R&D Project Report :
Development of upper limbs active Exoskeleton

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R&D Project - ROB5

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1 Description of the Project

In France and worldwide, musculoskeletal disorders (MSDs) represent the leading cause of work-related morbidity and the primary reason for compensated occupational diseases, accounting for 88% of such cases. Among professional workers in 2021 (Assurance Maladie - Occupational Risks data), the distribution of compensated MSDs reveals that shoulders are affected in 38% of cases, wrists/hands/fingers in 36%, elbows in 25%, and knees in 1%. These disorders not only rank as the **most recognized occupational illness** but also generate **substantial financial costs** for businesses and society alike.

In response to this growing concern, the objective of this R&D project was to design and develop a functional **exoskeleton** prototype capable of enhancing human capabilities through **mechanical assistance** and biofeedback integration. An exoskeleton is a wearable device that supports and augments the user's movements, providing additional strength, endurance, or precision. By creating a lightweight, ergonomic, and efficient solution, this project aimed to address applications ranging from rehabilitation and industrial work to personal mobility enhancement.

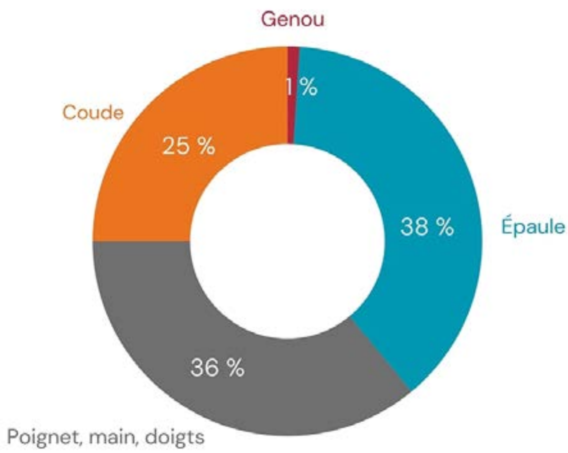

Figure 1.1: Distribution of MSDs in France in 2021 (Source: AMELI)

2 State of the Art

Currently, the exoskeleton market for upper limb assistance remains remarkably underdeveloped compared to lower limb solutions. The existing commercial products present several significant limitations:

- **Scarcity of Solutions**: Upper limb exoskeletons are considerably rarer than their lower limb counterparts, with only a handful of manufacturers offering viable products for industrial or rehabilitation applications.
- **Limited Assistance Capacity**: Most available upper limb exoskeletons provide minimal support, typically capped at approximately **1.5 kg** of assistance force. This limitation severely restricts their effectiveness for tasks requiring sustained arm elevation or handling of heavier loads.
- **Passive Assistance Mechanisms**: The vast majority of current solutions rely on **constant force mechanisms** such as springs or gas-loaded systems. While mechanically simple and reliable, these passive approaches present a fundamental drawback: they cannot adapt to the user's movements or varying task requirements. The assistance provided remains static regardless of the arm position, movement speed, or actual load being handled.
- **Lack of User Adaptation**: Without active sensing and control systems, these exoskeletons cannot modulate their support based on real-time user needs, muscular fatigue, or different working scenarios. This results in suboptimal assistance that may even hinder natural movement patterns in certain positions.

These limitations highlight the need for a new generation of **active, adaptive exoskeletons** that can dynamically adjust assistance levels based on user intent, detected through biofeedback systems such as EMG sensors, and real-time positional feedback. This R&D project aims to address these gaps by developing a prototype that integrates electronic control, motor-driven actuation, and user-responsive algorithms.

Figure 2.1: Examples of passive upper limb exoskeletons currently available on the market (Source: Ekso Bionics, Levitate Technologies)

3 Mechanical Design

The mechanical design of the exoskeleton prototype started in 2022 for an academic project that Loïc LEROY participated in. The initial concept [v1.0] focused on the assistance of elbow flexion/extension movements, which are common in various industrial tasks. Due to time constraints and resource limitations, the first version utilized off-the-shelf components, including a **DC motor with three-stage planetary gearbox** for actuation, driven by a simple H-bridge driver, and **3D-printed parts** for the frame with custom fittings. This approach allowed for rapid prototyping and functional testing of the core concept. This early version demonstrated the feasibility of motorized assistance but was too complex in its conception and weak because its frame was entirely 3D-printed, leading to insufficient structural integrity and durability. Therefore, it achieved a peak assistance of **8 kg** but it was too bulky and slow (7s/180°) for practical use.

Figure 3.1: Exoskeleton prototype versions: v1.0 (2022), v1.1 (2023), and v1.2 (2025)

Then came the second version [v1.1] which tried to solve the issues of the first one by redesigning the frame to use standard carbon fiber tubes which are both lightweight and strong. At this time the motor remained a problem because it was not powerful enough to provide a good level of assistance while being fast enough; for this reason, the second version stayed at the state of a 3D model only.

Finally came the third version [v1.2] in early 2025, which was the starting base of our R&D project this year. This version completely redefined the mechanical architecture to optimize simplicity, performance, and manufacturability. The frame was redesigned to use stainless steel laser-cut and bent parts for the main structure, ensuring high strength and durability while maintaining a low weight of **1.2 kg**. The actuation system was upgraded to a more powerful **brushless motor with integrated planetary gearbox**, capable of delivering up to **10 kg** of assistance with improved speed (< 1s/180°). Custom 3D-printed fittings were retained for specific joints and mounts, allowing for precise alignment and ease of assembly. This version also incorporated ergonomic considerations, such as better compactness.

3.1 Improvements to be made

While the third version of the exoskeleton prototype represents a significant advancement over previous iterations, several areas for improvement have been identified to enhance its overall performance, usability, and ergonomics:

- **Shoulder support**: The current design focuses primarily on elbow assistance, but adding shoulder support would provide a more comprehensive solution for upper limb tasks. This could involve integrating additional joints and actuators to assist with shoulder flexion/extension and abduction/adduction movements.
- **Back support**: Incorporating a lightweight back support structure could help distribute the load more evenly across the user's body, reducing fatigue during extended use. This could be achieved with adjustable straps or a harness system that connects to the exoskeleton frame.
- **Power source and electronics integration**: The current prototype relies on an external battery pack and separate electronic components. Future iterations could focus on miniaturizing and integrating the power source and control electronics directly into the exoskeleton frame or harness for improved portability and ease of use.

For the harness that secures the exoskeleton to the user's body and accommodates the battery pack and motor controller (ESC), we utilized a design inspired by a bulletproof vest. This choice effectively distributes weight evenly across the torso, ensuring comfort and stability during movement. The vest features adjustable straps and padding for a secure fit across various body sizes, which is essential for maintaining proper alignment of the exoskeleton components. Additionally, the harness incorporates rigid plate pockets in its lining, which serve as secure attachment points for the exoskeleton frame structure, providing a rigid mounting interface that ensures mechanical stability and prevents shifting during dynamic activities. Multiple attachment points are strategically positioned throughout the harness for seamless integration of the exoskeleton frame and accessories, enhancing user comfort and safety while keeping the exoskeleton firmly in place during dynamic activities.

Figure 3.2: Illustration of the harness design and custom mounting plate for the exoskeleton.

3.2 Design of the shoulder support

To reduce stress on the shoulder joint during arm elevation tasks, we designed a passive shoulder support mechanism that holds the weight of both the user's arm and the motorized elbow exoskeleton. This support system is made of laser-cut, 3 mm aluminum (6061) sheets bent to create a rigid structure that can be mounted on the harness. Its parts can rotate around two axes to follow the natural movement of the shoulder, providing support without restricting mobility.

Figure 3.3: CAD model of the passive shoulder support mechanism

The above system is then mounted on the main shoulder support structure which is screwed to the harness internal rigid plate. This structure is made of laser-cut aluminum (6061) 3 mm sheets bent to create a strong and lightweight frame. Like other plates of the exoskeleton, it is painted with a black epoxy powder coating to improve its durability and aesthetics. To reduce weight, several holes are cut in non-critical areas without compromising structural integrity. The rigidity of this part has been proven through material stress simulations done in SolidWorks, showing that it can withstand forces up to 200 N without significant deformation.

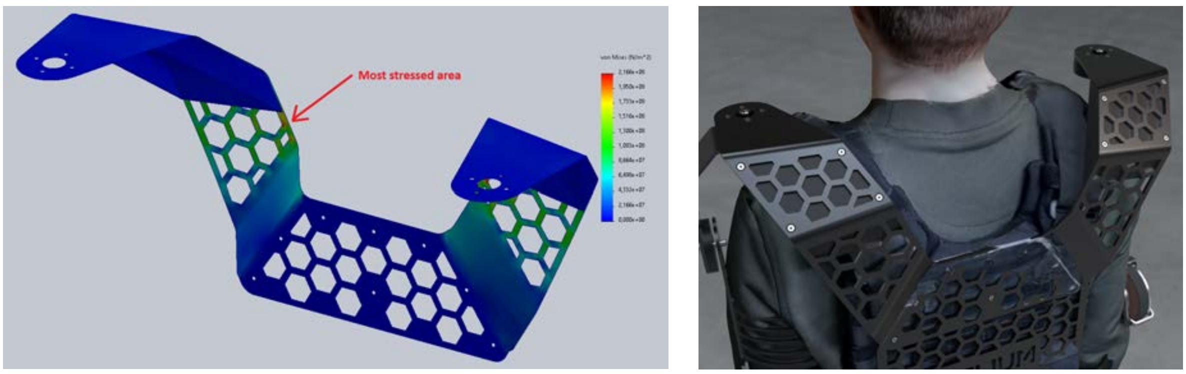

Figure 3.4: Stress simulation results of the shoulder support structure under 200 N load

3.3 Design of the left arm

The right arm is already motorized as explained previously, but to have a complete exoskeleton, we also designed a left arm that is purely passive. Its purpose is to balance the weight of the right arm and provide a more natural feel when wearing the exoskeleton. The left arm is made of laser-cut aluminum (6061) sheets bent to create a rigid frame that mimics the shape of the right arm. It includes adjustable straps to ensure a comfortable fit for various users. The passive left arm is connected to the harness in the same way as the right arm, using rigid plate mounts for stability. Like the right arm, the left arm features a magnetic encoder (AS5048A) to measure its position, allowing for synchronized movements between both arms during operation. This way, the left arm can be used as an input for the control of the right arm, which is simpler to implement than using EMG sensors in our early stage of development. Later, the same motor as the right arm could be added to the left arm to make it motorized as well, as all parts of the frame are identical from one side to the other. On the right side, the motor is used as a pivot, whereas on the left side, we used two 25 mm ball bearings to enable smooth rotation.

Figure 3.5: Passive left arm design and ball bearing assembly

4 Electronics Design

The primary objective was to create a robust, efficient, and integrated electrical architecture that supports the overall project goals with homemade PCBs. Therefore, two custom PCBs were designed: a **main control PCB** that serves as the central hub for processing and interfacing, and a secondary **PCB dedicated to motor orientation sensing**. These PCBs were engineered to ensure seamless integration with mechanical components, which was the primary objective of the specifications list, reliable connectivity, and full control over functionality and performance. The design process emphasized modularity, power efficiency, safety, and scalability, resulting in a system capable of handling real-time data processing, user interactions, and environmental monitoring.

4.1 Introduction to Custom PCB Design

In this project, we opted to develop custom PCBs rather than relying on off-the-shelf solutions. This decision was driven by several key factors that aligned with the project's mechanical and functional requirements:

- **Integration with Mechanical Parts**: Custom PCBs allowed for precise form-factor optimization, enabling them to be embedded directly into the mechanical assemblies we designed. This eliminated bulky enclosures, reduced overall system weight, and minimized spatial constraints. For instance, the PCBs were shaped and sized to fit within custom housings, ensuring mechanical stability and vibration resistance during operation.

- **Optimized Cable Management and Connectors**: By designing the PCBs from scratch, we could select and integrate connectors that perfectly matched our cabling needs. This included using high-reliability connectors (e.g., JST-XH) for power, signal, and data lines, reducing signal loss, preventing loose connections, and enhancing durability in dynamic environments. Custom routing also allowed for shorter cable lengths, which improved signal integrity and reduced electromagnetic interference (EMI).

- **Full Control Over PCB Usage and Functionality**: Developing homemade PCBs provided complete oversight of component selection, layout, and firmware integration. This enabled us to tailor the boards to specific performance criteria, such as low power consumption, fault tolerance, and expandability. It also facilitated easier debugging, version control, and future iterations without dependency on third-party vendors.

- **Prototyping**: Numerous exposed test pads were strategically placed across critical power rails to ensure there are no issues during soldering. As well, jumpers were added to confirm each part of the PCB is working correctly before final assembly. Moreover, status LEDs were included to provide immediate visual feedback on power status and operational states.

The design process involved schematic capture using tools like KiCad, followed by PCB layout and prototyping with services like JLCPCB. We adhered to best practices such as multi-layer board design (4-layers for the main PCB to separate power and signal planes), ground plane implementation for noise reduction, and thermal vias for heat dissipation.

4.2 Main Control PCB: Overview and Features

The main PCB acts as the "brain" of the electrical system, orchestrating all operations (Figure 4.1), data processing, and interfacing with peripherals. It is built around an **ESP32-WROOM-S3 microcontroller**. The board measures exactly 77 mm x 38 mm (based on the specifications for the mechanical fit) and operates with an input power of **48 V from a LiPo battery pack**, regulated down to 5 V and 3.3 V rails for various components. The PCB includes **multiple interfaces** for sensors, actuators, and user inputs such as I²C, SPI, and PWM. Key features are detailed below, including their specifications, purpose, and integration rationale.

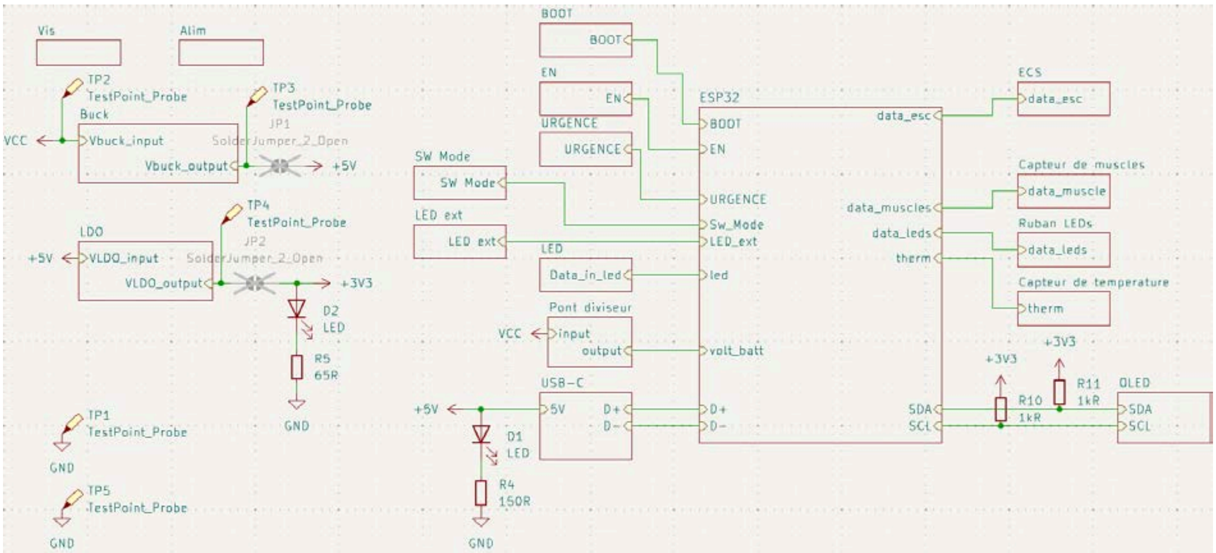

Figure 4.1: Main PCB: Schematics

- **Switches**:
  - Types and Specifications: The PCB incorporates multiple tactile switches with debounce circuitry (software debouncing) to prevent false triggers. These include a power switch for mode selection, an emergency switch, and reset buttons (BOOT and ENABLE for uploading to the ESP32).
  - Purpose: Switches provide user-friendly control for system activation, configuration changes, and emergency shutdowns. They interface directly with the microcontroller's GPIO pins, allowing for interrupt-driven responses.
  - Integration: Positioned for ergonomic access within the mechanical enclosure, and for the emergency button, a direct wire linked to the user's hand. This ensures reliable operation in user-facing scenarios.

- **Screen (Display Interface)**:
  - Types and Specifications: An OLED screen with 72x40 resolution that uses I²C interface, supporting graphical and text-based UI to display information.
  - Purpose: The screen displays real-time status information, such as battery levels, sensor readings, error codes, and current operational modes. It enhances user interaction by providing visual feedback without requiring external devices.
  - Integration: Firmware libraries do not handle rendering because of the usage of ESP-IDF. We preferred to use ESP-IDF instead of Arduino interface for more control of our microcontroller and ensuring low-latency updates. Therefore, we need to implement custom drivers for the OLED display.

- **LEDs**:
  - Types and Specifications: Multiple RGB or single-color LEDs (WS2812B, simple SMD LEDs with 20 mA current rating).
  - Purpose: LEDs serve as status indicators and provide visual cues for debugging or user alerts.
  - Integration: Strategically placed on the PCB edges for visibility through the mechanical housing. PWM channels from the microcontroller enable dynamic control, with current-limiting resistors to prevent overdrive.

- **ESC (Electronic Speed Controller)**:
  - Types and Specifications: A high-frequency PWM-controlled ESC compatible with brushless DC motors.
  - Purpose: Send signals to the motor to control its speed and direction. This is crucial for the actuation mechanisms in the project. The signal sent is determined by the data received from the AS5048A sensor on the secondary PCB.
  - Integration: Firmware implements PID control for precise speed regulation.

- **Temperature Sensor**:
  - Types and Specifications: Thermistor (NTC) with a resistance of 10 kΩ at 25°C, connected to an ADC channel of the microcontroller. Accuracy of ±1°C over the operating range (-20°C to 85°C).
  - Purpose: Monitors the battery temperature to prevent overheating and potential issues during charging or discharging cycles.
  - Integration: Placed as close as possible to the battery with long wires.

- **Battery Voltage Indicator**:
  - Types and Specifications: Voltage divider circuit with ADC input to the microcontroller, supporting 48 V LiPo with an accuracy of 0.1 V.
  - Purpose: Provides real-time battery monitoring to estimate remaining charge, prevent deep discharge, and alert users via the screen or LEDs.
  - Integration: Includes over-voltage/under-voltage protection. Firmware calculates battery percentage based on voltage readings.

- **Muscle Sensor (EMG Interface)**:
  - Types and Specifications: Electromyography (EMG) sensor module that amplifies and filters muscle signals.
  - Purpose: Detects muscle activity for biofeedback applications, such as operating the exoskeleton based on user intent.
  - Integration: Shielded traces minimize noise from EMI. Signal processing in firmware includes rectification, envelope detection, and thresholding for actionable data (all provided by the supplier of the component).

- **USB-C Interface**:
  - Types and Specifications: USB-C port to upload code to the ESP32 and for power delivery (5 V) when testing without the necessity of the battery.
  - Purpose: Uploading firmware, debugging, and providing an alternative power source during development.
  - Integration: Integrated with 2 resistors of 5.1 kΩ for proper USB data line termination.

The main PCB's power management includes a buck converter and an LDO for stable voltage regulation. Testing involved oscilloscope analysis for signal quality, thermal imaging for hotspots, and functional validation in simulated environments.

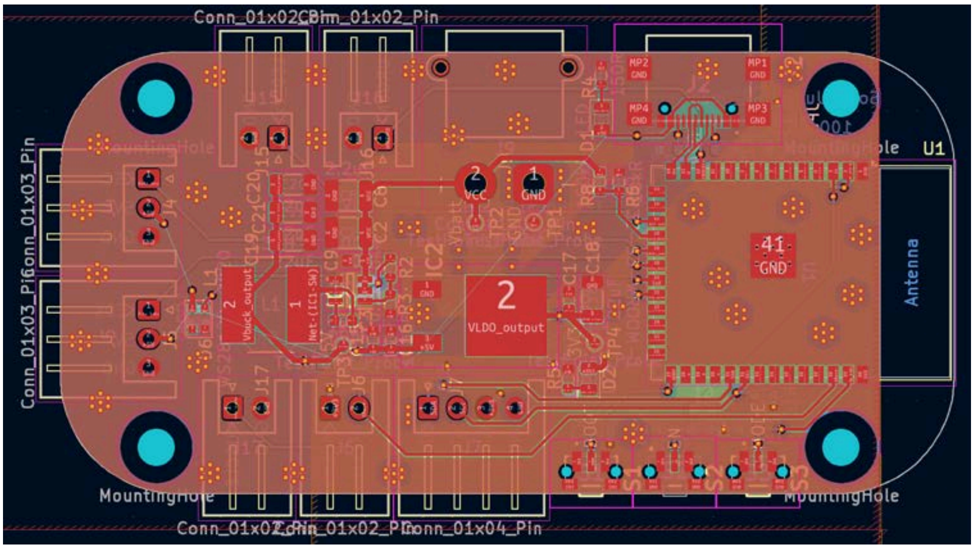

Figure 4.2: Main PCB: Layout

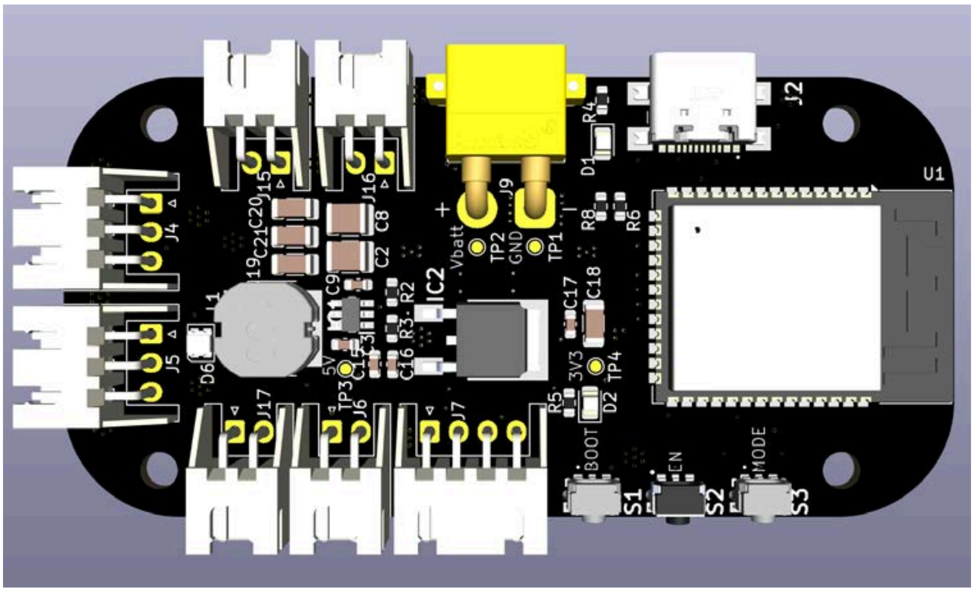

Figure 4.3: Main PCB: 3D View

4.3 Secondary PCB: Motor Orientation Sensing

The secondary PCB is a compact, specialized board (30 mm x 30 mm) designed solely for motor position detection and basic indication. It communicates with the main PCB with the SPI protocol for low-latency data transfer.

- **AS5048A Magnetic Encoder**:
  - Specifications: 14-bit resolution absolute encoder, SPI interface, angular accuracy of 0.05°, operating at 5 V.
  - Purpose: Detects the absolute orientation of the motor shaft using a diametrically magnetized magnet, providing precise feedback for closed-loop control.
  - Integration: Mounted adjacent to the motor, with SPI lines (MOSI, SCK, CS). Firmware is not provided by the supplier, so we implemented our own SPI driver to read the angle data from the sensor.

- **LED Indicator**:
  - Specifications: Single SMD LED, driven by the main PCB.
  - Purpose: Provides a simple visual confirmation of sensor activity or faults.
  - Integration: Low-power design ensures minimal impact on overall system efficiency.

The secondary PCB uses a 2-layer design for simplicity and cost-effectiveness.

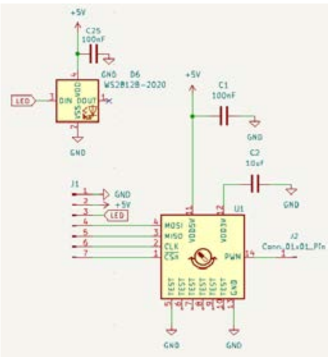

Figure 4.4: AS PCB: Schematics

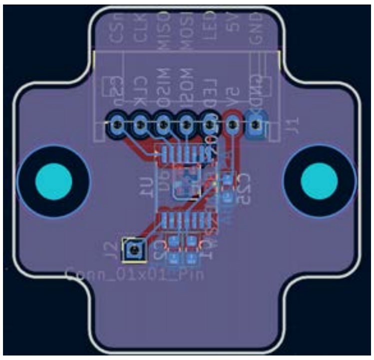

Figure 4.5: AS PCB: Layout

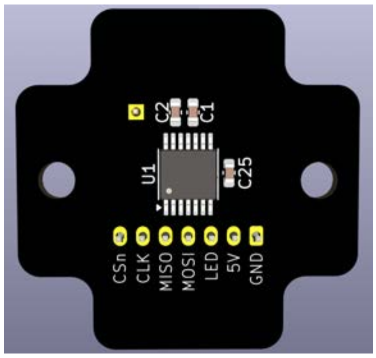

Figure 4.6: AS PCB: 3D View

5 Control and Software

The software architecture for the exoskeleton project is built around the ESP32-WROOM-S3 microcontroller, leveraging its dual-core processing capabilities and extensive peripheral support. The firmware is developed using the ESP-IDF framework, which provides low-level access to hardware features and real-time performance. The software is structured into modular components to handle sensor data acquisition, motor control, user interface management, and safety monitoring.

For the motor control, a PID control loop is implemented directly into the firmware of the motor controller (ESC) which is based on VESC open-source firmware. The ESC is a Flipsky 75100 (75 V, 100 A) that has been slightly modified to fit our needs. This controller is able to measure motor parameters such as the current, voltage, inertia, etc., and use them to optimize the motor control. The PID loop uses the angle data from the AS5048A encoder to control the motor in position mode. Using measurements from the motor allows us to perfectly tune the PID parameters and have very smooth and precise control of the motor.

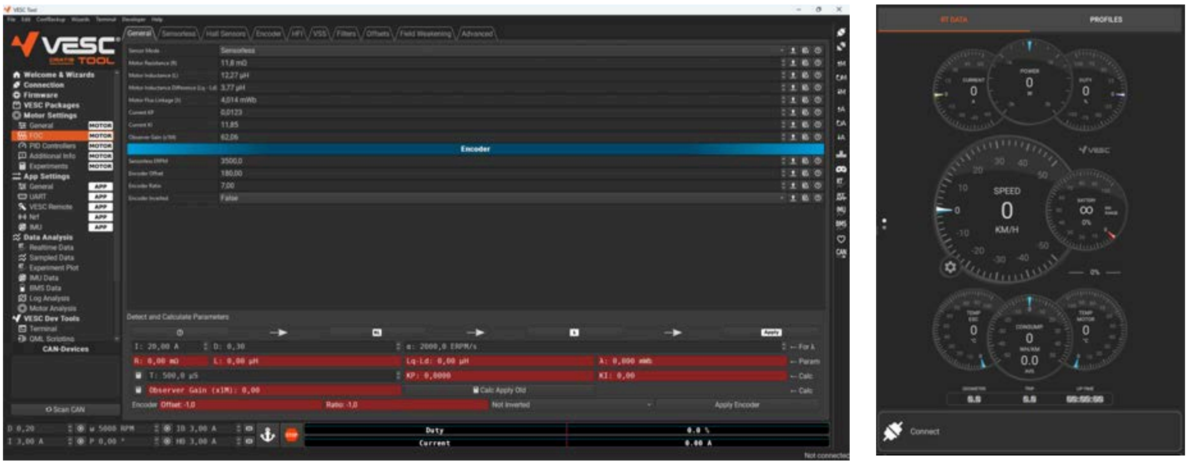

Figure 5.1: PID control loop visualization and real-time GUI displaying system status, battery voltage, motor angle, and operational modes

6 Conclusion and Perspectives

6.1 Mechanical Improvements

To enhance user comfort and accommodate different body morphologies, several mechanical improvements are planned:

- **Padding and Ergonomic Comfort**: Add high-density foam padding to contact surfaces (shoulder support, arm cuffs, harness) to reduce pressure points and improve weight distribution. Different padding thicknesses can be offered as interchangeable modules for customization based on individual sensitivity and body type.

- **Adjustable Sizing System**: Implement a modular frame design with adjustable straps and sliding joints to accommodate users of varying heights, arm lengths, and shoulder widths. The shoulder support mechanism will feature adjustable pivot points and extension arms to allow for personalized fit without requiring complete frame redesign.

- **Harness Customization**: Develop multiple harness sizes (S, M, L, XL) with adjustable internal rigid plates and strap positions. The vest-inspired design will include configurable attachment points to ensure the exoskeleton aligns correctly with each user's anatomical structure.
- **Cuff and Interface Adjustments**: Design modular arm cuffs with padded inserts and adjustable circumference to fit various arm diameters comfortably. Quick-release mechanisms will allow users to easily reconfigure or replace components between sessions.
- **Full Left Arm Motorization**: Replace the current passive left arm with an active motorized system identical to the right arm. This will enable symmetric bilateral assistance for balanced upper limb support. The motor, encoder, and control electronics will mirror the right-side implementation, allowing coordinated or independent actuation of both arms based on user requirements.
- **Shoulder Motorization**: Upgrade the passive shoulder support mechanism with brushless motors to enable active assistance for shoulder flexion/extension and abduction/adduction movements. Integrate multiple actuators with coordinated control to provide comprehensive shoulder joint support while maintaining natural movement patterns.
- **Back Support Motorization**: Design an active back support structure with integrated actuation to assist with trunk stabilization and load distribution. This will include adjustable mechanical assists to support the extended load from fully motorized arms and shoulder systems, improving overall user endurance during extended operations.

These improvements aim to make the exoskeleton accessible to a broader range of users while maintaining structural integrity and performance consistency across different morphologies, while significantly expanding the assistance capabilities to multiple body regions.

6.2 Electrical Improvements

The next PCB revision will keep the exact same size to fit the unchanged mechanical design, while integrating direct reading of the AS5048A on the main board, because this element had been initially forgotten in the specifications. It would also be very beneficial to replace the AS5048A (SPI) with the AS5048B (I^2C). This change unifies communication: both the screen and the encoder would use I^2C, simplifying firmware, reducing bus diversity, and improving overall maintainability without sacrificing resolution or performance. These updates will deliver a cleaner, more efficient, and future-proof electrical system.