FES Testbed for Multi-Channel Transcutaneous Stimulation Systems

Valtin M.[1], Schauer T.[1]

[1]Control Systems Group, Technische Universität Berlin, Germany

Abstract: *Troubleshooting advanced FES applications or stimulation devices by measuring the stimulation current and voltage over several minutes is often not possible because of the limited memory available in standard oscilloscopes. The developed FES Testbed, a specialised data acquisition system for transcutaneous electrical stimulation, enables such measurements. The galvanic isolated measurement system transfers the high-resolution data of every detected stimulation pulse via USB to a PC or Laptop. The stimulation pulse can use one of the 3 included skin replacement models or can be forwarded to standard electrodes, allowing to record a normal FES application. Modular postprocessing MATLAB functions round up the FES Testbed. These functions handle the data conversion, pulse detection, gathering of statistics, data management and data visualisation. A MATLAB GUI for efficient pulse examination completes the FES Testbed.*

Keywords: *Stimulation Device, FES, Current Measurement, Data Acquisition, Skin Model*

Introduction

Research involving functional transcutaneous electrical stimulation often includes some kind of control over the electrical stimulation. This may include the timing of the stimulation and/or the stimulation intensity, often based on sensor data [1]. Prominent examples of this structure are the FES based drop-foot correction [2] and the rehabilitation of the upper extremities, e.g. the hand [3]. In both cases, complex stimulation patterns are generated based on real-time sensor data. Monitoring and validating these stimulation patterns is often not easily possible, because the necessary measurement equipment is to large, to expensive, or to difficult to operate outside a lab environment.

Traditionally, the generated stimulation pulses are measured with an oscilloscope or with a data acquisition card for the PC. With a little bit of additional hardware, the stimulation voltage, as well as the stimulation current can be measured with these systems. Both methods usually use grid powered devices with no galvanic isolation, so the electrical safety of the whole setup must be kept in mind to protect the devices or the subject.

While oscilloscope measurements are great for real-time feedback, they cannot be used for long term evaluation (e.g. several minutes) or tracking of randomly occurring stimulation errors, because of the limited amount of memory available.

PC based data acquisition systems do not have this limitation, however, these, often stationary systems, are generally less practical because of the costs, system size and complexity. Data acquisition systems also require elaborate postprocessing to go through the millions of samples to extract the short stimulation pulses and convert the integer raw-data samples into ampere/volt.

The presented *FES Testbed* is a specialised data acquisition system for transcutaneous electric stimulation, enabling researchers to check and validate the safety and functionality of their advanced FES applications.

The second application of the *FES Testbed* is the validation and comparison of different stimulators and support of the development of new stimulation devices.

Since the various stimulators used in FES research all generate an electrical pulse, suitable to trigger a muscle contraction, the subtle and not so subtle differences, like symmetric and asymmetric biphasic pulses, are often neglected, conveying the idea that every stimulation pulse form is equally effective and can be easily exchanged.

With the *FES Testbed*, the high-resolution voltage and current wave forms of multiple stimulation pulses can be recorded and compared. Additionally, multiple realistic loads included in the *FES Testbed* simulate the electrode-skin interface and allow comparing different stimulators under the exact same load conditions.

Material and Methods

The *FES Testbed* consists of three individual parts:

- a small data acquisition system, specialised for FES,
- a PC based data recorder program,
- and MATLAB (MathWorks Inc., USA) post-processing scripts for efficient evaluation of the recorded stimulation pulses.

The FES data acquisition system is controlled by the PC data recorder, which saves the raw data for post-processing by the MATLAB scripts.

FES Data Acquisition System

Figure 1 depicts the basic structure of the whole system, with the PC or Laptop controlling the FES data acquisition system and the stimulation device. An optional demultiplexer, as well as the modules for additional input channels, are shown in grey.

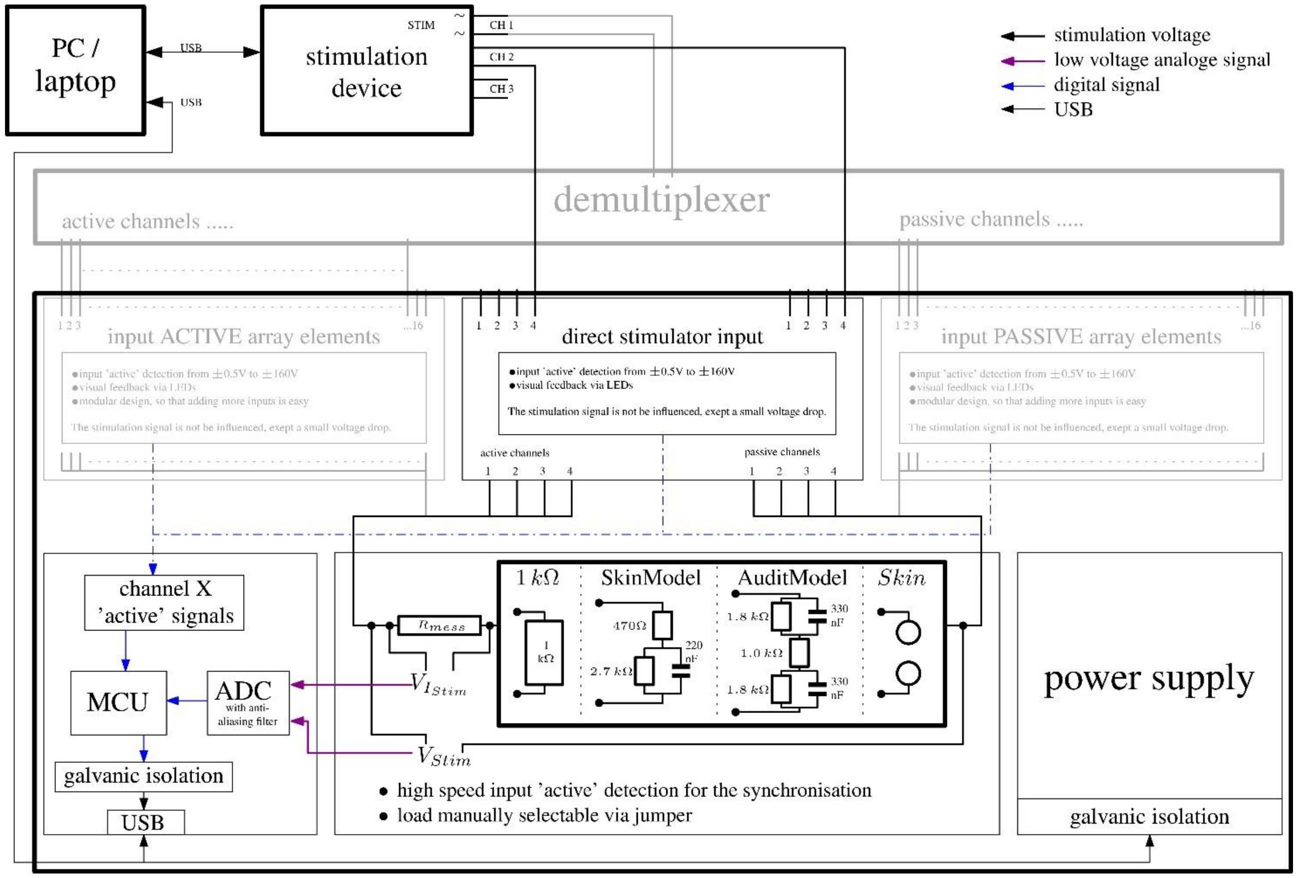

Figure 1: Overview of the FES Testbed, including the structure of the data acquisition system.

All devices are connected via USB to the PC, which also supplies the power for the data acquisition system. The power supply, as well as the USB communication channel, are galvanically isolated from the PC, to protect the PC from the high stimulation voltage and to protect against any ground loops, in case the FES Testbed is connected to a person. The power supply uses isolated DC/DC modules with at least 5.2kV isolation voltage (MEJ2 series, Murata, Japan). For the communication channel, the USB isolation IC ADUM4160BRWZ (Analog Devices Inc., USA) is used.

The *FES Testbed* supports 4 stimulation channels directly and up to 96 additional channels with optional extension modules, e.g. if a demultiplexer for electrode arrays needs to be tested. However, only one of these input channels can be active at a time. So, the stimulator must have a multiplexed current source, if this feature is used. The input stage is identical for every input channel and consists of a 'stimulation active' detection, which determines which stimulation channel is used. This is realised with an opto-coupler, which is driven directly by the stimulation current. An opto-coupler is used, because the stimulation current is not altered and because the resulting digital signal voltage is isolated from the stimulation voltage. Each input stage also has visual feedback of the stimulation pulse using LEDs.

After the input stage, all channels are connected to one single stimulation channel, which is routed to the current measurement resistor R_{mess} and the selected load.

Four via jumper selectable loads are included:

- a 1kΩ load for simple tests and comparison with oscilloscope measurements (1kΩ),
- a simplified linear skin model [4] (SkinModel),
- a model of the electrode interface according to test specification 09-01 03/2007 MDS-Hi (AuditModel),
- and a connector for standard stimulation cables (Skin).

The voltage drop over the measurement resistor R_{mess} and the voltage over the load are measured with a two channel, 16-bit analogue to digital converter (ADC) MAX11198 (Maxim Integrated Inc., USA). The ADC's sampling rate can go up to 2 MSample/s and is controlled via an external clock signal. The ADC features a dual serial peripheral interface (SPI), with one SPI output channel for each ADC channel and a maximum SPI clock frequency of 50MHz. However, it is not possible, to use two traditional SPIs, since only one SPI clock input is available. Therefore, one SPI interface was used in the master configuration to drive the SPI clock, accompanied by a second SPI interface in slave configuration, using the SPI clock generated by the SPI master. This allows the microcontroller (MCU) to utilise the direct memory access (DMA) unit for the data transfer, significantly reducing the MCU workload. The data transfer is triggered by the same MCU timer, which generates the ADC's clock, guaranteeing a valid data transfer after the ADC's data registers were updated.

The ADCs sampling rate was chosen to 1 MSample/s. This is because the stimulation pulse has a time resolution

of 1µs or greater. Passive first order anti-aliasing filters with ~500 kHz cut-off frequency are included in the signal preconditioning circuitry, before the ADC.
An ARM© based microcontroller (STM32L433, STMicroelectronics, Netherlands) was used to receive the SPI data, as well as the USB data. Because of the embedded USB 2.0 module, supporting 12 MBit/s, no USB to serial converter is needed. Since the highest data rate supported by the USB isolator IC is USB 2.0 'Full Speed' with 12 MBit/s, no faster external USB solutions are viable. Because the data rate is limited, the MCU needs to pre-process the continuous ADC data stream to identify the stimulation pulses, so that only the parts containing stimulation pulses are sent to the PC. This is done via configurable thresholds for the measured stimulation current and voltage. The data is buffered using the MCU’s RAM and send out in packages of two times 1000 samples. A 32-bit sample counter is sent with every package to enable the PC program to reconstruct the correct time vector of the stimulation pulses.

Data Recorder Program

The FES data acquisition system is controlled from a Linux PC via the Data Recorder program. This program initiates the measurement, receives, and saves the data excerpt. The following parameters are set during initialisation of the FES data acquisition system: data type to send (only the stimulation pulses or a continuous down-sampled data stream), sample rate divider, search width (number of samples to skip if detecting a stimulation pulse), detection thresholds, and if a demultiplexer is used. This initial setup is also stored in the custom binary format, used to store the measurement data. This allows the postprocessing script the correct conversion of the raw data stored. The data format is optimised for read-in speed and size, so only the time as a float value, and the raw 16-bit integer values for current and voltage are stored as vectors for one pulse. Therefore, before each pulse section, a small header is added with the meta information about the pulse, like the number of samples, the active stimulation channel(s), and so on. Figure 2 depicts the general structure of the resulting data file.

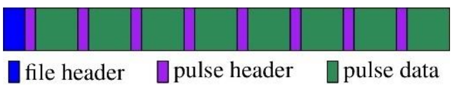

Figure 2: File structure of the custom binary data file.

The data about each stimulation pulse is also available via TCP/IP connection, to allow real-time visualisation and monitoring by other programs or scripts.

MATLAB based Postprocessing

Since the PC program only saves the raw data, the bulk of the conversion and postprocessing is done by modular MATLAB functions. A first function reads the binary file and converts the 16-bit raw data into volt and milliampere. The function also creates a MATLAB structure (struct) for the data, with an array of structs containing the stimulation pulse data. The meta data for each pulse is also taken over from the raw data and re-formatted for easy access in MATLAB. A second function is used to search for the expected pulse form, e.g. symmetric bi-phasic, and aligns the found pulse data, so that the pulses can be automatically compared and analysed. This function also collects various stats like the current or pulse width for later use. This step also saves all pulses which do not follow the expected form, so that they can be inspected manually later. Custom functions which, e.g., identify skin-model parameters can now be used on these normalised datasets.
Plotting these datasets is also very easy. A custom MATLAB GUI was developed to efficiently view the results and compare various stimulation pulses. This GUI has an overview function, where the complete, down-sampled vector of the stimulation current is plotted over time in subplot 1. One stimulation pulse, highlighted in the overview plot, can be selected via slider and shown in subplot 2. If the overview is disabled, subplot 1 is going to display the stimulation current of N pulses, while subplot 2 is going to display the stimulation voltage for these N pulses. N, the number of pulses to display, is configurable in the GUI and includes the selected pulse as well as the previous N-1 pulses.
The MATLAB data structure containing all this information can be saved directly from the GUI with varying degree of raw data included, significantly reducing the needed file size.

Results

The FES data acquisition device with an extension module for additional 16 input channels is depicted in Figure 3.

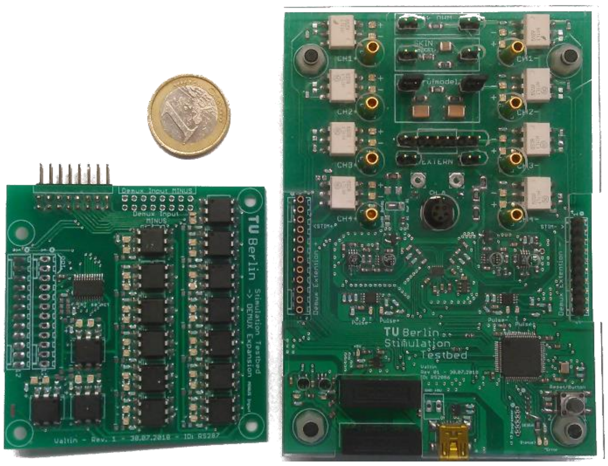

Figure 3: FES Testbed (right) and one 16 channel extension module (left).

The small size (115 mm × 80 mm × 20 mm) and the single USB connection makes the device very portable and easy to operate.
The quality of the measured data is also very good for such a simple system. The time resolution of 1 µs is sufficient to capture even very short spikes and sharp transients. The 16-bit ADC resolution provides a theoretical resolution for the stimulation current of ~5 µA

and enables low noise measurements from 0 mA up to ±150 mA without the need to adjust the measurement range. Figure 4 shows the stimulation voltage of a stimulator with adaptive high voltage generation [5] over the AuditModel, measured with the FES Testbed and with a 10-bit oscilloscope (Rode&Schwarz, RTM3004).

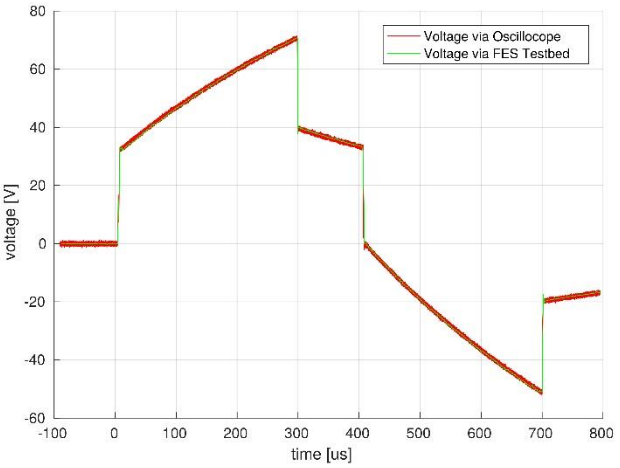

Figure 4: Stimulation voltage over the electrode interface model, measured with the FES Testbed (green) and an oscilloscope (red) (cur=25 mA; pw=300 µs).

Figure 5 shows the MATLAB GUI for a data set of 60 seconds or 1200 pulses (cur=25 mA; pw=300 µs) with 50 ms between each pulse. In the lower part of the GUI, stimulation current (blue) and voltage (orange) is displayed as well as the automatically detected boundaries of the different parts of the pulse (red). The file size of this one-minute long data set is about 34.9 MB. The postprocessing is also very fast, taking less than one second for the 1-minute data set, which would make the postprocessing real-time capable.

Figure 5: FES Testbed GUI showing the overview with 1200 pulses and the details for pulse 240.

The only limitation of the FES data acquisition system is its inability to continuously stream the data with 1 MSample/s. However, the need for galvanic isolation requires this compromise. On the other hand, most of this data would be discarded anyway, since the relevant stimulation pulse is very short, compared to the stimulation period. The MCUs buffer capability of 2 ms (sampling rate 1 MSample/s) should be sufficient for most applications, even where multiple pulses are used. In all other cases, reducing the sample rate will increase the pulse length the buffer can hold accordingly.

Conclusions

We developed a testbed aimed at supporting developers of intelligent stimulators, researcher who study electrical stimulation and its effects on the body, and clinicians who want to check and monitor the stimulation pulses generated by their FES application, over the entire treatment session.
The FES Testbed gives new insight into the physical effects of electrical stimulation and may aid in the development of smarter stimulators, which e.g., warn the health care professional if the stimulation voltage saturates because of poor electrode-skin contact. The FES Testbed could also prove invaluable for the validation and accreditation of complex stimulation systems.

Future work will focus on the automatic parameter identification for various skin models [6] [7] and the change of these parameters over stimulation intensity and time.

References

[1] T. Schauer: Sensing motion and muscle activity for feedback control of functional electrical stimulation: Ten years of experience in Berlin, *Annual Reviews in Control*, vol. 44, pp. 355-374, 2017

[2] T. Seel, C. Werner, T. Schauer: The Adaptive Drop Foot Stimulator – Multivariable Learning Control of Foot Pitch and Roll Motion in Paretic Gait, *Medical Engineering Physics*, vol. 38, pp. 1205-1213, 2016

[3] C. Salchow-Hömmen, T. Thomas et. al.: Automatic control of grasping strength for functional electrical stimulation in forearm movements via electrode arrays, *at-Autom*, vol. 66, pp. 1027-1036, 2018

[4] A. Boxtel: Skin resistance during square-wave electrical pulses of 1 to 10 mA, *Medical & biological engineering & computing*, vol. 15, pp. 679-687, 1977

[5] C. Wiesener: Current-Controlled Stimulator with Variable High Voltage Generation, *Submitted to Proc. of the 13th Vienna International Workshop on Functional Electrical Stimulation*, 2019

[6] J. L. Vargas Luna et. al.: Dynamic impedance model of the skin-electrode interface for transcutaneous electrical stimulation, *PloS one*, 2015 10(5), e0125609

[7] S. Dorgan, R. Reilly: Model for human skin impedance during surface functional neuromuscular stimulation, *IEEE transactions on rehabilitation engineering*, vol. 7, pp. 341-348, 1999

Author's Address

Markus Valtin
Technische Universität Berlin
Sekretariat EN 11
Einsteinufer 17
D-10587 Berlin, Germany
markus.valtin@campus.tu-berlin.de
http://www.control.tu-berlin.de