Doctoral Dissertation

Doctoral Program in Electrical, Electronics and Communications Engineering (37^{th} cycle)

Robust and Adaptive Control for Upper Limb Prostheses via Enhanced Human-Machine Interface

By

Dario Di Domenico

******

Supervisors:
Prof. Marcello Chiaberge (Politecnico di Torino)
Ing. Nicolò Boccardo (Istituto Italiano di Tecnologia)
Dr. Marianna Semprini (Istituto Italiano di Tecnologia)

Doctoral Examination Committee:
Prof. Kia Nazarpour, Referee, University of Edinburgh
Prof. Ivan Vujaklija, Referee, Aalto University

Politecnico di Torino
2025

Robust and Adaptive Control for Upper Limb Prostheses via Enhanced Human-Machine Interface

Dario Di Domenico

Human interaction with the environment relies on dexterous hand and upper limb movements, enabled by the coordinated synergy of multiple muscle groups. The loss of an upper limb disrupts essential functions, complicates daily activities, and diminishes quality of life. Traditional prostheses, while beneficial in partially restoring lost abilities, often fall short due to limited functionality and challenging control schemes, leading to high abandonment rates. Myoelectric prostheses, which use muscle signals detected via sensors for the actuation of the electric motors, have helped in partially restoring lost functionalities. However, achieving truly intuitive control remains difficult, as users continue to experience barriers to perceive such devices as part of their body. Recent advances in robotics and artificial intelligence have accelerated the development of sophisticated, multi-actuated prosthetic devices, designed to mimic complex human hand movements with increasing fidelity. Machine learning (ML) has emerged as a promising tool to enhance control of these devices, improving the prediction of upper limb movements based on electromyographic (EMG) signals, i.e., myocontrol. Despite this, practical applications are limited by input signal variability, also known as data distribution shift, which can degrade performance and hinder clinical adoption of ML-based prosthetic control. This doctoral research investigates how to robustly decode human gestures for controlling upper limb prosthetic devices with multiple actuated degrees of freedom. Specifically, my work focused on expanding the sources of biological data, as well as on exploring new ML-based techniques for upper limb prosthetic control. To this end, I have designed and validated a high-density surface electromyography (HD-sEMG) socket that captures detailed muscle activity across the forearm through 64 dry electrodes. This innovative setup, arranged for maximum coverage and user comfort, provides an enriched stream of data that enhances gesture recognition and remains practical for daily wear, with an easy donning and doffing procedure. The novel HD-sEMG system can be integrated into standard prosthetic devices, replacing existing acquisition interfaces without altering the current manufacturing process. Exploiting this setup, I have addressed the challenge of EMG signal non-stationarity by incorporating incremental learning strategies. I have applied ML models that can adapt to new data in real time, reducing performance degradation over extended use. These adaptive control models not only handle EMG signal variability over time but also foster a more dynamic interaction between user and device. Furthermore, using a deep learning model, I was able to decode

up to ten upper limb gestures through the HD-sEMG setup, enabling real-time prosthetic myocontrol. Finally, I have explored how the control commands are generated for driving the prosthetic joints, thus comparing position-based control with velocity-based control to determine which technique provides a more intuitive and responsive user experience. To assess the validity of these methods for real life applications, they have been evaluated in real-time on both able-bodied individuals and those with limb differences, through virtual reality and physical tests on the Hannes prosthesis, including the Target Achievement Control test and clinical evaluations. An important outcome of my work for the scientific community is the public release of datasets generated from my work, which offer a valuable benchmark to support future advancements in prosthetic control research. In summary, by developing a practical, wearable interface that enables robust, real-time gesture decoding, and by leveraging incremental and deep learning algorithms, this thesis significantly contributes to upper limb prosthetic control.