Assembly and control system implementation of an Upper-limb exoskeleton [EduExo Pro]

Scientific work within the Ingenieurspraxis
from the Department of Electrical and Computer Engineering at the
Technical University of Munich.

Supervised by	Univ.-Prof. Dr.-Ing. Sandra Hirche M. Sc. Severin Beger Chair of Information-Oriented Control
Submitted by	Ahmed Aziz Jouili Connollystr. 3 80809 Munich
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Abstract

This engineering practice aimed to explore and evaluate different control systems for an upper-limb exoskeleton. We focused on three specific control systems: EMG control, which utilized electromyography signals for direct user-device interface; an expanded EMG control system incorporating multiple EMG signals from opposing muscles for enhanced understanding of user intentions; and the implementation of an admittance control system to regulate human-exoskeleton interaction force. Additionally, a wireless interface was developed to enable the command and control of the exoskeleton remotely. Moreover, a C++ library was developed for simplified application and further development of the exoskeleton. Through experimentation and analysis, the strengths and limitations of each control system were identified.

Contents

Chapter 1

Introduction

In the field of assistive technology for the upper-limb, wearable robotics has been one of the main focus for several research groups in the last thirty-five years. [PAPM22] The exoskeleton is an electromechanical structure worn by operator and matching the shape and functions of human body. It is able to augment the ability of human limb and/or to treat muscles, joints, or skeletal parts which are weak, ineffective or injured because of a disease or a neurological condition. Moreover, it merges the machine power and the human intelligence in order to enhance the intelligence of the machine and to power the operator. The exoskeleton works mechanically in parallel with human body and can be actuated passively and or actively [AG22].

Figure 1.1: EduExo Pro kit
[https://www.auxivo.com/product-page/eduexo-pro]

1.1 Goal of the project

The aim of this project was to put the EduExo Pro into operation and explore its possibilities. This includes the mechanical assembly and setting up the electronics of the device. Furthermore, developing the software for the EduExo Pro [1] was a crucial task included in this project. It included building a code basis for the given processor, an Arduino Nano, to take the device quickly into operation. Additionally, we were tasked with developing and implementing intention-driven control systems. A wireless interface was developed to control the exoskeleton over a network. Finally, the experimental evaluation involved mechanical and electrical assessments, communication analysis and control implementation as well as identifying the limitations of the device. The purpose of the EduExo Pro is to about exoskeletons and their development which will be discussed in more details in next chapters.

1.2 Work plan

Familiarization with the device and setup

1. familiarize with exoskeleton design and its control
2. mechanical setup of the EduExo Pro for the right arm and related functional tests
3. electrical setup including wiring and soldering of electronic components

Software development for the EduExo Pro

1. building a code basis for Arduino Nano
2. commissioning of the installed components (servo motor, torque sensor, Arduino Nano, EMG sensor)
3. development of a preliminary, passive-supporting control system
4. development of an intention-driven control system
5. development of a wireless interface to the exoskeleton's micro-controller for control over a network
6. development of a control system over a network connection

[1] EduExo Pro is a robotic exoskeleton kit for the arm. It consists of pre-fabricated mechanical components and electronic parts such as an Arduino Nano 33 IoT, a servo motor, a Force sensor, and an EMG sensor. A handbook is available to guide through the process of assembling and programming the exoskeleton. Its purpose is to teach about exoskeletons and their development.

Experimental evaluation of the device

1. Mechanical evaluation
2. Electrical evaluation
3. Communication evaluation
4. Control evaluation

Chapter 2

Device setup

2.1 Mechanical setup

2.1.1 Overview EduExo Pro Hardware

The EduExo Pro is an arm exoskeleton spanning the shoulder and elbow joint. A textile vest attaches the exoskeleton to the upper body. In the back, the attachment of the shoulder piece is adjustable such that you can align the EduExo shoulder joint with the shoulder joint of the user. The EduExo Pro shoulder joint has 2 degrees of freedom (DoF).

Figure 2.1: EduExo Pro
[https://www.auxivo.com/eduexo-pro]

The first is the shoulder rotation joint, which allows the internal and external rotation. This joint is a simple passive joint without any motor or spring support, and it is implemented with pre-assembled ball bearings. The second DoF is a hinge joint that allows you to flex and extend your arm. This joint has an integrated rotational spring that can be pre-tensioned during assembly to provide support when lifting your arm. We can adjust the size of the upper arm segment to align with the elbow joint. Almost all the electronics parts and the batteries are integrated into the upper arm segment underneath a cover.
A cuff connects the upper arm to the upper arm segment of the EduExo Pro. The elbow joint has an integrated servo motor that actively supports the elbow movements. To measure the human-exoskeleton interaction forces, a force sensor is provided in the forearm segment. A second cuff connects the forearm to the EduExo Pro. The mechanical setup of the EduExo Pro involved assembling the mechanical components such as a torsion spring, shafts, covers and arm cuffs to build the exoskeleton for the right arm.

2.1.2 Assembly

The base components, carrying the load, are made of steel sheet metal. They have slots with corresponding sliding blocks to adjust the points of rotation of the device to the user. The cover for the electronics is a 3D-printed part with inserted threads for fixation. We began by carefully reading and following the assembly instructions and guidelines in the handbook, which described exactly how to assemble the exoskeleton. This involved screwing and connecting parts together using wrenches, screwdrivers, pliers and many other tools. Following, we performed a preliminary mechanical test to ensure that the exoskeleton was functional and correctly aligned with the user's arm. This involved manually moving the exoskeleton through a range of motion and checking for any malfunctions, such as ensuring that the spring stretches and releases properly to assist the movement. We also checked for proper fit and comfort for the user.

2.2 Electrical Setup

2.2.1 Overview of the Electronic Components

Microcontroller : Arduino Nano 33 IoT

The Arduino Nano 33 IoT is a compact microcontroller board designed for IoT projects that require wireless connectivity. It features WiFi and Bluetooth Low Energy connectivity, a 6-axis IMU, and various analog and digital I/O pins. In this project, the Arduino Nano 33 IoT was used to control and interface with the sensors and the servo motor of the exoskeleton. The microcontroller's compact size and low power consumption made it suitable for integration into the exoskeleton design.

The Arduino Nano 33 IoT board offers a range of features suitable for various applications, including real-time applications. When it comes to real-time applications, two important factors to consider are the maximum sample rate and usability of the board. In terms of the maximum sample rate, the Arduino Nano 33 IoT is equipped with a powerful microcontroller, the SAMD21 Cortex-M0+, which operates at a clock speed of 48 MHz. This enables the board to handle data acquisition and processing tasks at a relatively high rate.

Servo motor and Angle Sensor

The servomotor in the arm exoskeleton serves as both an actuator and an angle sensor. To control the servomotor's position, it is connected to a PWM (Pulse Width Modulation) pin of the microcontroller, which sends PWM-encoded angles to the servo's integrated position controller. With the standard Arduino library, we can only control the position of the servomotor and not its speed or force. The position control is always executed at maximum speed or torque, which is approximately 5 Nm. Additionally, we have the option to control the position either in the degree range or by specifying the duration in microseconds. The output of the potentiometer will be connected to an analog input pin of the arduino to measure the joint angle and displaying a value betweeen 0 and 1023 (10 bit resolution). With these two features, we can precisely control the position of the servo motor by sending values to the servo and reading out the joint angle.

Force Sensor

The force sensor measures the interaction force between the exoskeleton and the human. The force sensor is a piece of metal with some special resistors called strain gauges glued onto it. Strain gauges change their resistance when they are deformed. When a force is applied, the metal deforms slightly, causing a change in the electric resistance. The force sensor is electrically connected with a Wheatstone bridge, an amplifier and then to the Arduino that reads the amplified signal.

EMG sensor

The EMG sensor is a wearable device that measures muscle activity by detecting the electrical signals produced by the muscle contractions. It allows the detection and analysis of variations in muscle contractions. It consists of a circuit board with an amplifier and filters, as well as electrodes that are placed on the skin on the muscle. It is connected to an analog pin of the arduino and display signal ranging from 0 to 1023 (10 bit resolution).

2.2.2 Connection of the Electronic Circuit

We began by preparing the necessary cables and connectors for each component, following the handbook to ensure the correct size and type of cable was used for each component. We then proceeded to connect and solder the components to the prototyping board. When all the components were connected, we used simple Arduino codes to test each component individually, immediately after it was attached, to check that it was well connected and wired. This allowed us to detect wiring or connection errors early in the assembly process. These codes involved sending basic commands to each component through the Arduino, such as turning on a motor, reading data from a sensor, switching on an LED or checking that the buttons work. We observed the function of each component and checked for any errors in its operation.

Chapter 3

Software development

3.1 Commissioning of the components

In this section, we have used short Arduino programs to test the interaction between the sensors and the servo, verifying that the system was functioning as expected. Overall, this process of experimenting with simple codes and calibrating the sensors was essential to ensuring the correct functionality and performance of the system.

3.1.1 Calibration of Angle sensor

We calibrated the Angle sensor integrated into the servo motor so that instead of an analog signal with a 10-bit resolution, we get an angle in degrees using the linear interpolation equation :

$$y = y_{min} + (x - x_{min}) \cdot \frac{(y_{max} - y_{min})}{x_{max} - x_{min}} \tag{3.1}$$

to come up with the joint angle as a function of the sensor value :

$$\varphi_{elbow} = \frac{(\varphi_{90} - \varphi_0)}{(s_{90} - s_0)} \cdot (s_{elbow} - s_0) + \varphi_0 \tag{3.2}$$

In our testing, the parameters were $s_0 = 938$, $s_{90} = 526$, $\varphi_0 = 0$, $\varphi_{90} = 90$

3.1.2 Calibration of the force sensor

Similar to the angle sensor, we aim for the measured values to be more intuitive rather than being represented as a 10-bit value. To do so, we start by subtracting the offset value which is the measurement of the sensor when no force is applied.

$$\mathrm{F}_{calibrated} = \mathrm{F}_{is} - \mathrm{F}_{offset} \tag{3.3}$$

After the calibration, we can see that the force signal changes sign when we apply forces in opposite directions. With the help of some known weights, we were able to calibrate the force sensor to calculate the actual force in Newton applied to the arm. This was done by applying a known force through attaching a known weight and measuring the sensor value. The measurements could then be used for a correlating function between force and sensor signal. For this to be valid we assumed the sensor to behave linearly.

3.2 Development of a passive support system

A passive controller was incorporated by introducing a spring in the shoulder joint. This passive support mechanism aimed to enhance arm stabilization and reduce the required exertion for movement. The spring acted as a counter-force, opposing the arm's motion and providing resistance. Additionally, we can preload the spring, allowing us to customize the amount of resistance provided.

3.3 Development of intention-driven control systems

The development of a control concept for the exoskeleton is essential in order to enable precise and coordinated movements that align with the user's intentions. By implementing a control system, the exoskeleton can interpret and respond to the desired actions of the user.

3.3.1 EMG sensor controller

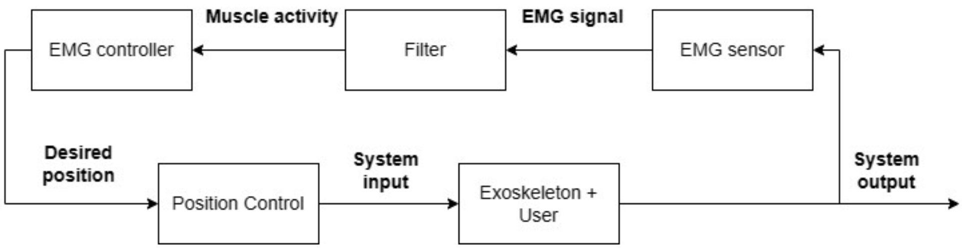

Figure 3.1: EMG controller

The proposed control system begins by reading signals from the EMG sensor placed on the biceps muscle. The EMG data, which has been rectified and low-pass filtered, is still too noisy to be used directly. Therefore, we implemented a moving average filter to smooth the signal. Moving average filters, despite introducing a delay in the output signal that can impact timing and synchronization in real-time applications, have been found to be beneficial for dealing with noisy EMG signals.
The EMG signals are then mapped to an angle between 0 and 100 degrees to predict the user's intentions. Parallely, the actual position of the exoskeleton is measured,

and the controller ensures that the new desired position falls within the predetermined range of maximum and minimum angle thresholds (between 0 and 100 degrees) to ensure the user's safety. If the angle limits are not exceeded, the servo motor is activated to move the exoskeleton to the desired position and waits until the servo reachs the desired position before doing the next iteration. (see Figure 3.1) Figure 3.2 represents the recorded EMG over time while testing with the EMG sensor.

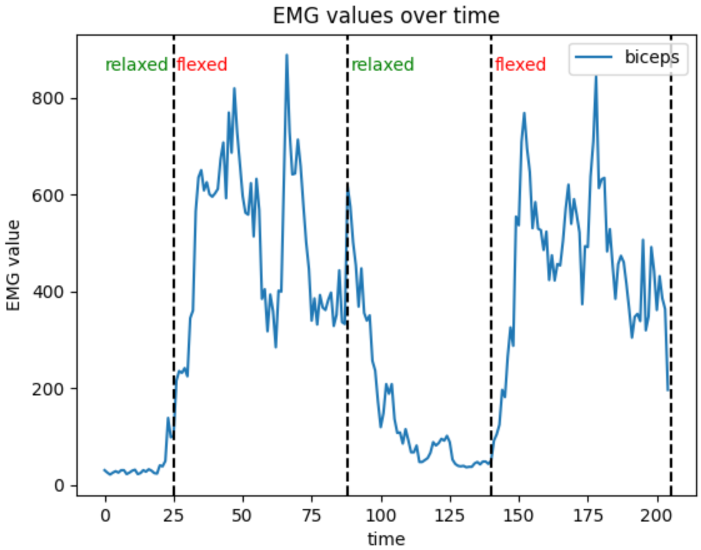

Figure 3.2: EMG signals

3.3.2 Extension of the EMG controller

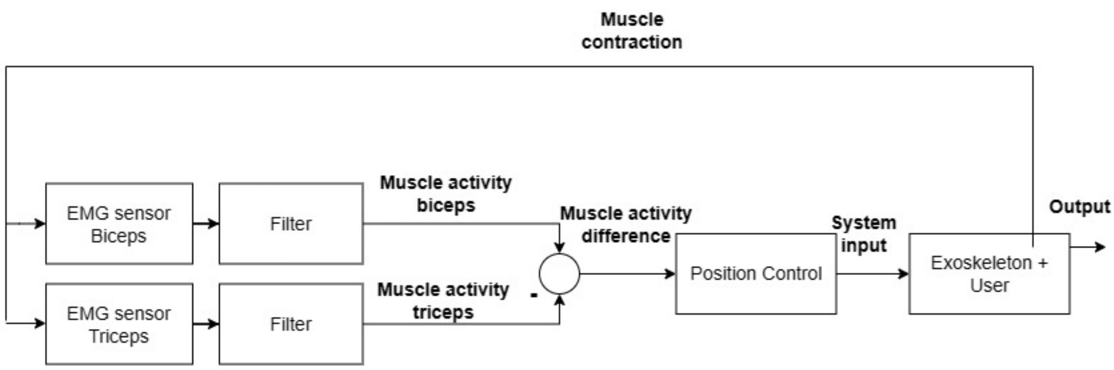

Figure 3.3: 2-EMG controller

The controller for this system involves measuring the activity of two opposing mus-

cles, the biceps, and triceps. The first step is filtering the EMG signals with a moving average filter. Two muscle activity measurements are taken, filtered and then compared to determine which muscle is more active. (see Figure 3.3)
If the signal from the biceps is found to be greater than that of the triceps by a certain determined value, then the servomotor is moved 5 degrees in a positive direction. Conversely, if the triceps signal is greater by a certain determined value, then the servomotor is moved 5 degrees in the opposite direction (this was an arbitary choice, after testing with different values, we found it to to be the best value). It is important to ensure that the angles of the servomotor remain within the range of 0 to 100 degrees to ensure the safety of the user preventing hyperflexion of overextension of the arm. If both muscles are activated simultaneously and the difference between the two signals does not exceed the threshold, then no action is taken. When this controller is implemented in a loop, continuously processing the EMG signals, it effectively translates the user's intentions for arm movement. Figure 3.4 represents the recorded EMG signals over time while testing with 2 EMG sensors.

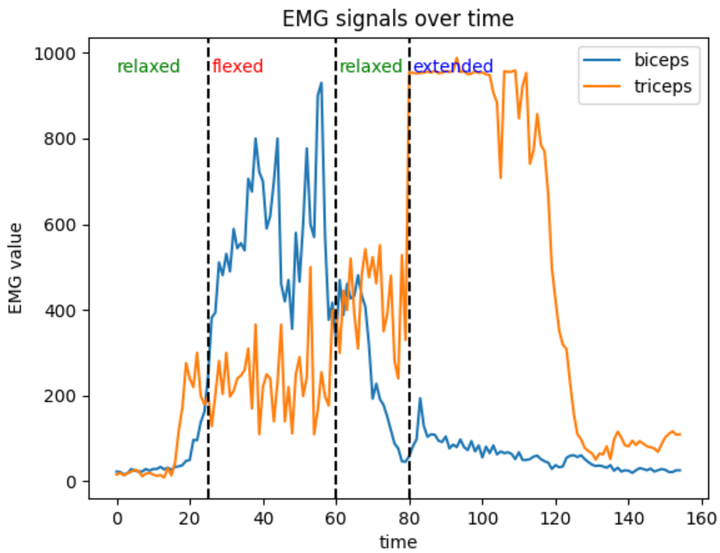

Figure 3.4: EMG signals

3.3.3 Force sensor controller (Admittance Controller)

Besides the position and the torque/force, the interaction force between human and the exoskeleton are considered in the exoskeleton robot. The interaction force controller is applied as the high-level controller. The main goal is to provide proper help for the users in performing a task so that the force of human-exoskeleton interaction goes to zero. The interaction force can be controlled by either the impedance controller or the admittance controller. [AAA12] This controller involves measuring

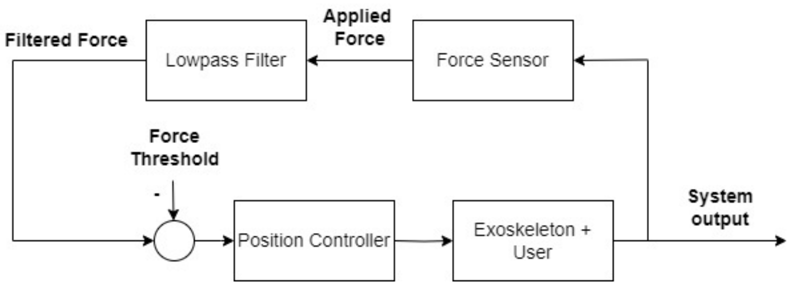

Figure 3.5: Admittance controller

the interaction force applied to the forearm of the exoskeleton using a force sensor and the controller adjusts the position of the servo motor to counteract this force accordingly. (see Figure 3.5)

$$F_{\text{filtered}}(t) = (1 - \alpha) \cdot F_{\text{is}}(t) + \alpha \cdot F_{\text{filtered}}(t - 1) \tag{3.4}$$

The force reading from the sensor is first filtered using a low-pass filter and then compared to a desired force. If the absolute value of the force exceeds the desired force by a given threshold, the controller calculates the new desired position using a proportional gain to reduce the force applied to the forearm of the exoskeleton. The proportional gain was manually tuned.

$$q_d = q_{\text{is}} - K_d \cdot (F_{\text{filtered}} - F_d) \tag{3.5}$$

Where q_d is the desired position, q_{is} is the actual position, K_d is the proportional gain, $F_{filtered}$ is the filtered force value and F_d is the desired force.
The controller also limits the servo angle between a maximum angle and a minimum angle that are pre-determined in our case it is between 0 and 100 degrees which corresponds to the flexion and extension of the arm. Figure 3.6 represents the recorded force signals over time while testing with the force sensor.

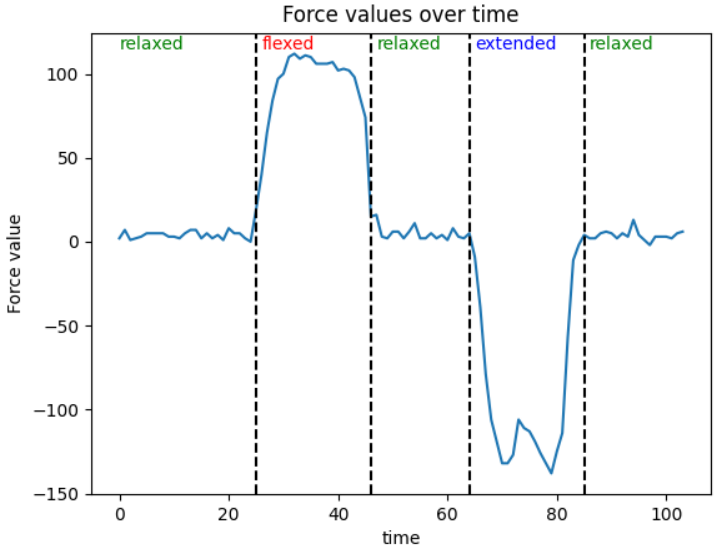

Figure 3.6: Force sensor signals

3.4 Connectivity via WiFi and BLE

The network connectivity played a crucial role in enabling wireless communication between the Arduino and external devices. The Arduino Nano 33 IoT was equipped with both WiFi and Bluetooth Low Energy (BLE) capabilities, providing versatile options for data transmission and control.

Initially, the focus was on establishing a reliable connection between the Arduino and a remote device using WiFi and BLE. Through WiFi and BLE connectivity, we transmitted wirelessly sensor readings and other relevant data. This wireless data transfer eliminated the need for physical connections, enhancing the flexibility and mobility of the exoskeleton system.

We also implemented a BLE control which provided a user-friendly interface for commanding the exoskeleton's movements. By simply sending the appropriate command via BLE, using the LightBlue smartphone aplication, the Arduino executed the corresponding function, which was implemented in a code file enabling a convenient control over the exoskeleton's actions.

Furthermore, we have successfully implemented a network-based control system using WiFi. The process involves transmitting sensor values wirelessly from the Arduino to a computer running MATLAB. Within MATLAB, we have developed an admittance control system, determines the desired servo position based on the sensor values. Additionally, we have also calculated the computation times using WiFi for communication in each iteration.

Overall, the integration of WiFi and BLE connectivity in the arm exoskeleton system facilitated wireless data transfer and enhanced control capabilities. This connectivity opens up possibilities for further advancements in the field of exoskeleton robotics, enabling improved user experiences and expanding the potential applications of such assistive technologies.

Chapter 4

Experimental device evaluation

4.1 Mechanical difficulties and limitations

The exoskeleton has several limitations that can affect the mobility and the comfort of the user. The device can restrict movement, particularly for lateral shoulder raises, which are intentionally neglected and thus blocked by the given design. The design of the system has intentionally been kept simple to ensure its accessibility to a wide range of students and researchers. However, it is important to note that further optimizations and enhancements can be made to adapt the system for medical applications. Additionally, aligning the exoskeleton with the arm and shoulder is also challenging, requiring the user to unscrew and re-screw the device to make adjustments. Furthermore, aligning the exoskeleton joint with the user's elbow is limited, and those with long arms may encounter difficulties with this process. The exoskeleton is not easy to don alone and for a satisfactory alignment of the device the user needs help from a second person.

The force that the motor generates is limited by its size and the power. The actuator won't be able to provide the force needed to lift something heavy. The vest is a little bit too tight. It is not comfortable for a long time use and it does not fit a user with overweight.

4.2 Electrical difficulties and limitations

4.2.1 EMG sensor

Cross-talk

EMG signals from adjacent muscles can interfere with each other, which makes measurement of a single muscle activity unfeasible.

Sensitivity to movement artifacts

EMG sensors are sensitive to movement artifacts, such as noise caused by the motion of the skin or the position of the sensor. These artifacts can interfere with the accuracy of the sensor, making it challenging to differentiate between muscle activity and noise. Also, the EMG will most likely be placed on a different position on the arm, every time it is worn.

User variability

EMG signals can vary significantly between individuals, depending on many factors such as muscle size, placement of the sensor and body fat percentage. This can make it challenging to compare data between different individuals or to create generalized models.

Limited signal interpretation

The EMG sensor reacts only to variations in the muscle. When a continuous force is applied from the user without moving the arm or with moving it in a constant velocity, no significant signal will be measured. For example, when flexing the biceps we detect an increase in the signal but when maintaining the biceps flexed and force exerted, the signal will decrease significantly.

4.2.2 Power supply

When powering the Arduino and servo motor with the same power supply, a voltage drop occurs due to the high current draw of the servo motor, particularly when it is moving quickly or under heavy loads. This results in the voltage dropping, and causing the Arduino to reset. When the program is restarted, it changes back to a starting position, because the Arduino has no permanent memory (EEPROM). To prevent this problem, it is recommended to use a separate power supply for the servo motor and the Arduino.

Chapter 5

Conclusion

In conclusion, the engineering practice has provided valuable insights and practical experience in the field of exoskeleton robotics. Throughout the engineering practice, three control systems were developed and evaluated:
The EMG control system demonstrated the potential of using EMG signals as a control input for exoskeletons, providing a direct interface between the user and the device. Expanding upon the EMG control, the second control system introduced the measurement of two opposing muscles, the biceps, and triceps. The integration of multiple EMG signals provided a comprehensive understanding of the user's intentions and improved the overall performance of the exoskeleton. Additionally, the implementation of the admittance control system offered a different approach to controlling the interaction force between the user and the exoskeleton. The admittance control system aimed to reduce the force of human-exoskeleton interaction.
Overall, the engineering practice has highlighted the importance of control system design and implementation in the development of arm exoskeletons. Each control system has its own strengths and limitations, and further research and optimization are necessary to fully unlock the potential of exoskeleton technology.[PCRBJ16]

List of Figures

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