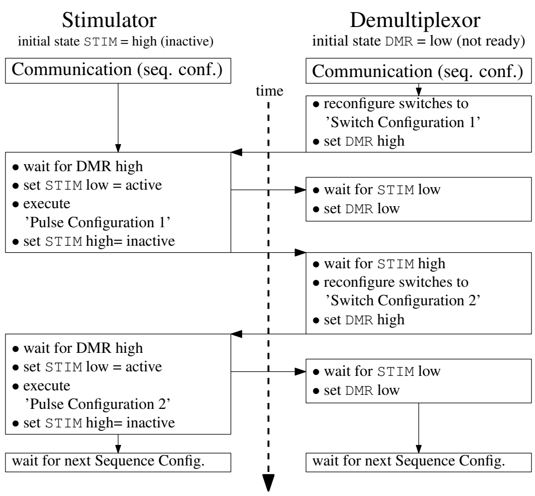

Figure 3: Execution of a sequence where two stimulation pulses are generated and distributed over different switch configurations.

If more than one demultiplexer is connected to the stimulator, the DMR signal will be set high by the slowest demultiplexer indicating that all demultiplexers are ready. The STIM signal is shared by all demultiplexer devices.

6 EMG MEASUREMENT

The measurement of EMG from a stimulated muscle is of interest in order to detect residual volitional muscle activity. The latter might be used to control the stimulation. The use of array electrodes for stimulation does not allow the placement of additional EMG electrodes close to the virtual active electrode due to the larger size of the array electrode. Therefore, EMG measurement must be performed from virtual EMG electrodes formed by elements of the stimulation array. As shown in (Shalaby, 2011), EMG can be directly measured from the stimulation electrodes during stimulation if the EMG amplifier is protected and the electrodes are periodically discharged.

The EMG protection circuit consists of multiple PhotoMOS relays and a high pass filter. The required timing diagram for the PhotoMOS switches is shown in Figure 4. During delivery of stimulation pulses two

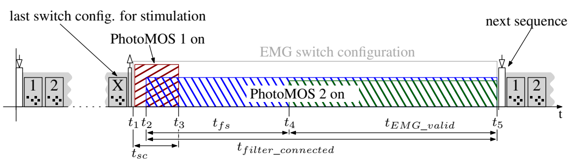

Figure 4: EMG protection and discharging timing, $t_1 \dots t_4$ depend on sequence length and array setting.

PhotoMOS switches are used to mute the EMG measurement (PhotoMOS 2 off). After the stimulation is completed, another PhotoMOS relay short circuits the electrodes over which the EMG signal is measured for an user defined time interval to eliminate any residual charge on the electrodes (PhotoMOS 1 on). The electrodes then are connected to the high-pass filter (PhotoMOS 2 on) which reduces low frequency disturbances. The actual EMG measurement however is performed by an external standard EMG amplifier.

The duration of the short circuit t_{sc} is between 7 and 8 ms. The high-pass filter needs the time t_{fs} to settle. Thus it is best to activate PhotoMOS 2 as early as possible to maximize the valid EMG recording time t_{EMG_valid}. The stimulation-induced EMG response (M-wave) falls together with the filter transients and is excluded from the EMG measurement. Basically, only volitional muscle activity is captured in the time interval t_{EMG_valid}. An EMG recording of the wrist extensor under stimulation is shown in figure 5. Parts of the EMG recording which are disturbed by filter transients are already blanked in the shown EMG signal.

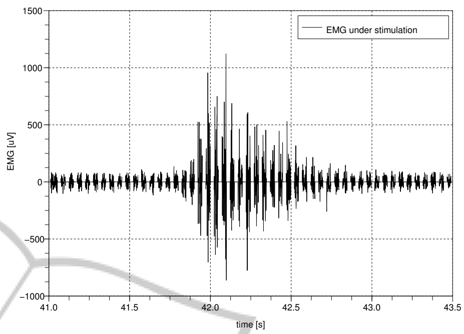

Figure 5: EMG recording of volitional muscle activity from the stimulated wrist extensor (pulse width 100 μs, I=15 mA).

7 CONCLUSIONS

The system enables researchers and health professionals to use array electrodes without large effort. The developed software simplifies the setup of complex stimulation patterns and permits a straightforward integration of array electrodes into existing stimulation setups. Parameters like pulse widths, stimulation currents or demultiplexer configurations can be adjusted in real-time. The demultiplexer supports array sizes up to 60 elements for the active electrode and up to 4 elements for the indifferent electrode. The small *switch* module can be placed near to the array electrode, avoiding extensive wiring. The ability to measure volitional EMG signals from a pair of virtual electrodes makes array electrodes usable for diagnostics or control applications. In future work, the remaining problem of filter transients must be solved by introducing digital filters and including the EMG amplifier into the *switch* module.

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