Doctoral Dissertation
Doctoral Program in Electrical, Electronics and Communications Engineering
(36th cycle)

Bio-inspired sEMG-based embedded systems for human-machine interactions

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Summary

The modern technology landscape is fiercely competitive, driven by advancements in power efficiency and miniaturization. These innovations have transformed embedded systems, increasing the popularity of high-performance, compact smart devices. Efforts to enhance computational capabilities while reducing device size have enabled applications in human-machine interactions. Gesture recognition technology, relying on precise data acquisition, is used in fields such as unlocking mobile devices, controlling video games, and managing prosthetic limbs. In biomedical applications, surface electromyography (sEMG) is the dominant method, using non-invasive electrodes to record muscle activity. Typically, machine learning algorithms such as Support Vector Machines (SVM) or Artificial Neural Networks (ANN) are then used for gesture recognition. However, transmitting sEMG signals for processing on an external unit can significantly increase power consumption, and developing machine learning algorithms at the edge requires computational resources and memory space, thus posing a challenge for wearable devices.

This doctoral dissertation focuses on developing a bio-inspired sEMG-based acquisition node, the Apollux, and its application as part of different embedded systems in various fields, such as diagnostics, rehabilitation, and assistive technologies. The key innovative concept is the integration in such devices of the Average Threshold Crossing (ATC) technique, which is applied to the sEMG signal to extract in hardware an event-driven feature positively correlated with the exerted force. Thus, it can drastically decrease the computational effort required on-board and the necessary transmission throughput, providing a longer operating time for the final applications.

The Apollux devices, other than implementing the ATC hardware extraction process in the analog sEMG acquisition chain, are equipped with several digital components to connect with other devices and systems. The core of the digital part is the Apollo3 Blue MCU, which enables wireless data transmission thanks to the embedded Bluetooth Low Energy antenna. As detailed in Chapter 2, the developing process included several validation procedures, resulting in an sEMG signal with a satisfying 15 dB signal-to-noise ratio. Moreover, exploiting the low-power nature of the ATC technique, the device demonstrated its capability to transmit data continuously for up to 230 h. Other releases

followed the first prototype, further enhancing the device's functionalities and aiming toward a patchable solution for everyday usage.

Wiring together seven Apollux devices, a wearable armband for hand gesture recognition is subsequently developed, as described in Chapter 3. The armband, to be worn on the proximal 1/3 of the forearm, can classify eight hand gestures with 91.93 % average gesture accuracy thanks to the embedded fully connected ANN. The system's operating time, with only one battery involved, is estimated at 60 h. After the first system validation, an automatic orientation routine was developed, allowing for the random wearing of the armband and bringing the accuracy up to 93.36 %.

Then, in Chapter 4, the design of a modular system for facial expression recognition is reported. Starting from a rudimental version involving commercial acquisition devices, the system evolves until the final wearable prototype. This device comprises five active probes for the first amplification stage of the sEMG, a main board containing the second amplification and the digital part (like for the Apollux design), and a headset. By placing the probes directly on the facial muscles of interest, a 93.95 % average accuracy is obtained while recognizing eleven different expressions.

As summarized in Chapter 5, the developed systems are all suitable for continuous operations, recognizing inputs from impaired people and monitoring their muscular wellness, thus improving everyday life.