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Wireless Low Energy System Architecture for Event-Driven Surface Electromyography

Fabio Rossi[1], Paolo Motto Ros[2], Stefano Sapienza[3], Paolo Bonato[3], Emilio Bizzi[4], and Danilo Demarchi[1]

[1]Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Turin, Italy
[2]Electronic Design Laboratory, Istituto Italiano di Tecnologia, Genoa, Italy
[3]Dep. of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, USA
[4]Dep. of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, USA

Abstract. The development of surface ElectroMyoGraphy (sEMG) acquisition system having an optimal trade-off between accuracy, resolution, low dimension and power consumption is a hot topic today. The event-driven Average Threshold Crossing (ATC) technique applied to the sEMG signal allows the reduction of both complexity and power consumption of the acquisition board.

The paper presents an sEMG acquisition system, based on this approach, and shows the advantages of the ATC in this field. A framework for developing bio-signal ATC-processing applications is provided, enabling the comparison with a standard sEMG sampling approach. Both system performance and power consumption analyses are carried out to obtain promising results in terms of real-time behavior and energy saving. As a sample application, the system is employed in the control of Functional Electrical Stimulation (FES) in way to verify the behavior of the ATC approach in such application.

Keywords: Surface Electromyography, Event-Driven, Average Threshold Crossing, Bluetooth Low Energy, Functional Electrical Stimulation

1 Introduction

The surface ElectroMyoGraphy (sEMG) is a non-invasive electrodiagnostic technique for evaluating and recording the electrical activity produced by the skeletal muscle [1]. The features obtained processing and classifying the sEMG signal are employed in many applications as the determination of the muscle activation timings, the estimation of the force produced by muscle, movement recognition and prostheses control [2–4]. The miniaturization of the acquisition channel, the wireless transmission, and the power consumption are the key aspects for the development of wearable detecting system to be inserted into the Internet of Things (IoT) network [5, 6]. The Average Threshold Crossing (ATC) is an event-driven technique, applied to the sEMG signal, that allows to obtain an optimal trade-off between these requirements. The approach concerns the thresholding of the muscle signal: every time the signal crosses a static or dynamic threshold, an event

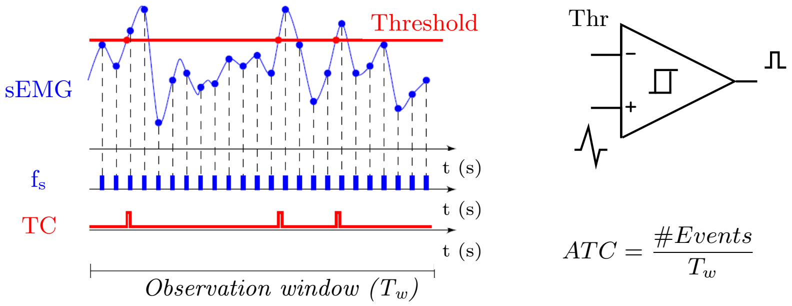


Fig. 1: Average Threshold Crossing (ATC) technique: on the left, a comparison with standard sampling approach; on the right, HW implementation of the ATC.

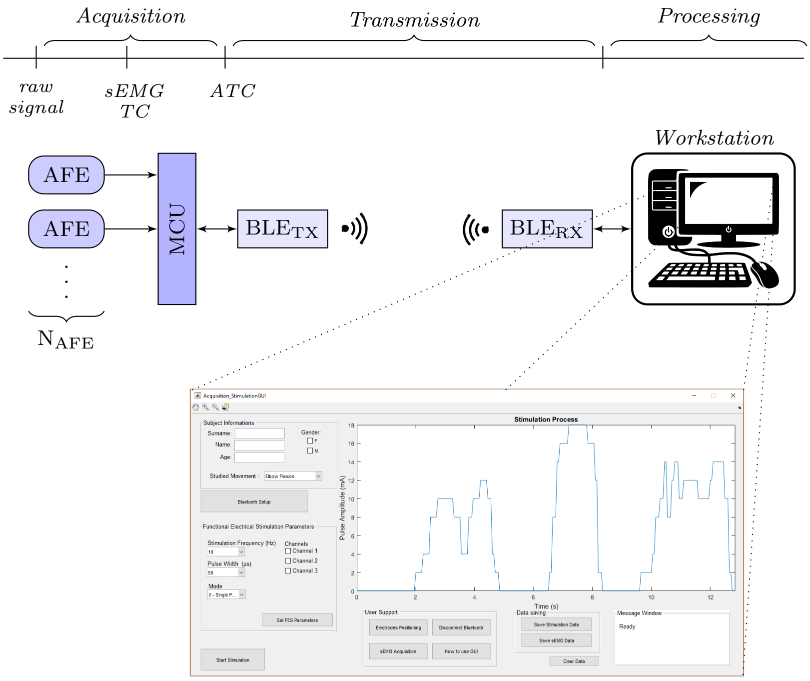
is generated, producing the quasi-digital Threshold Crossing (TC) signal. It is characterized by a digital-shape and analog timing information, i.e., the number of events and their timing in general, which make it directly interpretable by digital electronics. The simple hardware implementation of this technique, shown in Fig 1, allows to perform an on board TC features extraction in order to reduce data digitalization, storing and transmission. The ATC parameter, which is calculated as the ratio between the number of TC events detected during an observation window and the length of the window itself, has proven to be highly correlated to the muscle force (i.e., 95% ATC-force correlation) [7]. We have previously shown the benefits of the ATC in the sEMG field [8, 9] as well as the reduction of both circuitry complexity and system dimension and the energy saving for the wireless transmission, i.e., using the Impulse Radio-Ultra Wide Band (IR-UWB). Nevertheless, IR-UWB does not provide an easy interface with common computers; therefore, in this work, in order to provide a standard development framework, we replaced IR-UWB with the now ubiquitous Bluetooth Low Energy (BLE).

We employed the developed system in the control of the Functional Electrical Stimulation (FES), which is a rehabilitative technique that applies low energy electrical pulses to promote the muscle contraction. Considering the same flow of [10], the basic idea is to use the ATC parameter, instead of the sEMG signal, to define a stimulation pattern in a *real-time* mode.

To the best of our knowledge, our system is the first one to apply an sEMG event-driven approach w.r.t. common bio-signal acquisition boards (e.g. Bitalino, FreeEMG and OpenBCI boards [11–13]).

2 Hardware System Architecture

The hardware architecture can be conceptually divided into two main parts: the acquisition board, already presented in a previous paper [14], and the BLE module. Here we discuss about the interface between the ATC Analog Front End (AFE) and a MicroController Unit (MCU) and about the transmission of the event data using the BLE protocol. The system has the dual purpose of acquiring the sEMG and generating the TC signals in order to carry out a performance comparison about the two techniques and to fulfill the real-time constraints. Fig. 2 gives an overview about the whole system.



Studied Movement : Elbow Flexion

Stimulation Frequency (Hz): 10

Pulse Width (μs): 50

Mode: 0 - Single P...

Message Window: Ready

Fig. 2: Overview of the overall system: on the top, a schematic representation of the hardware architecture; on the bottom, the graphical user interface developed for the FES application.

The TI MSP430FR5969 MCU has been chosen due to its high performance and ultra-low power features. The raw sEMG signal is acquired using the integrated ADC, sampling at 1 kHz, 8 bit. The resources required to implement the ATC are minimal w.r.t. typical bio-signal digitalization [15]. The time sparseness of the TC signal allowed us to consider each rising edge as an interrupt, used to increase a counter. An internal timer has been used to reset the counter at the end of the observation window. Low Power Mode (LPM) has been used to reduce the power consumption.

The Microchip RN4020 and the TI CC2540-USBDongle have been chosen as the devices connected to the acquisition system and computer, respectively. Both Generic Access Profile (GAP) and Generic Attribute Profile (GATT) are defined according to the Bluetooth 4.0 specification [16]. In agreement with the

GAP description, the CC2540 acts as central/master device while the RN4020 as peripheral/slave one: in that situation the user can supervise the system moving from one function to another, depending on the required task, once the connection with the acquisition board is established.

Next step is to consider the structure definition for data exchange that is based on a server/client architecture. The suitable idea is to define the server on the RN4020; so, every time new data are available, they are updated into the specific location, and a *notification* message is sent to the client. As defined in GATT, we decided to use the *private* service and characteristic, instead of the public one, in way to have an autonomous control on characteristic data dimension, permission, security and identifiers.

The server structure is organized as follows: a private service contains four different private characteristics for ATC data, sEMG data, control command and threshold value. ATC characteristic has 4 B data dimension in order to include the information of each AFE in the same packet. The sEMG characteristic has a dimension of 20 B, the maximum data size available by RN4020 [17], so to maximize data throughput. The interfacing commands between the user and the acquisition board are stored in the *command* characteristic; the possible operation are *ATC evaluation* of each channel simultaneously, *sEMG acquisition* of one channel at time and *Threshold setting* to setup a different threshold for TC generation. The last characteristic is used for setting the threshold. All the characteristics have an handle as identifier and the ATC and sEMG ones present notification permission, in addition to the read/write one, to send the packet data to the master when new data are available.

An analysis about data throughput in both ATC and sEMG wireless transfer is needed to define the most suitable connection parameters for the application, i.e. *connection interval*, *slave latency* and *connection supervision timeout*, considering that six packets can be transmitted for each connection event. TC data are available every 130 ms for each channel and so its data throughput corresponds to:

$$ATC_{throughput} = ATC_{data,\,4\,Ch} * \frac{1}{ATC_{availability\ time}} = 4\,\mathrm{B} * \frac{1}{0.13\,\mathrm{s}} \simeq 30.7\,{}^{\mathrm{B}}/_{\mathrm{s}}$$

Therefore, the ATC transmission needs $\frac{1}{0.13\,\mathrm{s}} \simeq 7\,{}^{\mathrm{events}}/_{\mathrm{s}}$ to transmit the amount of data, one ATC packet per event, and so we set up the connection interval at 130 ms.

On the other side, the sEMG signal is sampled one channel at time at 1 kHz with 8 bit resolution, obtaining a data rate of $1\,{}^{\mathrm{kB}}/_{\mathrm{s}}$. So, the connection interval parameter have to be changed when the sEMG acquisition is enabled. The new parameter is calculated in agreement with the following formula:

$$\frac{sEMG_{throughput}}{sEMG_{packet\,size}} * \frac{1}{\#packets_{MAX}} = \frac{1\,\mathrm{kB\,s^{-1}}}{20\,\mathrm{B}} * \frac{1}{6\,\mathrm{event}^{-1}} \simeq 8.33\,{}^{\mathrm{event}}/_{\mathrm{s}}$$

that corresponds to an interval of 110 ms, 9 connection events per second and the transmission of 6 packets per event. The connection interval and supervision timeout are set to the value of 0 and 2 s for both the acquisition types.

3 Software System Architecture

The goal of our project, in the FES field, is the control of a commercial stimulator (RehaStim2 by Hasomed®) defining the stimulation pattern as the result of the ATC parameter processing. The device provides a SIMULINK® model to interface the stimulator with the simulation software, which allows precise control of each pulse features. We used MATLAB®, coupled with SIMULINK®, for providing a well-known software environment for the development of ATC-related application. Therefore we developed a Graphical User Interface (GUI) for data processing and inter-systems control. The implemented GUI allows the management of BLE connection and acquisition board, the driving of the RehaStim2 and the monitoring of both acquisition and actuation process by a *multi-threading* approach in order to fulfill the *soft real-time* requirement. Fig. 2 (bottom) shows the proposed GUI during the active stimulation: on the graph is plotted the amplitude of FES pulses modulated by the value of the ATC parameter.

4 Performance and Discussion

In conclusion, we perform some analyses regarding the power consumption of the acquisition board, and the soft real time performance of the system.

We measured the acquisition board consumption (4 AFE and 1 MCU) of 5.126 mW using LPM. Considering also the wireless transmission we measured the value of 20.23 mW and 23.47 mW for TC and sEMG transmission. The advantage of the event approach is easily valuable, with the same energy dissipation, considering the transmission of four AFE TC information instead of a single sEMG one.

The time performance are evaluated in terms of delay between the muscle contraction and stimulation initialization, using an articular goniometer to trigger a timer when a movement is detected. We measured a mean time of 774.5 ms: this relatively high value for a real-time application is related to the use of the BLE protocol, which is not completely suited for event-driven transmission, and to the employed software that will be replaced by an embedded computing system in future.

5 Conclusion

In this paper we present a framework for the acquisition and processing of the sEMG signal, based on the ATC event-driven approach. We designed and tested the interfacing of event data with a microcontroller and a standard BLE transmission, obtaining good result in terms of firmware complexity and power consumption w.r.t. the standard bio-signal acquisition approach. As sample application, we employed such system for the control of a FES stimulator: we developed a multi-threading GUI for the management of MATLAB® and SIMULINK® soft real-time ATC-processing system.

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