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Real-Time Embedded System for Event-Driven sEMG Acquisition and Functional Electrical Stimulation Control

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Abstract. The analysis of the surface ElectroMyoGraphic (sEMG) signal for controlling the Functional Electrical Stimulation (FES) therapy is being widely accepted in the active rehabilitation field due to the high benefits in the restoration of functional movements for subjects affected by neuro-muscular disorders. Portability and real-time functionalities are major concerns, and, among the others, two correlated challenges are the development of an embedded system and the implementation of lightweight signal processing approaches. In this respect, the event-driven nature of Average Threshold Crossing (ATC) approach, considering its high correlation with the muscle force and the sparsity of its representation, could be an optimal solution.

In this paper we present an embedded ATC-FES control system equipped with a multi-platform software featuring an easy-to-use Graphical User Interface (GUI). The system has been tested on 5 healthy subjects in order to test the effectiveness of the ATC approach in controlling the FES: we obtained a correlation coefficient value of 0.86±0.07, as similarity index between the healthy movement and the stimulated one during the elbow flexion exercise.

Keywords: Surface Electromyography, Event-Driven, Functional Electrical Stimulation, Embedded System

1 Introduction

Nowadays, an increasing number of active rehabilitation techniques are moving to the *bio-mimetic* approach, which relies on the analysis of the surface ElectroMyoGraphy (sEMG) signal for, e.g., the application of Functional Electrical Stimulation (FES) [1], with the aim of physiologically control the muscle functional restoration as much as possible [2]. In particular, FES employs low energy current pulses to promote the muscle contraction [3] following this approach: a complex stimulation pattern, useful to activate the group of muscles involved in a movement, is regulated by sEMG envelope evaluation or by muscle force indicators (e.g., RMS, ARV) [4].

In a practical application, the sEMG processing and FES control is a fundamental task to be carried out in *real-time* [5]. Since the time-performance bottleneck could be easily related to the use of a general purpose computer for the FES control (often concurrently running, or loaded with, many other unrelated applications or functionalities, leading to unpredictable performances), here the idea is to replace it with a dedicated embedded system. In this regard, major concerns will be the effectiveness and safety of the stimulation and the resulting performances, i.e., a latency short enough to fulfil the real-time constraints and the quality of the stimulated movement.

We propose an embedded bio-mimetic FES system based on the Average Threshold Crossing (ATC) event-driven technique applied to the sEMG signal. The ATC, which essentially compares the sEMG signal with a threshold, enable the implementation of a low-complexity on-board feature extraction process directly in hardware [6, 7], able to support, e.g., the recognition of different gestures [8]. The minimal data size of the ATC information [7] and its sparsity (due to its event-driven nature), perfectly matches with the low computational capabilities of an embedded system. Evolving from the architecture presented in the previous work [7], with the aim of making the system portable and improving the run-time performance, we replaced the personal laptop, and the software based on the Matlab® & Simulink® environment, with a Raspberry Pi 3 B+ as the processing and control core of the system, running a multi-platform software. Its main tasks are the management of the sEMG multi-channel wireless acquisition, the computation and update of the FES parameters from the ATC data, and the safe control of the stimulator. The software features a Graphical User Interface (GUI) as well, to monitor and control every aspect of the system, eventually guiding the user into setup different stimulation sessions.

2 System Architecture

2.1 Hardware

The developed system represented in Fig. 1 can be conceptually divided into three main parts: the sEMG acquisition modules and the articular electro-goniometers as inputs, the Raspberry Pi acting as central control and processing unit and the FES stimulator. The sEMG acquisition can be performed using two different types of device depending on the application-case: we provide a complete four-channels board (*a*), suitable for multiple-muscle monitoring on the same limb, or four single sEMG modules (*b*), that can be employed individually or in group on different body regions. In both the cases the ATC is implemented in hardware, using the standard window of 130 ms [6], and the data are wirelessly transmitted via Bluetooth Low Energy (BLE) to the Raspberry Pi. Moreover, we developed digital articular electro-goniometers (*c*) that can be employed as optional input in the case the user needs a visual feedback on the angular limb motions helpful to evaluate the running stimulation.

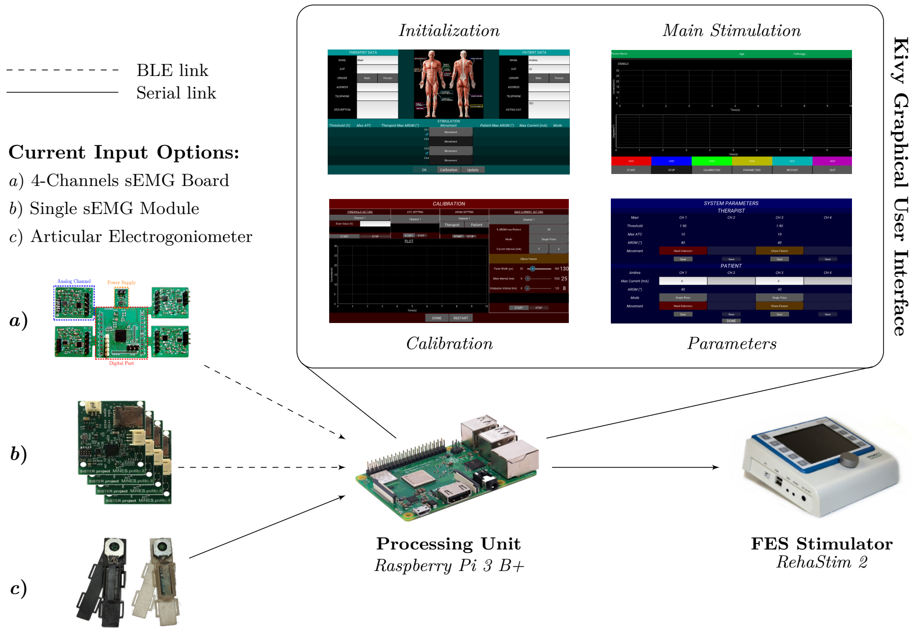


Fig. 1: System hardware and graphical user interface architecture.

On the other side, we employ the commercial medical-certified RehaStim2 stimulator device provided by the HASOMED GmbH company, which is able to generate biphasic rectangular current pulses on up to eight channels simultaneously [9]. The stimulator is interfaced with an external device by means of `ScienceMode2` bidirectional communication protocol [10], which supports the control of complex stimulation patterns and training scenarios since intensity, pulse-width, frequency are user-selectable pulse-by-pulse.

Lastly, the Raspberry Pi, model 3 B+, manages all the system functionalities receiving the ATC and angular data in input, converting them into a FES stimulation pattern and controlling its application.

2.2 Software

The software has been based on a object-oriented design in order to promote flexibility and modularity [11] (e.g., leveraging encapsulation, inheritance, and composition features), both to enable a seamless integration and management of different devices (e.g., input devices, see Sec. 2.1) and to enable the future development of new processing algorithms. A multi-threaded architecture has been developed in order to map the functional tasks onto different running threads [12], so to optimize the use of computational resources and to avoid complex (run-time) code interdependencies. From the development standpoint, we based the software on the Python language, because of its cross-platform nature, its widespread adoption, and the large availability of third-party multi-platform libraries (in particular, we used the standard library for implementing the multi-threading features, and the Kivy library [13] for the GUI).

Referring to Fig. 1, the GUI is organized in four full-screen views, through which the user is able to properly configure and perform the system actions: after the login, the *Initialization* view for setting the acquisition and stimulation parameters by user-input, from database information or using the calibration procedure, which has the dedicated *Calibration* view; once the parameters have been set, the user can modify or save them using the *Parameters* view; finally, the *Main Stimulation* view is the core of the GUI, allowing the user to start/stop the stimulation session, and providing visual feedback by showing both the FES intensity and the angular information.

A calibration procedure, divided into four sub-steps, is essential to define the ATC-FES control parameters on a per-user basis: first, the ATC threshold is set just above the sEMG baseline in order to maximize the threshold crossing events with the minimal muscle effort; second, the maximum ATC value and the maximal current intensity are evaluated in way to create the proper relationship between acquisition and stimulation data; in the end, the Angular Range Of Motion (AROM) is evaluated. In this way, we are able to obtain a calibrated set of parameters enabling the implementation of a simple, yet effective, ATC-FES control algorithm based on lookup tables.

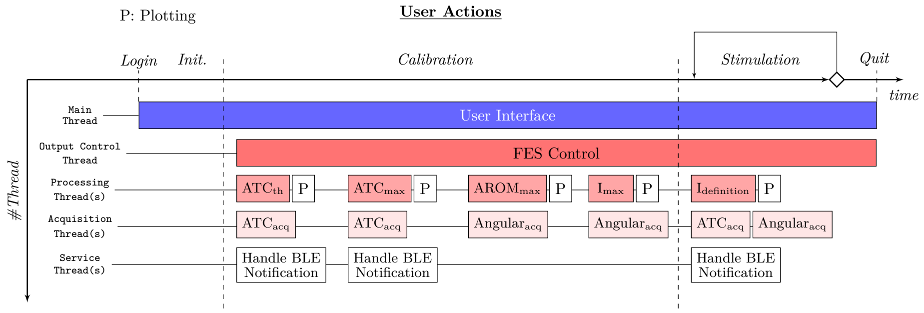
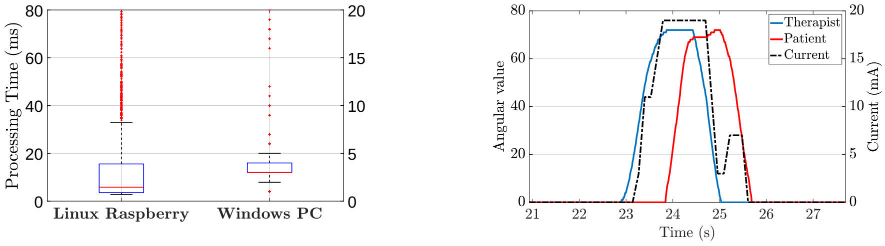


Fig. 2: Multi-threading structure during a typical stimulation session.

The multi-threading structure of the system and the running state of the involved threads during a typical stimulation session is reported in Fig. 2. The *Main Thread* runs all along the session waiting for the user input and creating child threads: the *FES Control* manages the communication with the RehaStim 2, also providing the watchdog timer function; ATC_{th}, ATC_{max}, $AROM_{max}$ and I_{max} represent the four calibration steps which trigger the *acq* threads;



a) b)

Fig. 3: In (a) the delay distribution between ATC packet reception and FES current modification is shown. In (b) the recorded angular signals (blue: therapist, red: patient) associated to a single movement repetition, along with the applied stimulation current (black dashed line), are represented.

3 Results and Discussion

The characterization of the computational resources consumption, including CPU usage percentage and RAM utilization, has been carried out using the *htop* GNU/Linux common tool available on the Raspberry Pi system. During the idle state, the CPU use is less than at 5.3%, and it increases up to 50 % to 70 % range during a normal operation (i.e, stimulation session), considering one or four ATC active channels as minimum/maximum configuration, respectively. The RAM utilization memory slightly is in the 84 MB to 92 MB range. Real-time performances have been estimated by considering the duration of the processing time, which is defined as the elapsed time between the 4-channels ATC data reception and the current update on the FES device. The analysis, performed both on a GNU/Linux platform (Raspberry Pi) and a Microsoft® Windows® one (laptop equipped with an Intel® Core® i3-3227U clocked at 1.9 GHz and with 4 GB of RAM), is graphically reported in the boxplots on Fig. 3a. As shown in the left boxplot, the 95% of the data is lower than 50 ms with a mean value of 11.8 ms. On the other side, the computational power of a personal computer allowed us to obtain a mean value of 3.6 ms for the ATC processing. Anyway, both platforms completely fulfill the real-time constraints considering the ATC window and the state of the art of the FES control system, and confirm the benefits of the sEMG event-driven approach.

Lastly, the system has been tested on 5 healthy subjects (3 males, 2 females, 24-27 years old) performing the elbow flexion, as a functional rehabilitative movement, in the therapist-patient scenario. In order to quantify the effective movement reproducibility, the limbs motion is acquired by means of the described electro-goniometers and the correlation coefficient between the signals is employed as similarity measurement. We obtained the majority of the correlation values above of 0.8 (median value, mean value of 0.86±0.07), which proves the high-fidelity reproduction of the movement, as shown in the example in Fig. 3b.

4 Conclusion

The paper proposes an implementation of a multi-channel real-time embedded system (running a multi-platform software) for event-driven (ATC) sEMG-FES control. The promising results in terms of real-time processing, computation resources usage, and high-fidelity movement reproduction show the advantage of an event-driven approach w.r.t. literature sEMG-driven-FES system. Future investigations about optimal FES parameters computation and multi-channel cross-processing information will further improve the quality of the FES control.

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