A Bio-Inspired Processing Unit for Surface Electromyography Applications

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Device wearability and operating time are trending topics in recent state-of-art works on surface ElectroMyoGraphic (sEMG) muscle monitoring. No optimal trade-off, able to concurrently address the several problems of the acquisition system like robustness, miniaturization, versatility, and power efficiency, has yet been found. This thesis aims to present a feasible solution to overcome most of these issues, embedding in a single device both an sEMG acquisition channel, exploiting the custom event-driven hardware feature extraction technique (named Average Threshold Crossing - ATC), and a digital part, which includes a microcontroller unit, for (optionally) sEMG sampling and processing, and a Bluetooth communication, for wireless data transmission.

The combination of the design paradigms with an accurate selection of each single component results in a very efficient prototype, with a comfortable final size of 57.8 mm length × 25.2 mm height × 22.1 mm width and a weight of 27.4 g (rechargeable battery included), perfectly suitable to be worn without impacting the freedom of movement. It features a consistent signal-to-noise ratio of the acquired sEMG (higher than 15 dB) tested on various sessions, from static isometric standardized exercises to dynamic contraction (e.g., human gait). Furthermore, a precise design of the firmware has been performed, handling both signals acquisition and Bluetooth transmission concurrently, thanks to a custom implementation of the FreeRTOS kernel. In particular, the system adapts to both sEMG and ATC transmission, with an application throughput up to $2\,\mathrm{kB\,s^{-1}}$ and an average operating time of 80 h (for high resolution sEMG sampling), relaxable to $8\,\mathrm{B\,s^{-1}}$ throughput and about 230 h operating time (considering a 110 mAh battery), in case of ATC acquisition only.

Its application in building biomedical systems led to very promising results. In the active control of the Functional Electrical Stimulation (FES), a good similarity (above 85 %) has been obtained in replicating voluntary and stimulated movements during simulated therapist-patient rehabilitative sessions, also achieving the ATC-FES pulses pattern definition within 10 ms, largely satisfying the typical 300 ms real-time constraint for bio-medical data processing. For Human-Machine Interface (HMI) applications, seven units have been arranged to create an armband, to be worn around the forearm, able to recognize 9 hand gestures by using an embedded Artificial Neural Network (ANN) classifier, which, combining an accuracy of 91.6 %, a minimal prediction latency of 1.49 ms, and limited power consumption of 10.8 mW, allows the device to run unaltered for up to 60 h.

The following paragraphs report the organization of the Ph.D. thesis manuscript:

- **Chapter 1 (Introduction)**: This first chapter reports the background information to provide the reader with adequate comprehension of the work described in the following parts. It starts with an introduction to the anatomy and physiology of the neuro-muscular system,

then moves to the theory of the generation of the sEMG signal and the standard acquisition and processing techniques. After a summary of the commercial sEMG acquisition systems and their limitations, the last section presents the ATC technique (and the three design paradigms), focusing both on the theoretical aspects and the related state-of-the-art works.

- **Chapter 2 (Event-based sEMG Acquisition Node Design)**: This chapter aims to provide the reader the design rules and the electronics circuits for the realization of an event-based acquisition and processing system suitable for sEMG. The first section analyzes the fundamental aspects for the development of such a system, starting with a discussion about the different methodologies for sEMG processing to be coupled with the selected design paradigms, and ending with the definition of the complete framework. The second section describes in details, one block at a time, the analog circuits for conditioning the raw sEMG signal and for extracting the quasi-digital TC signal. Thereafter, the last section completes the design of the acquisition node by interfacing the analog chain with the digital part, clarifying the main routines of the firmware and giving the specifics for wireless connectivity.

- **Chapter 3 (Launching the Prototype: The *Apollux*)**: This chapter reports all the phases starting from the physical realization of the ATC board prototype to the final wearable device. The first section quickly presents the physical design of the Printed Circuit Board (PCB) to provide an overview of the arrangement of each component between the layers of the structure. Then, the second section guides the reader through the 3D project for the design and print of the wearable case for the Apollux device. In conclusion, last section describes the implementation of the software which, also featuring a Graphical User Interface (GUI), allows a user to efficiently interact with the system used during the functional operation.

- **Chapter 4 (Apollux - Testing Performance**: After the complete integration of the hardware, firmware, and software functionalities, this chapter reports the validation tests carried out to analyze the performance of the system. It has been analyzed firstly by assessing the quality of the detected sEMG signals in terms of signal-to-noise ratio and frequency response, then evaluating the correctness of the ATC extraction. A reliability analysis compares the Apollux prototype with a gold standard device in order to evaluate the consistency of the measurements. An in-depth power consumption analysis, along with a discussion of the operating time w.r.t. the acquisition mode, concludes the experimental parts. The last section reports a final comparison between the Apollux device and the current academic and industrial solutions, highlighting the similarity and advantages of the proposed design and discussing its applicability in the sEMG scenario.

- **Chapter 5 (Application - Control of Functional Electrical Stimulation**: The *Apollux* boards have been employed to build a bio-mimetic system for the control of FES therapy. After an initial introduction of the proposed functionalities, the architecture of the system and the control mechanism are explained. The validation analysis includes both the offline tests to assess the real-time and reliable processing of the ATC data to define the FES profile and the experimental campaign conducted to study the system performance during simulated therapist-patient rehabilitative sessions. The last section reports a brief comparison about the developed system and the state-of-the-art ones.

- **Chapter 6 (Application - Hand Gesture Recognition**: The second application in which the *Apollux* device have been tested is the recognition of hand movements. The first section introduces the background studies investigating the ATC as input features for hand gesture classification. The following two sections report two minimal setups (based on the Apollux units) to achieved ATC-HMI interfaces with three or more degrees of freedom; then, the fourth section (the longest one) describes in details all the designing and prototyping phases for the realization of an armband, also focusing on its experimental validation and discussing its pros and cons w.r.t. similar state-of-the-art works.

- **Chapter 7 (Conclusions)**: This last chapter summarizes the outcomes of this Ph.D. project, retracing step-by-step all the design phases and the biomedical applications for the proposed *Apollux* boards. The chapter concludes with a personal analysis of the advantages and limitations of the ATC technique, also providing the indications for future directions.