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An Event-Driven Closed-Loop System for Real-Time FES Control

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***Abstract*—Active functional rehabilitation procedures, exoskeleton application and prosthesis employment are essential tools for the society life reinstatement of subjects affected by neuromuscular disorders or victims of serious physical accident. In this paper we propose a closed-loop system for the control of the Functional Electrical Stimulation (FES) based on the Average Threshold Crossing (ATC) event-driven processing technique applied to the sEMG signal. It allows an energy saving, low complex, and real-time muscle activity monitoring suitable for bio-feedback lines applications. Two functional modalities are implemented: *self-administered stimulation*, in which a person is able to self-stimulate herself/himself, and *two-subjects stimulation*, that covers the standard rehabilitation flow in which both the therapist and the patient are involved. The system has been tested on 19 healthy subjects to evaluate its performance in term of reproducibility between the voluntary movement and the stimulated one, obtaining a median value of the correlation coefficient, used as similarity measurement, above 0.9 across a wide range of benchmark movements. The promising results confirm the feasibility of controlling myoelectric exoskeleton and prosthesis with the ATC processing approach.**

***Index Terms*—event-driven sEMG, smart rehabilitation, functional electrical stimulation**

I. Introduction

The Functional Electrical Stimulation (FES), an active rehabilitation technique that applies low energy electrical pulses by means of superficial electrodes, allows the partial or complete motor functions restoration for subjects affected by neuromuscular disorders [1], e.g., spinal cord injury and stroke patients. New frontiers of the FES therapy are moving toward the analysis of the surface ElectroMyoGraphic (sEMG) signal in order to define the most appropriate stimulation pattern to be applied, a method that is defined as sEMG-Driven-FES [2], [3]. Since the real-time FES application and the on-line stimulation pattern modulation are key aspects of such systems [4], [5], current studies are focusing on the best approach to minimize the acquired muscle information in order to set up a control-FES-chain able to reduce the sEMG processing time and cost as much as possible, while maintaining a safe and accurate stimulation.

We propose the event-driven processing of the sEMG signal, i.e., the thresholding features extraction process, as a promising technique to accomplish this task: the sEMG signal is amplified and then directly compared with a threshold; each Threshold Crossing (TC) represents an event and their count over a fixed time period defines the Average Threshold Crossing (ATC) feature. Since a high correlation between the ATC and the force exerted by a muscle has been previously proved [6], the ATC can be employed as proper indicator to discriminate among different muscular-activation levels. Moreover, due to the low-complex on-board ATC implementation, the information data-size, transmission payload, and further processing steps are extremely minimized allowing the development of energy-efficient biomedical acquisition systems [7].

Starting from these considerations, in this paper we discuss an event-driven sEMG closed-loop system for the real-time FES application that provides a current intensity modulation driven only by the ATC information. Basically, the sEMG signals are firstly acquired and processed directly on our wearable acquisition board, and then wirelessly transmitted to a control unit. Here, a MATLAB® and SIMULINK® inter-communicating environment implements a model able to manage the acquisition flow and control the FES stimulator, updating its stimulation parameters every time a new ATC data is received. A Graphical User Interface (GUI) has been developed in order to easily supervise the stimulation process, thanks to a graphical real-time representation of both the FES modulated-current and the angular limb motions.

As demonstration of the approach versatility, we employed the ATC-FES system in two functional applications: the *therapist-patient* controlled stimulation [8], in which the muscle information of an healthy subject (*therapist*) is used to set up the stimulation features to be applied to a second subject (*patient*), and the *self-administered* stimulation [9], properly designed for hemiplegic people able to self-control the stimulation of the paretic limb, processing the muscular data related to the healthy one. As result, a proper FES definition allows a high fidelity mirroring between voluntary and stimulated movement, with a replication of both the Active Range Of Motion (AROM) trajectory and limb movement velocity. These performances have been proven by analyzing the similarity between angular signals acquired during real-case stimulation scenarios, in which 19 healthy subjects have been enrolled. The promising results validate the ATC-Driven-FES control which, also considering acquisition and no-processing complexity advantages, can be generalized to a wide range of medical applications involving an on-line and real-time myoelectric control, e.g., exoskeleton, prosthesis or human-machine interaction.

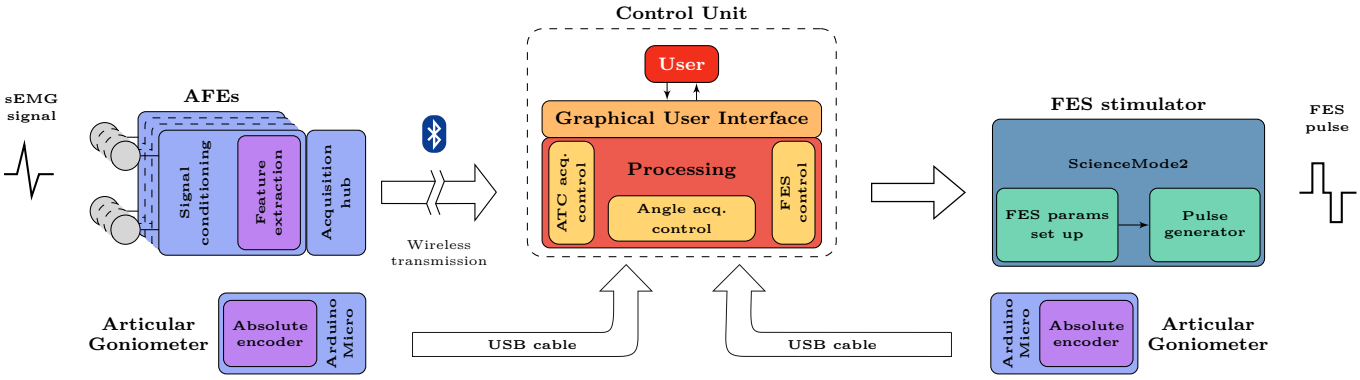


Fig. 1: Schematic representation of the system. *Inputs*: sEMG multi-channel acquisition board and articular electro-goniometers; *Output*: FES stimulator; *Processing*: MATLAB® & SIMULINK® control unit supported by a GUI for user interface.

II. System Architecture

The developed system is composed by an *acquisition unit* for the ATC feature extraction, an *actuation unit* represented by the FES stimulator and a *control unit* which handles the previously two processes and runs the GUI, as schematized in Fig. 1 where hardware and software resources are highlighted.

The sEMG acquisition board [10] has a modular structure organized with a central digital section surrounded by four Analog Front-Ends (AFEs). Each AFE is properly designed for the differential sEMG acquisition, providing the 33 Hz to 397 Hz band-pass filter with 922 gain. Ferrites and protection diodes are placed on the channel inputs in order to couple it with a FES system avoiding over-voltage circuitry damage risk. At the output, the TC signal is extracted in hardware using an hysteresis voltage comparator in order to avoid spurious spikes generation. The TC signals are used as input to a micro-controller (µC) of the MSP430 TI family, which computes the ATC parameters of all the channels and wirelessly transmits them using Bluetooth 4.0 protocol.
Additionally, we developed custom electro-goniometers, as optional inputs, if a visual feedback on the angle limbs motion is required. They are composed by a digital absolute encoder (12 bit resolution, 0.2° accuracy) and an Arduino-micro µC unit [11], which samples the signal at 80 Hz (compliant with the articular velocity of human movements [12]). The use of a bio-compatible lightweight resin for the 3D printer process allows the creation of an anatomical, comfortable and movement free structure.

On the other side, the *stimulation unit* is composed by the FES stimulator and its control logic. In particular, we chose the commercial medical-certified RehaStim2 (HASOMED GmbH company), a portable device that generates biphasic rectangular current pulses on up to 8 channels simultaneously, setting numerous power and time parameters related to the progression of the stimulation individually for each channel [13]. We based the pulse amplitude definition (0 mA to 130 mA) on the ATC parameter while the pulse-width (20 µs to 500 µs), the stimulation frequency (f_s, 10 Hz to 50 Hz) and the stimulation mode (single, doublet or triplet) are user-selectable depending on the muscles and movement considered.

In the middle, the *control unit* interfaces the user with the system and links the acquisition process with the actuation one. Since the RehaStim 2 could be connected to an external device by means of the `ScienceMode2` bidirectional communication protocol [14] and a SIMULINK®-compatible block has been implemented by the authors of [15], we developed the entire software architecture in the MATLAB® and SIMULINK® inter-communicating environments, providing a multi-threading SIMULINK® model linked to the MATLAB® GUI. Although the GUI provides a user-practical system supervision, the running core of the processes is represented by the model: it has a multi-submodel structure which allows the synchronous management of the ATC acquisition, the limb motion recordings and the FES stimulator control. Moreover, in order to properly set up the acquisition and stimulation parameters depending on the user(s) application-case, a *calibration* procedure, divided into four phases, defines the ATC-FES relationship:

1) *ATC threshold*: set just above the sEMG signal baseline in order to maximize the TC events with the minimal muscle effort.
2) *Maximal ATC value*: calculated as the median value among the maximum ATC values recorded during some repetitions of the desired movement.
3) *AROM evaluation*: measure of the maximal AROM of the involved articulation.
4) *Current Limitation*: the maximal FES current intensity is defined as the 110% of the current that permits to reach the 30% of the AROM in the stimulated subject.

If the goniometers are not employed, step 3) is skipped and 4) is visually achieved. Steps 2) and 4) are essential to create a stable user-dedicated relationship between the input ATC data and the stimulation pattern to be applied. Fig. 2 shows the low-complex, noise-robust ATC-FES intensity definition process (ATC_{array}-$Current_{array}$) optimized by the calibration phases. Every time a new ATC value is received, the median

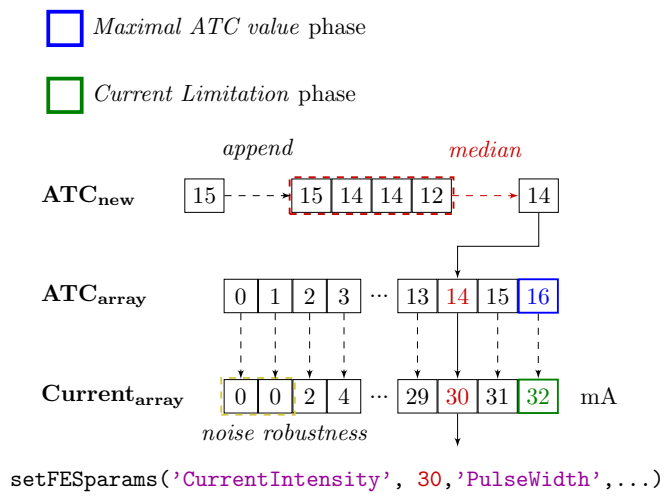


Fig. 2: ATC-processing flow for the FES current definition.

value between that one and the previous three is calculated and the FES current is determined using the simply yet effective calibrated *lookup table* structure.

An application example is reported in Fig. 3: the top graph shows the FES current modulation based on the count of TC events (ATC) while the bottom graph represents the angle signals acquired during the stimulation. The high reproducibility between the voluntary movement (blue) and the stimulated one (red), in terms of AROM similarity, is clearly visible.

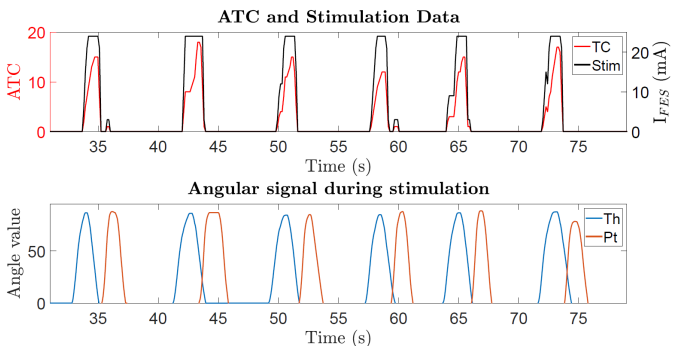


Fig. 3: On-line stimulation: FES current modulation on ATC (top); voluntary and stimulated limb motions (bottom).

III. Experimental Tests

The performance of the ATC-Driven-FES system has been evaluated in terms of reproducibility between the voluntary and induced movement in the *therapist-patient* case, in order to avoid the intrinsic bias due to the self stimulation. The general idea is to simultaneously acquire the angular motion of the limbs during on-line stimulation session, employing the electro-goniometers, and to evaluate the similarity between signals using the maximum of the cross-correlation coefficient (σ). A database has been created enrolling 19 healthy subjects (12 males, 7 females, 24-40 years old), which provided their informed consent to take part to the data collection protocol (approved by the University Bioethics Committee of Università degli Studi di Torino). The participants are organized into 12 therapist-patient couples, ensuring that each person covers both the roles only once and that both the tasks can not be performed in the same couple in order to assure high variability and diversity in the trials. Each couple has to perform a list of four exercises: Elbow Flexion (EF) and Elbow Extension (EE) related to the upper arm, Ankle Dorsi Flexion (ADF) and Ankle Plantar Flexion (APF) for foot control (details in Table I). The data-set robustness has been obtained by repeating each movement 30 times, organized into 3 sessions of 10 repetitions each one and suspended by short pause to avoid muscle fatigue. The stimulated subject has been maintained blindfolded during the entire sessions, so that she/he could not be influenced by the timing and the entity of the controller's limb movement. Moreover, in order to prevent conditioning effect, the execution order of the movements is randomly chosen for each couple.

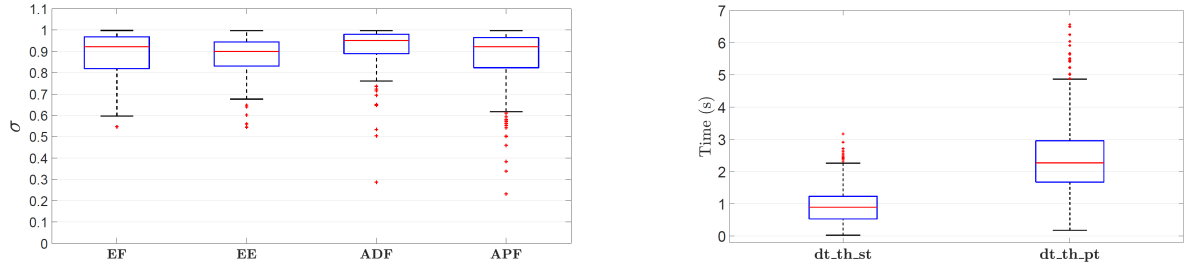
TABLE I: Experimental test settings.

Mov.	muscle	pulse-width	f_s	mode	electrode
EF	*biceps brachii*	150 µs	40 Hz	triplet	5 cm × 9 cm
EE	*triceps brachii*	200 µs	40 Hz	triplet	3.5 cm × 4.5 cm
ADF	*tibialis anterior*	300 µs	40 Hz	triplet	3.5 cm × 4.5 cm
APF	*gastroc. medialis*	350 µs	40 Hz	triplet	5 cm × 9 cm

We employed the H124SG Covidien Kendall™ electrode for sEMG acquisition, along with SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) guidelines for electrode positioning and skin preparation. On the stimulation side, we used the reusable self-adhesive HASOMED RehaTrode™ electrodes of different size depending on the stimulated muscle.

The box plots reported in Fig. 4a show the σ populations of the four exercises, where each σ value is calculated dividing the entire signal into epochs containing a single movement repetition and neglecting the signal baseline since it can be different depending on the limb starting position. The high fidelity of the movement replication is proven by the median σ value of each population, which results above 0.9 and Q3-skewed in all the cases. Moreover, the benefits of the ATC approach in the active control of the stimulation are further testified by the narrow InterQuartile Range (IQR) of the boxes, which are all located above the 0.8 σ value, and by the extremely low number of outliers ($Q_{3,1} \pm 1.5$ IQR).

A second test regards the latency of the system (measurements in Fig. 4b), computed considering both the time elapsed between the voluntary movement and the stimulation initialization, and the total delay in the movement replication. The median processing time spent in the definition of the new FES parameter is below 1 s, mainly due to the



(a) Cross-correlation coefficient analysis.

(b) Latency analysis.

Fig. 4: ATC-Driven-FES performance: a) cross-correlation similarity analysis between voluntary and stimulated movements for the EF, EE, ADF and APF exercises; b) latency measurements: `dt_th_st` represents the time elapsed between the *therapist movement* and the FES parameters update, while `dt_th_pt` indicates the total delay between the *therapist* and *patient* movement.

TABLE II: Comparison with state-of-the-art works.

Work	control feature	#ch[1]	FES params	σ	latency[2] (ms)	#subj[3]
[3]	RMS	8	current	n.a.	300	1
[4]	envelope	4	current	n.a.	n.a.	3
[5]	thresholds crossing	2	frequency	0.77	142	6
[8]	force/angle	4	current	0.99	n.a.	2
This	ATC	4	current	0.91	932[4] 11.8[5]	19

[1] number of channels; [2] feature-FES processing; [3] number of subjects; [4] MATLAB® & SIMULINK®; [5] Embedded version [16].

MATLAB®, SIMULINK® and MS® Windows operating system multi-threading callbacks priority order, while the total delay is approximately around the value of 2.3 s, which primarily depends by the muscular subject condition and by the muscle physiology. In any case, both the values are largely acceptable considering the type of application and related requirements. However, we have also developed an embedded version (on Raspberry Pi 3 B+) of the system [16], in which we fully exploit the sEMG event-driven processing advantages reducing the ATC-FES definition time to 11.8 ms.

IV. Conclusion

The paper proposes an event-driven sEMG-control-FES system based on the ATC muscle processing approach, which allows an online and real-time FES intensity modulation. The promising outcomes of our experimental tests, both in terms of movement reproducibility and system processing latency (thanks to the low ATC computational cost), demonstrate the feasibility of the ATC-control-FES in the rehabilitation scenario, which provides satisfactory results similar to other state-of-the-art works (as reported in table II). Starting from this point, we will further investigate additional applications in which an event-driven control could be implemented, e.g. the exoskeleton or prosthetic control.

References

[1] J. P. Reilly, *Electrical Stimulation and Electropathology*, ch. "Skeletal Muscle Response to Electrical Stimulation" by Sweeney, J. D. Press Syndicate of the University of Cambridge, 1 ed., 1992.

[2] G. Alon, "Functional Electrical Stimulation (FES): Clinical successes and failures to date," *Journal of Novel Physiotherapy and Rehabilitation*, vol. 2, pp. 080–086, 11 2018.

[3] Y. Zhou, Y. Fang, J. Zeng, K. Li, and H. Liu, "A Multi-channel EMG-Driven FES Solution for Stroke Rehabilitation," in *Intelligent Robotics and Applications* (Z. Chen, A. Mendes, Y. Yan, and S. Chen, eds.), (Cham), pp. 235–243, Springer International Publishing, 2018.

[4] Y. Fang, S. Chen, X. Wang, K. W. C. Leung, X. Wang, and K. Tong, "Real-time electromyography-driven functional electrical stimulation cycling system for chronic stroke rehabilitation," in *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 2515–2518, July 2018.

[5] HP Wang and ZY Bi and Y Zhou and YX Zhou and ZG Wang and Lv XY, "Real-time and wearable functional electrical stimulation system for volitional hand motor function control using the electromyography bridge method," in *Neural Regen Res*, p. 133–142, 2017.

[6] S. Sapienza, M. Crepaldi, P. Motto Ros, A. Bonanno, and D. Demarchi, "On Integration and Validation of a Very Low Complexity ATC UWB System for Muscle Force Transmission," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, pp. 497–506, April 2016.

[7] F. Rossi, P. Motto Ros, S. Sapienza, P. Bonato, E. Bizzi, and D. Demarchi, *Wireless Low Energy System Architecture for Event-Driven Surface Electromyography*, pp. 179–185. 05 2019.

[8] K. Shima and K. Shimatani, "A new approach to direct rehabilitation based on functional electrical stimulation and EMG classification," in *2016 International Symposium on Micro-NanoMechatronics and Human Science (MHS)*, pp. 1–6, Nov 2016.

[9] Z. Huang, Z. Wang, X. Lv, Y. Zhou, H. Wang, and S. Zong, "A novel functional electrical stimulation-control system for restoring motor function of post-stroke hemiplegic patients," *Neural Regeneration Research*, 2014.

[10] D.A. Fernandez Guzman, S. Sapienza, B. Sereni, and P. Motto Ros, "Very Low Power Event-Based Surface EMG Acquisition System with Off-the-Shelf Components," *IEEE Biomedical Circuits and Systems Conference (BioCAS)*, 2017. doi:10.1109/BIOCAS.2017.8325152.

[11] "Arduino micro." https://store.arduino.cc/arduino-micro.

[12] D. Jessop and M. Pain, "Maximum Velocities in Flexion and Extension Actions for Sport," *Journal of Human Kinetics*, vol. 50, 03 2016.

[13] HASOMED GmbH, *Operation Manual RehaStim 2, RehaMove 2*, September 2011.

[14] B. Kuberski, *ScienceMode2 - Description and Protocol*, December 2012.

[15] T. Schauer and R. Stephan, *Simulink interface for soft real-time control of the RehaStim2 stimulator*. Technische Universität Berlin.

[16] F. Rossi, R. M. Rosales, P. Motto Ros, and D. Demarchi, "Real-Time Embedded System for Event-Driven sEMG Acquisition and Functional Electrical Stimulation Control," *Springer Lecture Notes in Electrical Engineering*, vol. In Press, 09 2019.