ECE 445 Design Document

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1 Introduction

1.1 Problem

Lifting and carrying heavy objects is a physically demanding activity common to both personal and industrial settings. No matter it is an individual moving items at home or a logistics worker handling packages in a warehouse, these repetitive actions place high loads on the musculoskeletal system. This load on workers and households is the main cause of many common injuries and skeleton-related long-term diseases. According to the U.S. Bureau of Labor Statistics, repetitive motion and loading-related injuries remain among the leading causes of workplace injuries, resulting in workdays lost and economic costs annually.

Moreover, many of the exoskeleton designs and assistive devices are bulky, heavy, and locked to the drivetrain whenever the system is powered. These design lack backdrivability, which makes them impractical for daily use. A lightweight, safe, and efficient wearable system that provides reliable and robust support while preserving user's freedom is still missing. By addressing this problem, we could effectively improve worker safety, reduce injury rates, and extend the application of assistive technologies to a broader population.

1.2 Solution

We designed a lightweight, modular exoskeleton that is powered when needed and backdrivable when idle. The whole design is divided into modularized subsystems (elbow BLDC drive, servo drive, clutches, sensors, PCBs, and control panel). At the elbow, a BLDC motor drives a compact planetary gearbox whose output is coupled to the elbow joint through a dog clutch; near the shoulder, a high-torque servo actuates a compact linkage train (spur + bevel + rack-and-pinion) whose armor rack avoids possible interference at large joint angles. A forearm control panel provides mode selection, status, battery level, and a hard E-stop. Lastly, an EMG interface detects muscle activation so users can command assistance with their hands full.

Backdrivability and user comfort drive the control strategy. By default both clutches are disengaged so the limb moves freely with minimal added inertia. When a load is detected (via EMG + joint/torque estimation), the system engages the appropriate drive: the BLDC module for dynamic lifting and high joint-speed work, the servo module for steady holds and low-speed positioning, or both for precise micro-motions near a setpoint (with torque bias to the servo and BLDC supplying supplemental torque). Engagement is synchronized by matching speeds across the clutch, and fault handling always returns the system to a safe, unpowered, backdriven state. The result is a durable, easy-to-use assist device that feels unobtrusive when idle and strong when engaged.

1.3 Visual Aid

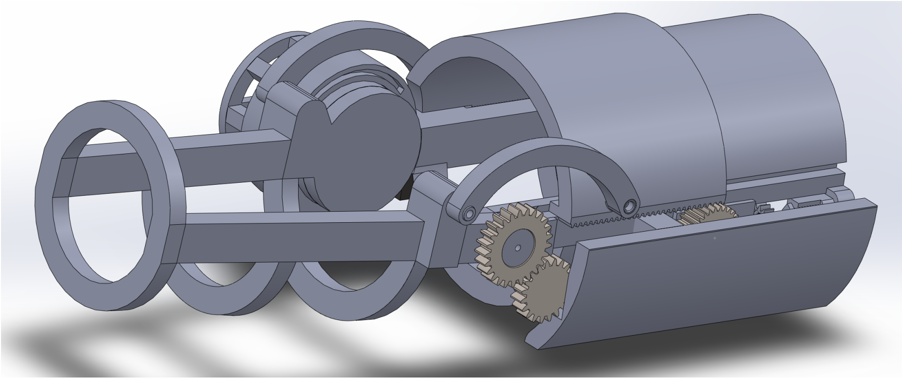

Figure 1: CAD model of in-progress design

As shown in the figure above, arm will go through the central axis of the design. In the finalized design, armor will cover the opening section in the lower limb skeleton and the BLDC-Planetary drive at the back of the design.

1.4 High Level Requirements

- The exoskeleton will deliver $\geq$ 40 $\text{N} \cdot \text{m}$ of net torque at the elbow, able to lift a 10 kg weight located 0.40 m from the joint, through a 0°–90° motion at $\geq$ 60°/s, while the user contributes $\leq$ 10% of the required torque.
- With a full charge, the system will operate for $\geq$ 3.0 h under 10 per minute of a 0°–90° lift of a 10 kg payload (2 s lift, 2 s hold, 2 s lower), with power active during idle intervals.
- The control system will use EMG-based motion detection with $\leq$ 150 ms command latency and $\leq$ 5% false-activation rate in normal use, and the clutch will engage or disengage in $\leq$ 200 ms while limiting peak torque ripple to $\leq$ 15% of torque.

2 Design

2.1 Block Diagram

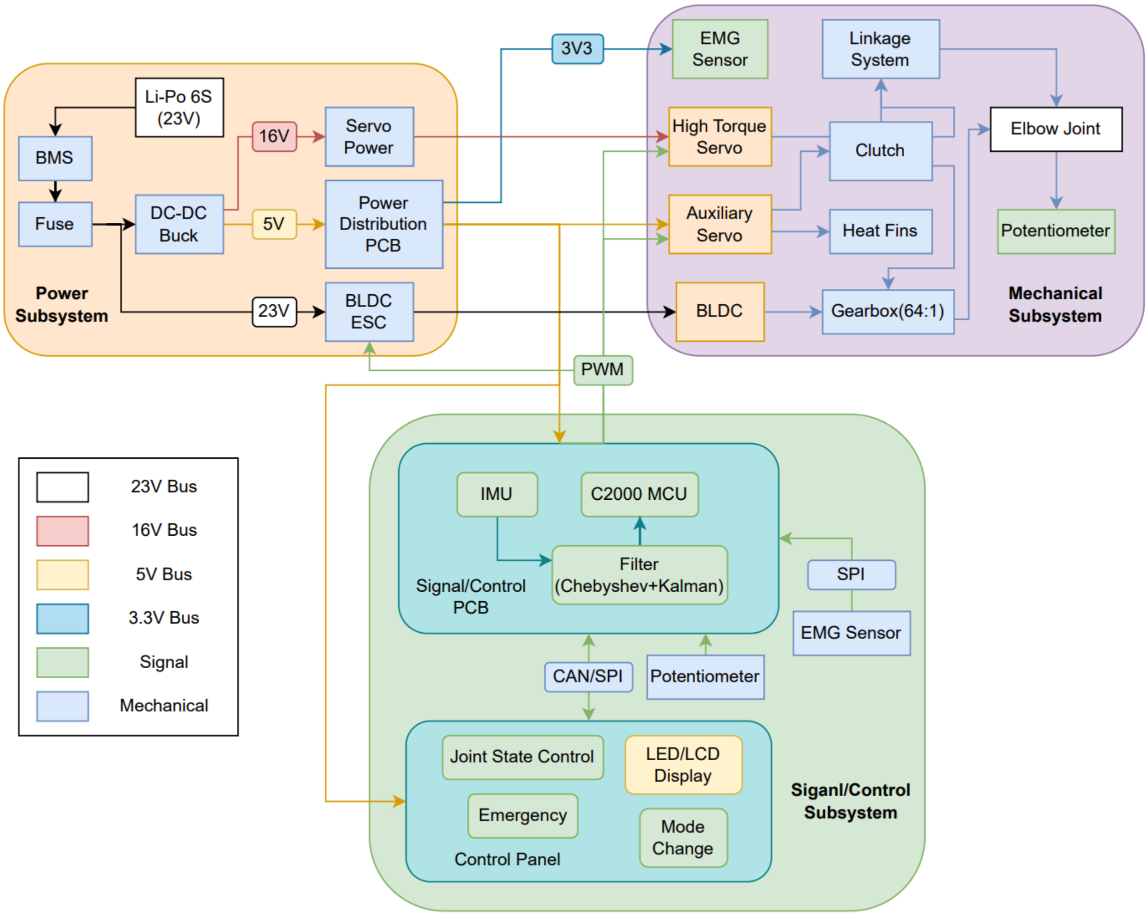

Figure 2: Block Diagram

The system is composed of three main subsystems: the Power Subsystem, Mechanical Subsystem, and Signal/Control Subsystem. The Power Subsystem is responsible for converting the 23 V supply from the Li-Po 6S battery into regulated 16 V, 5 V, and 3.3 V outputs to power different components across the system. The mechanical subsystem transforms electrical energy into mechanical motion and provides mechanical advantage through elements such as the gearbox, linkage, clutch, and servo mechanisms that drive the elbow joint. The Signal/Control Subsystem manages communication and coordination among sensors, actuators, the C2000 MCU, and the control interface, ensuring synchronized operation between motors, EMG input, and safety features like the emergency stop and control panel.

2.2 Mechanical Subsystem

2.2.1 Tasks

Function & contribution. Converts motor outputs to elbow torque while preserving backdrivability; meets assist capacity for lifting and smooth engagement for comfort/safety.

Interfaces (quantitative).

- **Power:** 23V BUS (peak ≥ 20 A); 16V SERVO (continuous ≥ 10 A, peak ≥ 20 A).
- **Signals:** ESC PWM (1000–2000 Hz), servo PWM (3.3 V logic), clutch enable GPIO.
- **Sensing:** Elbow potentiometer $\rightarrow$ C2000 ECAP (0–3.3 V).

Must-meet requirements.

- **Joint torque:** deliver ≥ 40 N·m sustained over $0 - -90°$ and ≥ 45 N·m peak combining BLDC (0.5 N·m × 64:1) and servo (≥ 80 kg·cm).
- **Backdrivability (idle):** both clutches default open; reflected friction torque ≤ 2 N·m; user can move joint at ≥ 120°/s with < 5 N·m effort.
- **Clutching:** engage/disengage in ≤ 200 ms.
- **Structural safety:** factor of safety ≥ 2.0 at 40 N·m; rack retraction ensures ≥ 5 mm clearance at worst posture; mechanical end-stops prevent over-rotation.
- **Thermal:** continuous operation at rated load does not exceed 70 ° C at gearbox/servo case (ambient 25 ° C).

2.2.2 Subsystem Explanation

The 3D-printed modular frame holds the elbow joint, the 64:1 planetary gearbox with BLDC motor, the dog clutch, the 16 V high-torque servo with its spur–bevel–rack linkage (the rack retracts to avoid interference at large angles), and auxiliary actuators for clutch engagement and disengagement. Joint angle is measured by a potentiometer mounted at the elbow. This subsystem delivers the joint torque and is capable of backdrivability: clutches default open for free motion; when assistance is requested, the clutch engages and connects the joints with the BLDC motor and powers the exoskeleton.

The 3 principal views of the mechanical design are given below. The design is 50% of the way done, with all significant features modeled.

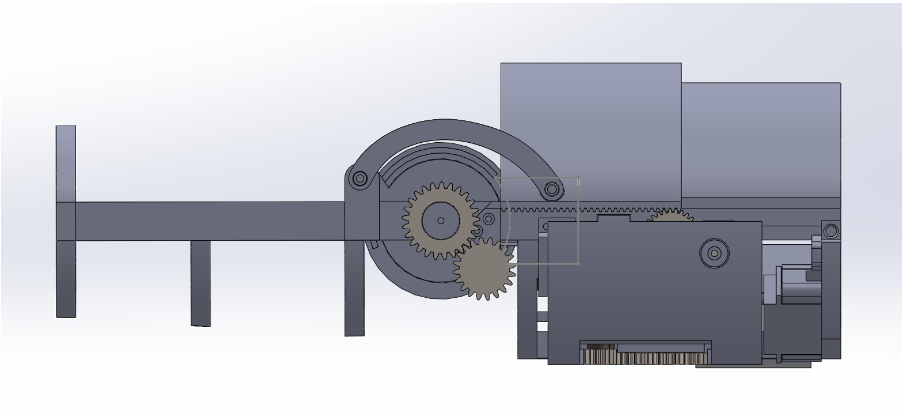

Figure 3: Side view

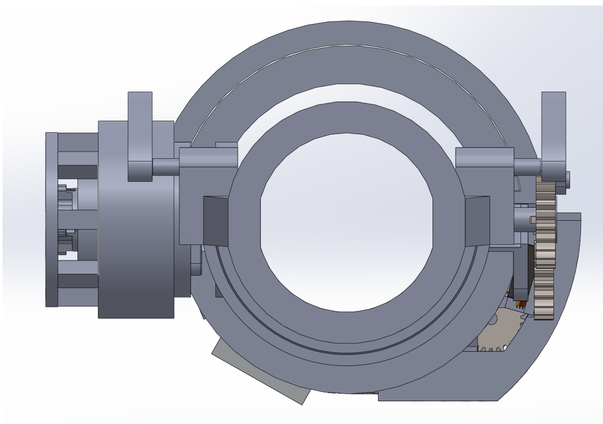

Figure 4: Front view

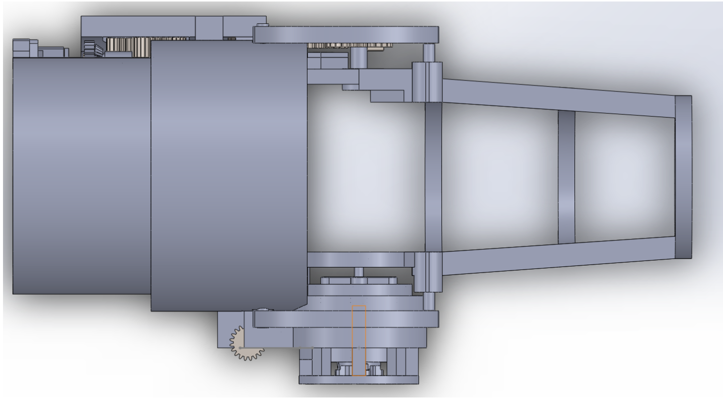

Figure 5: Top view

The inner radius of the skeleton is 11 cm. This excludes the TPU padding that will be added to the inner surface of the skeleton to provide extra comfort and also distribute the load along the whole surface instead of creating point loading. The thickest component design, which is the servo drive clutch module at the top left of figure 5 and bottom right of figure 4 is around 4 cm thick from the inner surface, ignoring the BLDC drive train. The BLDC drive module is considered the most bulky module in the design, for the thickness of the gears in the 3-stage 64:1 planetary gearbox cannot be effectively reduced for the sake of safety and stress analysis. In the future, if the gearbox section could be manufactured using aluminum alloy, it could be reduced in half, and that will be very promising.

The BLDC drive module is given in the figurew below, with the BLDC motor marked in blue.

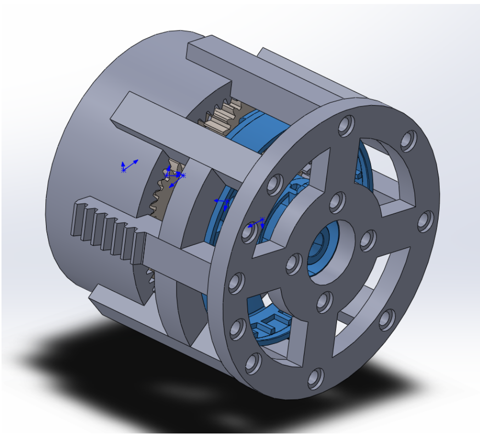

Figure 6: BLDC drive module

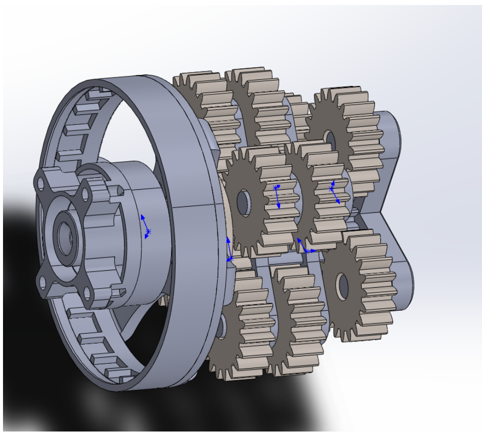

Figure 7: BLDC drive module without ring

Each layer of the gear train contains four planet gears and a single sun gear connected to the planet gear holder in the next stage with module 0.9 and teeth number of 20. The calculation of the total reduction is given below.

$$
\begin{aligned}
&\text{Given } Z_s = 20,\ Z_p = 20 \Rightarrow Z_r = Z_s + 2Z_p = 20 + 40 = 60,\\
&i_{\text{stage}} = 1 + \frac{Z_r}{Z_s} = 1 + \frac{60}{20} = 4{:}1,\\
&i_{\text{total}} = (i_{\text{stage}})^3 = 4^3 = 64{:}1.
\end{aligned}
\tag{1}
$$

Notice that there is a gear rack on the feature in figure 6. This is the rack&pinion mechanism used for clutch of the BLDC drivetrain.

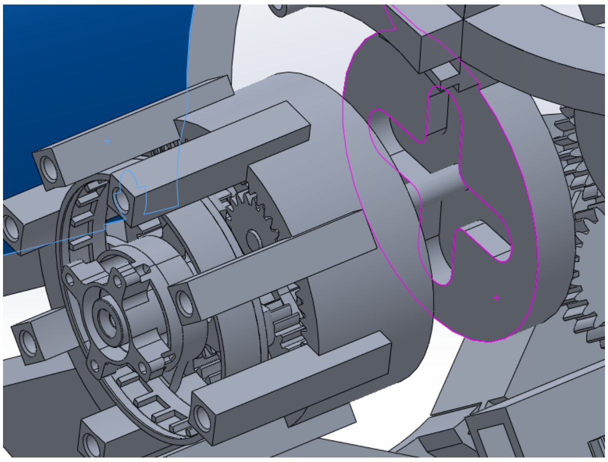

Figure 8: Clutch mechanism for the BLDC drivetrain

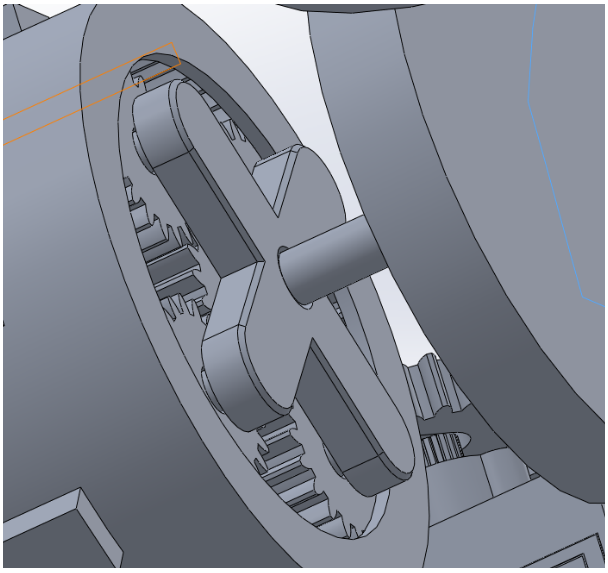

Figure 9: Clutch mechanism for the BLDC drivetrain

The whole drive module is designed to slide axially along the direction of 8 locating features around the outer surface of the ring gear. The dogs are placed at the final stage of the reduction gear as the planet gear holder, and another half of the clutch is placed on the lower limb skeleton. The upper limb skeleton grounds the drive module and allows only axial motion for engage/disengage. Therefore, the rotation of the motor will be reduced to the rotation of the dogs on the final stage, which drives the lower limb skeleton to rotate with respect to the upper limb skeleton. The clutch engagement drive is still under development since it is not too smooth for the current 1-slot-only design. The gear will produce moment that tends to tilt the drive module on the z axis since only the left portion of the drive module is actuated thorugh the auxiliary servo.

The servo drivetrain is given in the figure below.

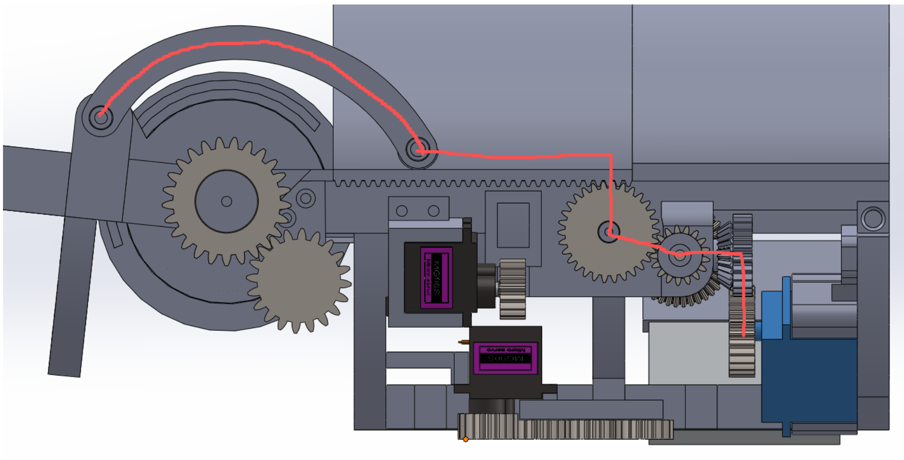

Figure 10: Servo drive train

The drivetrain is marked using red line. The high-torque RS700v2 servo is mounted near the shoulder, and driving a gear train that finally convert the output of the servo motor to the sliding motion of the slider that sits on the top of upper limb skeleton. This slider will be connected to two couplers that connnect the lower limb skeleton using pin joints with a mechanical advantage of 3 at 90 degrees. The total mechanical advantage from the servo to the lower limb skeleton is calculated as:

$$\begin{aligned} \mathrm{MA}_{\text{total}} &= \underbrace{\frac{Z_{24\text{ spur}}}{Z_{27\text{ spur}}}}_{\text{27 spur - 24 spur}} \times \underbrace{\frac{Z_{40\text{ bevel}}}{Z_{27\text{ bevel}}}}_{\text{27 bevel - 40 bevel}} \times \underbrace{\frac{Z_{30\text{ bevel}}}{Z_{17\text{ bevel}}}}_{\text{17 bevel - 30 bevel}} \times \underbrace{2}_{\text{rack @ }90^\circ} \\ &= \frac{24}{27} \times \frac{40}{27} \times \frac{30}{17} \times 2 = \frac{57600}{12393} \approx 4.65{:}1 \end{aligned} \tag{2}$$

In other words, the load torque at the joint will be effectively reduced by 5 times when it arrives at the high-torque servo. The clutch for the servo drive is different from what we have for the BLDC. The clutch is given in the figure below.

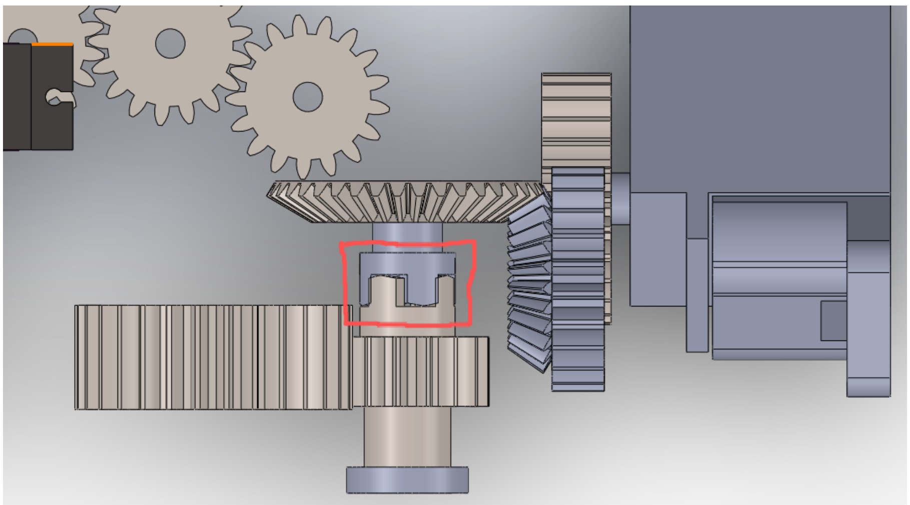

Figure 11: Clutch for servo drivetrain

The bottom half of the red box in the figure is sliding axially, which is connected to the shield-like structure in Figure 3. This shield will be driven by two MG90S auxiliary servos as shown in figure 10.

The shield slides in the direction normal to the skeleton surface for a distance that just disengages the clutch in the red box but still keeps the two spur gears in the bottom meshed up so that the two gears will not be affected by the clutch. An overview of the bottom servo drive for the clutch is given in the figure below.

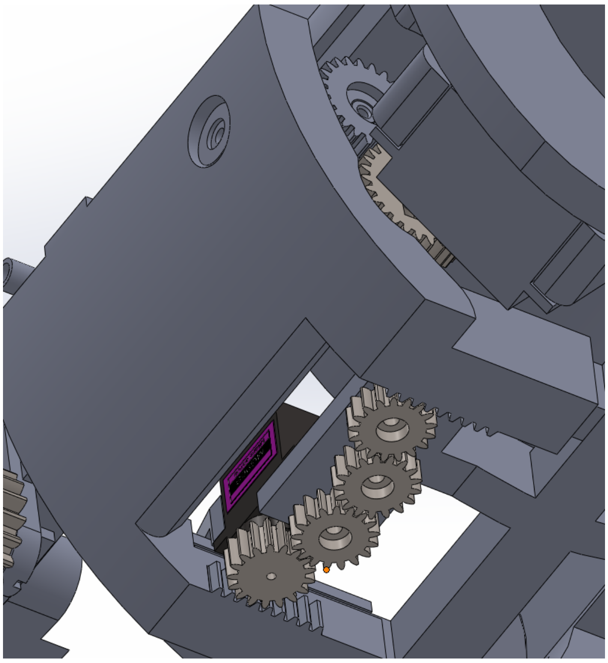

Figure 12: Left shield disengagement drivetrain

Both sides of the device are shielded to protect sensitive electronics. The left shield is actuated to engage/disengage the servo-drivetrain clutch, while the right shield is rigidly grounded to the upper-limb skeleton. Both shields will incorporate vented louvers sized for two micro chassis fans to provide forced-convection cooling; the fins rotate open to circulate air and dissipate heat from the left high-torque servo and the right step-down buck converters. The outer-elbow joint is further protected by a multi-stage, sliding armor that travels axially along the lower-limb skeleton but remains electrically grounded to the upper-limb skeleton. Due to mechanical interference at the inner elbow, full hard shielding is impractical; this area will be covered with a compliant fabric shroud. Finally, the lower-limb skeleton will host a control panel for real-time telemetry—motor and buck temperatures, angular velocity, battery status, and other diagnostics.

2.2.3 Requirements and Verificaiton

Table 1: Mechanical Subsystem — Requirements & Verification

Requirements	Verification
• **Clutch Smoothness:** The servo drivetrain clutch shall engage/disengage smoothly with no chatter, with engagement time $\leq t_{\text{eng}}$ and output torque ripple $\leq r_{\text{torque}}$ during transition.	• Mount the arm on a fixture; command repeated engage/disengage cycles at slow/nominal speeds. • Log motor current and output torque; compute transition time and torque ripple. • Pass if $t_{\text{eng}} \leq$ spec, ripple $\leq r_{\text{torque}}$, and no audible/visual chatter.
• **Clutch Strength (10 kg Load):** The clutch shall transmit the torque required to hold/move an equivalent *10 kg* load at the specified lever arm without slip or damage, with safety factor ≥ 1.5.	• Lock the output at the test radius; apply torque matching a 10 kg load (convert using the lever arm), then increase to 1.5× this torque using a brake/dynamometer. • Hold for 60 s while monitoring for slip and abnormal noise. • Pass if no slip occurs, teeth remain intact, and backlash change is within limit.
• **Skeleton Strength (10 kg Load):** The upper/lower limb skeleton shall withstand the forces and moments produced by an equivalent *10 kg* load at the forearm without cracking, yielding, or loosened joints; elastic deflection $\leq \delta_{\max}$.	• Perform a static load test: apply the 10 kg-equivalent force at the defined radius; impose the corresponding elbow moment. • Measure deflection and inspect with visual/dye checks. • Pass if deflection $\leq \delta_{\max}$ and no permanent set or cracks are observed.
• **Maximum Output Torque (10 kg Load):** The actuator train (servo / gearing / clutch) shall produce net output torque $\geq T_{10\text{kg}}$ sufficient to lift/hold an equivalent *10 kg* load at the specified radius.	• Instrument the output with a load cell or hang calibrated masses via pulley at the test radius. • Command a slow lift/hold; record steady torque. • Pass if measured torque $\geq T_{10\text{kg}}$ with stable operation and no slip.
• **Shield Venting Ports:** The left/right shields (outer shell) shall include actuated vent fins that enable forced-convection cooling to keep the servo and step-down converters within safe temperature limits during continuous use.	• Operate the system at steady load with vents closed, then open vents and turn on both micro fans. • Record temperatures of the servo and buck converters until steady state. • Pass if temperatures with vents open are lower and remain below the specified limit.

2.3 Power Subsystem

2.3.1 Tasks

Function & contribution. Provides protected energy to meet the 3-hour endurance goal while isolating noisy loads so EMG latency and clutch smoothness stay within spec.

Interfaces.

- **Input:** 6S Li-Po, 25.2–19.0 V into BMS .
- **Outputs:**
  - **23V BUS:** 19–25.2 V, $\geq$ 20 A peak (100 ms)
  - **16V SERVO:** 15.5–16.5 V, $\geq$ 10 A continuous, $\geq$ 20 A peak (100 ms)
  - **5V LOGIC:** 4.90–5.10 V, $\geq$ 2 A continuous
- **Control&Signals:** `/PGOOD`, `/FAULT` to MCU; **E-STOP** loop (NC) cuts 23 V/16 V power stages.

Must meet requirements.

- Must support $\geq$ 3.0 h operation under the typical usage and workload (10 kg) while voltage of each system remains within $\pm 2\%$.
- Per-branch fuse/limit: trip on $>$ 20 A fault within $<$ 200 ms on 16 V branch.
- E-STOP removes power to BLDC and 16V SERVO in $<$ 100 ms.
- Star distribution of + and GND: ESC, 16 V buck, and 5 V buck branch from a single node.

2.3.2 Subsystem Explanation

The power subsystem splits the battery into three protected rails—23 V for the BLDC, 16 V for the high-torque servo, and 5 V for control (regulated locally to 3.3 V through the Power PCB)-each with its own fuse. A 6-cell Li-Po pack (25.2-19.0 V) feeds a BMS and main fuse, creating a protected 23 V bus that feeds the BLDC ESC directly and also serves as the input to two step-down branches: Buck #1 produces 16 V for the high-torque servo, and Buck #2 produces 5 V for the Power PCB and peripherals. The 5 V rail enters the Power PCB and is converted locally to 3.3 V on the signal board. The Power PCB also provides current sensing on the BLDC and 16 V branches, an E-STOP that removes 23 V/16 V while keeping 5 V/3.3 V alive for fault reporting, and an 8 V boost used with the 16 V rail to create a 0–8–16 V supply for the EMG analog front-end (V+ = 16 V, VMID = 8 V from the boost, V- = 0 V). The EMG power and signal grounds are independent; the EMG signal side remains referenced to system ground.

First, the performance of the power subsystem will be evaluated by taking a load condition of 10kg load in the palm and a joint state of 90 degrees. Maximum available output torque at the elbow is estimated from actuator torques and mechanical advantage, and the maximum torque from the datasheet for the two motors will be used. For the BLDC through a 64:1 gearbox (ideal, neglecting losses):

$$T_{\text{BLDC,out}} \approx 0.63 \text{ N·m} \times 64 \approx 40.3 \text{ N·m}. \tag{3}$$

For the high-torque servo through the linkage with mechanical advantage of 4.65:

$$T_{\text{servo,out}} \approx 7.85 \text{ N·m} \times 4.65 \approx 36.5 \text{ N·m}. \tag{4}$$

If both actuators contribute additively about the joint (idealized):

$$T_{\text{combined,max}} \approx T_{\text{BLDC,out}} + T_{\text{servo,out}} \approx 40.3 + 36.5 \approx 76.8 \text{ N·m}. \tag{5}$$

The torque required to hold a static 10 kg load at elbow angle 90° depends on the effective lever arm $L = 0.4$m from joint axis to load:

$$T_{10\text{kg}} = mgL = 10 \text{ kg} \times 9.81 \text{ m/s}^2 \times 0.40 \text{ m} = 39.24 \text{ N} \cdot \text{m}. \tag{6}$$

where, as we can see, is about half of the theoretical limit of the torque that could be achieved using the two motors.

The current drawn will also be calculated using the datasheet of the two motors. For the BLDC (MN5006 KV300), the 100% data with the larger propeller gives approximately

$$V_{\text{BLDC}} \approx 23.0 \text{ V}, \quad I_{\text{BLDC,peak}} \approx 19.6 \text{ A}, \quad P_{\text{BLDC,peak}} = VI \approx 23.0 \times 19.6 \approx 451 \text{ W}. \tag{7}$$

which will not be taken into consideration since the BLDC loading condition is different in the design from copters, and OV/OA protections are included in the ESC that is connected to the 6V battery.

For the high-torque servo (RS700V2 at 16.8 V), the datasheet gives stall current and stall torque

$$I_{\text{servo,stall}} \approx 5.8 \text{ A}, \qquad T_{\text{servo,stall}} \approx 80 \text{ kg·cm} \approx 7.85 \text{ N·m}. \tag{8}$$

Assuming operation at 16 V is comparable, the 16 V branch peak current is

$$I_{\text{16V,peak}} \approx 5.8 \text{ A}. \tag{9}$$

The 5 V power branch on the Power PCB supplies auxiliary actuators and peripherals. Assume eight MG90S micro servos with an average operating current of 0.30 A each (only three active simultaneously), two 25×25×10 mm 5 V fans drawing 0.20 A each, aesthetic LED lighting allowance of 0.80 A, control panel and display consumption of 0.40 A, and a 1.0 A margin for the Signal PCB logic and sensors:

$$\begin{aligned} I_{\text{5V,avg}} &\approx 3 \times 0.30 + 2 \times 0.20 + 0.80 + 0.40 + 1.00 \\ &= 0.90 + 0.40 + 0.80 + 0.40 + 1.00 \\ &\approx 3.50 \text{ A}. \end{aligned} \tag{10}$$

Considering simultaneous clutch actuation or transient servo stalls, the instantaneous peak current is estimated as:

$$\begin{aligned} I_{\text{5V,peak}} &\approx 5 \times 0.60 + 2 \times 0.20 + 0.80 + 0.40 + 1.00 \\ &= 3.00 + 0.40 + 0.80 + 0.40 + 1.00 \\ &\approx 5.60 \text{ A}. \end{aligned} \tag{11}$$

Buck-converter selection is therefore consistent with the peak currents. Buck #1 (adjustable CC/CV, dual heatsinks) is set to 16 V and should be derated for continuous operation; a practical continuous current of 5–8 A with airflow covers the 5.8 A servo peak. Buck #2 (DROK 5.2 V) provides up to about 5–6 A at 20–25 V input, matching the estimated 5.6 A 5 V peak with minimal headroom but very robust for average current; airflow and short-term duty on auxiliary servos are recommended.

Fuse and protection sizing follow the peak values with margin and fast clearing on faults:

$$I_{\text{fuse,23V}} \approx 25 \text{ A}, \qquad I_{\text{fuse,16V}} \approx 8\text{–}10 \text{ A}, \qquad I_{\text{fuse,5V}} \approx 7 \text{ A}. \tag{12}$$

In light of this, we will place fuses close to the source, add input LC filters and TVS at each buck, and use star distribution so the ESC, 16 V servo rail, and 5 V rail branch from a single node on the 23 V bus.

2.3.3 Requirements and Verification

Table 2: Power Subsystem — Requirements & Verification

Requirements	Verification
• **E-STOP:** E-STOP shall remove power from the 23 V bus and 16 V rail within 100 ms; 5 V/3.3 V remain powered for logging/telemetry.	• Scope 23 V and 16 V rails during E-STOP; measure drop time to $\leq$ 10% nominal. • Confirm MCU stays alive on 5 V/3.3 V and records an E-STOP event. • Verify BLDC ESC and servo enter safe/disabled states.
• **Fuses:** Main battery fuse and per-rail fuses (23 V, 16 V, 5 V) shall be placed near the source and rated to pass normal peaks while clearing faults quickly.	• Inspect BOM/PCB for fuse locations and values; confirm placement near sources. • Compare ratings to measured peak currents and time–current curves. • Inject over-current with electronic load; verify fuse clearing and fault isolation.
• **Steady Rails:** 23 V, 16 V, and 5 V rails shall remain within specified tolerances under step loads and simultaneous operation; no nuisance droop affecting control/EMG.	• Step loads on BLDC/servo/peripherals; log rail droop and recovery time. • Verify tolerances during worst-case duty (peaks and concurrent loads). • Check EMG latency and MCU timing while pulsing motors.
• **BMS:** The BMS shall provide OV/UV/OC protection and cell balancing; the 23 V bus is protected against abnormal conditions.	• Review BMS specs; validate cutoff thresholds and balance operation. • Simulate OV/UV with a programmable supply; confirm disconnect/recovery. • Measure 23 V bus behavior during faults; verify downstream rails are not overstressed.
• **3.3 V Quality:** Power PCB shall regulate 5 V to 3.3 V with acceptable ripple and line/load regulation for MCU and sensors.	• Measure 3.3 V ripple at idle and under 5 V load steps; compare to spec. • Sweep input and temperature; verify regulation and no brownout/reset events.
• **Max Load Condition:** Under a 10 kg load at 0.4 m, the system shall supply and protect all rails while meeting endurance and thermal limits.	• Run worst-case profile with motors assisting; log 23 V/16 V/5 V currents and temperatures. • Confirm rail tolerances, fuse margins, and component temperatures within limits. • Record energy usage to validate runtime target.

2.4 Signal/Control Subsystem

2.4.1 Tasks

Function & contribution. This subsystem senses user intent and joint state, runs real-time control, arbitrates BLDC/servo engagement, drives the clutches, and manages safety and user I/O. It enables the high-level goals by (i) achieving $\leq$ 150 ms EMG-to-assist latency for responsive help, (ii) coordinating smooth clutching to limit torque ripple, and (iii) maintaining reliable operation over the full 3 hour endurance window without resets or mis-activations.

Joint State Control, Emergency button, and Mode Change inputs on the forearm control panel are used to override EMG control, the user can use these to directly control target joint angles, and use Emergency button to shutdown power and disengage clutch in case of danger or entrapment. A PWM module modulates control signals from C2000 MCU and to PWM signals for controlling motors and servos. LED/LCD Display is used to displays current mode, servo/motor/clutch angle, and remaining battery.

Interfaces.

- **Power:** 5 V input from power PCB; local 3.3 V generation. A3V3 noise $< 50\ \mu V_{\mathrm{rms}}$; D3V3 regulation 3.25–3.35 V with load steps up to 200 mA.
- **Sensors:**
  - **EMG:** *SPI AFE:* 3.3 V I/O; Mode 1; SCLK $\leq$ 1 MHz; `DRDY` interrupt at 2 kS/s/channel (24-bit). Tiny input RC at electrodes (e.g., 10 kΩ + 3.3 nF to reference).
  - **Elbow angle:** 10 kΩ potentiometer, ratiometric to 3.3 V; ADC $\geq$ 1 kS/s; RC f_c = 50–200 Hz; absolute error $\leq \pm 2^\circ$ over 0–90°.
- **Actuation outputs:** ESC PWM (1–2 ms pulses @ 50–400 Hz) with command-to-update delay $\leq$ 2 ms; servo PWM (3.3 V logic) with jitter $< 50\ \mu$s; clutch enable GPIO with debounce and interlock.
- **Safety I/O:** `/ESTOP_IN` (from hard NC loop), `/PGOOD`, `/FAULT` lines; watchdog reset pin.

Must meet requirements.

- **Latency & control rate:** EMG intent above threshold to motor command $\leq$ 150 ms end-to-end; main control loop $\geq$ 500 Hz with worst-case jitter $<$ 1 ms; PWM outputs update within $\leq$ 2 ms of command.
- **Filtering & features:** EMG digital band-pass 20–450 Hz + 60 Hz notch; rectification and envelope LPF 5–10 Hz; normalized envelope published at 100 Hz; false-activation rate $\leq$ 5% under normal wear.
- **Clutch coordination:** Close clutches only when speed mismatch $\leq 5^\circ$/s; engagement/disengagement completes in $\leq$ 200 ms; peak elbow-torque ripple during engagement $\leq$ 15% of steady assist.
- **State estimation accuracy:** elbow angle RMS error $\leq 2^\circ$ over 0–90°; IMU drift held $< 1^\circ$/min during static holds via fusion.
- **Comms robustness:** loss of 3 consecutive heartbeats ($\geq$ 150 ms) $\Rightarrow$ safe state (clutches open, power stage commands off).
- **Safety/failsafe:** `/ESTOP_IN` forces stop (disable ESC/servo commands, open clutches) in $<$ 100 ms; watchdog resets CPU on missed deadlines; on brownout $<$ 3.1 V the system reboots to Idle/Disengaged in $<$ 1 s.
- **Power integrity (local):** A3V3 ripple $< 50\ \mu V_{\mathrm{rms}}$ at the EMG/ADC reference; D3V3 holds within 3.25–3.35 V during 100 mA load steps; no missed control deadlines during simultaneous CAN traffic and sensor ISR activity.

2.4.2 Subsystem Explanation

We will use two EMG channels (biceps and triceps) plus the current elbow angle from a potentiometer. A small neural network (MLP) will learn the relationship between these inputs and the target angle so the system can assist or track motion smoothly.

Each EMG channel uses three pads: two active pads over the muscle belly (spaced 20 mm and aligned with the fibers) and one reference pad on a nearby bony area. One set goes on the biceps (flexor), the other on the triceps (extensor). The two channels capture complementary activation patterns: when the biceps tightens for flexion, triceps activity typically drops, and vice-versa for extension. Each channel passes through a standard EMG front-end: high-impedance differential input, band-pass filtering (~20–450 Hz). The goal is a stable 0–3.3 V activation value per channel that rises with contraction. The elbow potentiometer provides the current angle. All three signals feed the MCU's ADC.

The predictor is a lightweight multilayer perceptron that runs on the MCU. Inputs are: EMG_biceps envelope, EMG_triceps envelope, and current elbow angle. For better stability, we will include short history (e.g., the last 3–4 windows) by stacking features. Features are normalized with stored scalers. Output is a single continuous value: the desired elbow angle.

We will train the model on a PC using data recorded while the user performs a free-run session wearing the EMG sensors and moving the exoskeleton through its range. During this session, the MCU streams time-stamped EMG envelopes (biceps, triceps) and the measured elbow angle (potentiometer) to the PC over USB/serial, where they are logged. The PC script synchronizes signals, builds windowed features, normalizes them, and uses the measured angle as the training target. We then train a small MLP and save the trained weights plus normalization parameters.

After training, we export the network as static arrays and embed them in the C2000. The MCU performs inference only: it computes the same windowed features in real time, applies the stored normalization, evaluates the MLP, and outputs the predicted desired elbow angle. This keeps on-device computation lightweight and allows retraining on the PC whenever placement changes—only the weight header needs to be re-flashed.

For the joint state control, we will use torque control instead of task space control. The load on the high-torque servo and the BLDC will be shared. The big picture is that, when the user is moving the joint in a high angular velocity (30 degrees per second), BLDC drivetrain will be engaged and servo drivetrain will be disengaged. When the user is holding the load with a joint velocity smaller than 30 degrees per second or close to 0, servo drivetrain will be engaged, and the load on these two motors will be adjusted dynamically depending on the load on the BLDC. In light of this, the elbow joint uses a hybrid actuation scheme combining a BLDC motor and MG90S servo motors. Both actuators contribute torque to achieve the desired joint motion without internal conflict. The control method is based on torque control, where torque is estimated from measured or inferred current. The BLDC provides high dynamic torque for fast motion, while the servo motors maintain position and assist during holding or fine adjustments. A blending factor determines each actuator's contribution based on motion state.

The torque produced by each actuator is estimated from its current using the motor torque constant K_t or an experimentally identified mapping:

$$\hat{\tau}_{\text{bldc}} = K_t \, i_{\text{bldc}}, \tag{13}$$

$$\hat{\tau}_{\text{srv}} = a \, (i_{\text{srv}} - i_0), \tag{14}$$

where i_{bldc} and i_{srv} are the measured currents of the BLDC and servo, a is the servo's torque–current gain, and i_0 is its no-load current.

The outer control loop generates a total required torque from the position error and its derivative:

$$\tau_{\text{net}} = K_p(q_d - q) + K_d(\dot{q}_d - \dot{q}) + K_i \int (q_d - q) \, dt + \tau_g, \tag{15}$$

where q_d and q are desired and measured joint angles, and τ_g is a gravity compensation term given by

$$\tau_g = mgr \sin(q). \tag{16}$$

The total required torque is then distributed between the BLDC and servo actuators by a blending coefficient α:

$$\tau_{\text{bldc,cmd}} = \alpha \, \tau_{\text{net}}, \qquad \tau_{\text{srv,cmd}} = (1 - \alpha) \, \tau_{\text{net}}. \tag{17}$$

The factor α increases during fast motion so that the BLDC supplies most of the torque, and decreases near steady state so that the servo stabilizes the joint position.

The BLDC torque command is converted to current by

$$i_{\text{cmd}} = \frac{\tau_{\text{bldc,cmd}}}{K_t}, \tag{18}$$

which drives the BLDC through its ESC. The servo torque command is converted to a small angular adjustment around its neutral position:

$$\theta_{\text{srv,cmd}} = q_d + \frac{\tau_{\text{srv,cmd}}}{k_{\text{virt}}}, \tag{19}$$

where k_{virt} is the virtual stiffness mapping servo torque to angle command.

By estimating torque through current sensing and distributing control effort adaptively between the BLDC and servos, the system achieves smooth, efficient, and thermally safe motion across both rapid movements and steady holds.

For the SoC controller, we will be using F280049C MCU. Two headers are used. All lines are 3.3-V CMOS; I^2C uses pull-ups to 3.3 V and CAN is differential on the bus side only (the MCU pins connect to the transceiver). Series resistors/ESD diodes are recommended at the header to protect the MCU and to tame edges.

The two connector headers aggregates the analog and discrete inputs. The labeled ADC channels (e.g., ADCINA2/5/8, ADCINC1/4/14) receive: the joint-state potentiometer, the EMG envelope, a clutch position/torque pot, and up to three debug inputs. Each input is conditioned to 0–3.3 V with a small anti-alias RC (10 kOhms/3.3 nF typical) and shares the MCU analog ground. The hardware reset (XRSn) is also available on this header for external supervision. Sampling is performed by the F280049C ADCs at ¿= 1 kS/s per active channel; firmware computes low-pass envelopes for EMG and averages the pots to reduce noise. The +5 V pin on Jsig1 powers sensors only; it does not feed the MCU core. Together, these headers provide a clean, protected path from field sensors to the controller while keeping all signaling within the C2000's electrical limits.

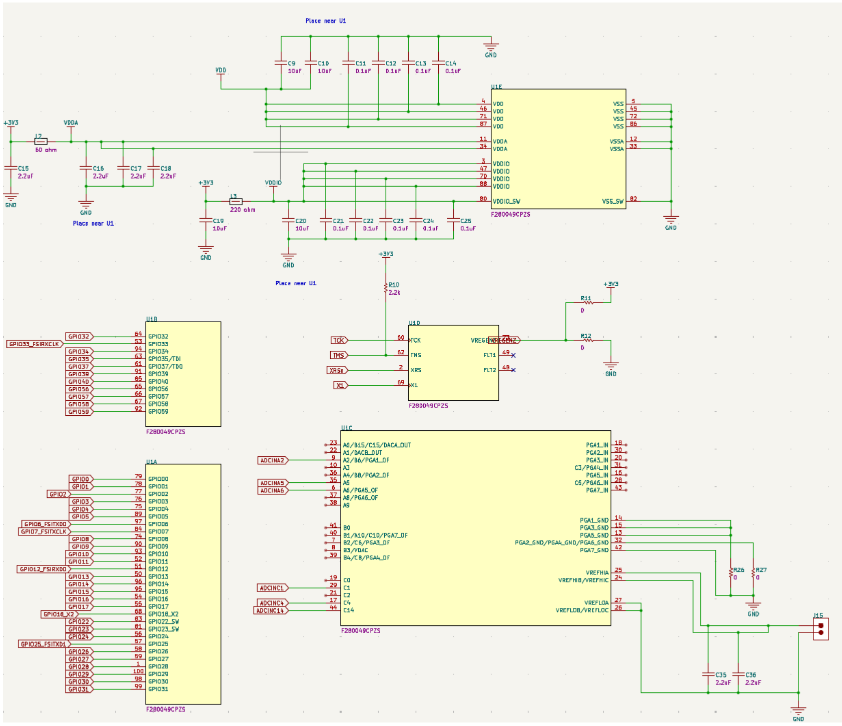

Figure 13: MCU I/O Schematic

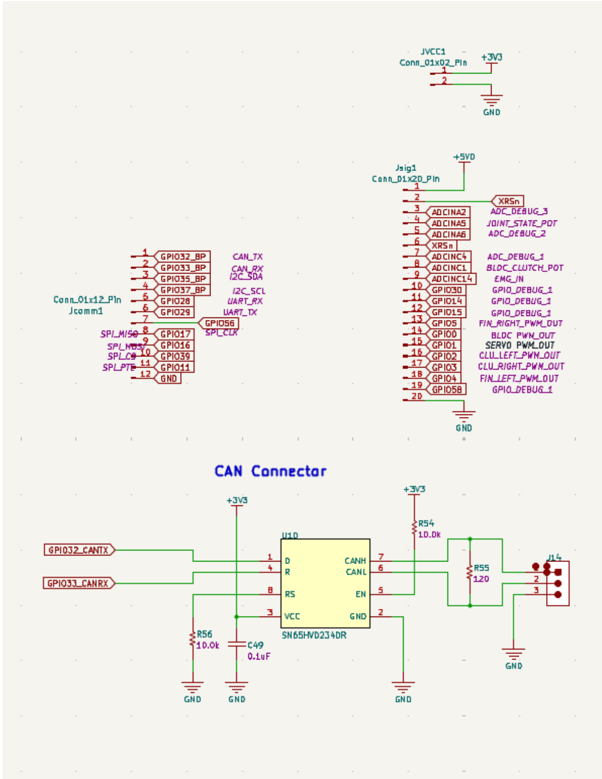

Figure 14: PCB Connectors

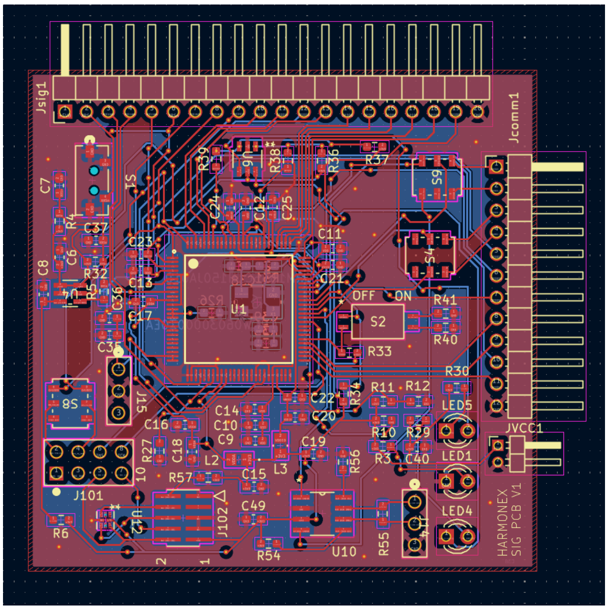

Figure 15: PCB front.

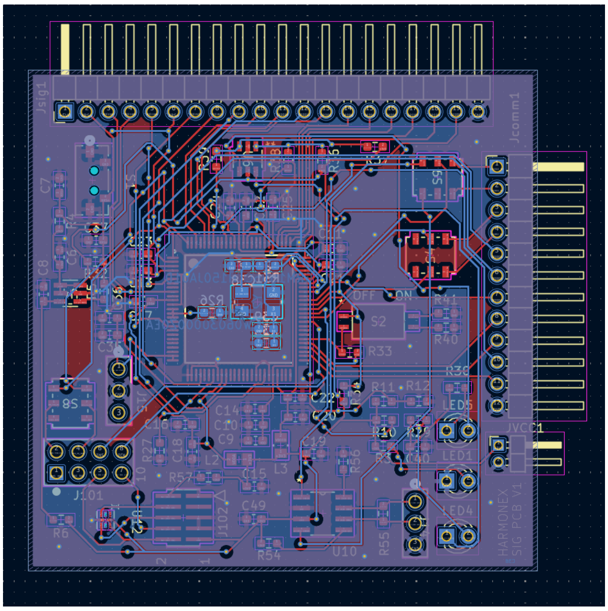

Figure 16: PCB back.

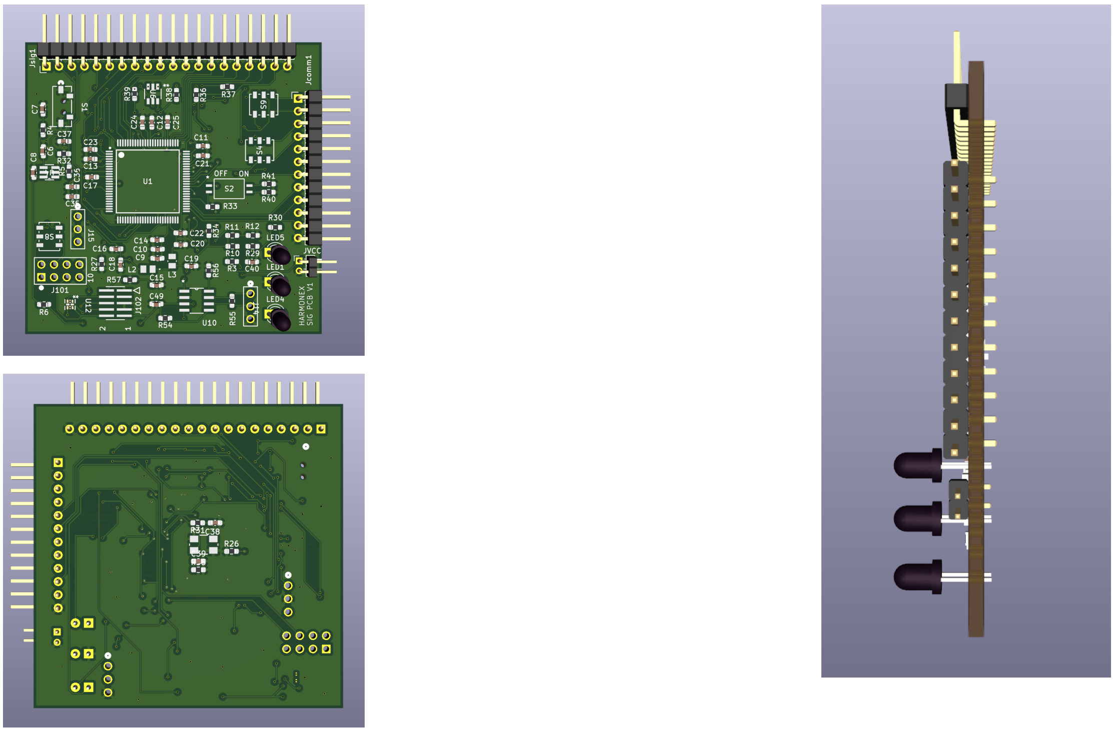

Figure 17: PCB renders (top/bottom at left; side view at right).

2.4.3 Requirements and Verification

Table 3: Signal/Control Subsystem — Requirements & Verification (EMG, MLP, Controls)

Requirements	Verification
• EMG electrodes: two bipolar channels with ≈ 20 mm spacing plus a reference; high-impedance differential AFE; no clipping in normal use.	• Placement audit with photos; verify spacing/alignment and strain relief. • Inject EMG-like bursts; confirm headroom and no saturation.
• EMG filtering: band-pass 20–450 Hz with 60 Hz notch; rectification + envelope LPF 5–10 Hz; envelope output 0–3.3 V with ≤ 50 ms analog latency.	• Measure filter magnitude response; verify cutoffs and notch depth. • Step input; measure envelope latency ≤ 50 ms and 0–3.3 V range.
• EMG sampling: ADC ≥ 1 kS/s/channel (raw) or ≥ 100 Hz (envelope); publish normalized envelopes at 100 Hz; false-activation rate $\leq 5\%$.	• Log rates and normalization (rest ≈ 0, MVC ≈ 1). • 30 min wear test with motion; count false triggers $\leq 5\%$.
• MLP predictor: inputs = [biceps, triceps, angle] with short history; ReLU hidden layers; linear output; features normalized with stored scalers; MCU inference ≥ 100 Hz with compute time < 1 ms.	• Unit-test preprocessing and layer sizes against spec. • Profile MCU inference time and update rate.
• PC training on synchronized logs covering full angle/speed/load; hold-out validation; median absolute error ≤ 3–$5°$ over 0–90°; slew-limited output with low-confidence guard.	• Report train/val/test MSE and learning curves; check coverage. • Replay held-out session through firmware; compute MAE and verify guard behavior.
• Torque-control robustness I: current→torque mapping (BLDC K_t; servo gain) accurate and monotonic; estimation error $\leq 10\%$ over operating range; anti-windup and saturation handling prevent instability.	• Bench dynamometer: command currents; compare estimated vs measured torque; compute $\leq 10\%$ error. • Force saturation conditions; verify bounded response and no oscillation.
• Torque-control robustness II: blending factor α avoids actuator fighting; during fast motion BLDC share $\geq 80\%$, during holds servo share $\geq 70\%$; step disturbance recovery < 200 ms with overshoot $< 20\%$.	• Execute fast and hold trajectories; log torque split and verify share bounds. • Apply load steps; measure recovery time and overshoot at the joint.

Table 4: Signal/Control Subsystem — Requirements & Verification (Signals)

Requirements	Verification
• Actuation outputs: ESC PWM 1–2 ms @ 50–400 Hz; servo PWM 3.3 V; command-to-update delay ≤ 2 ms; clutch GPIO with debounce and interlock.	• Toggle commands and measure PWM edge latency with a scope; verify ≤ 2 ms. • Validate clutch debounce and interlock timing.
• Sensor inputs: elbow pot 10 kΩ ratiometric to 3.3 V (ADC ≥ 1 kS/s, RC f_c=50–200 Hz, error $\leq \pm 2°$); EMG 0–3.3 V envelope to ADC; IMU SPI/I^{2}C ≥ 400 kHz with fused pose at 200 Hz.	• Sweep elbow angle against a reference; verify $\leq \pm 2°$ error. • Confirm EMG envelope range at ADC; sniff IMU bus and 200 Hz output.
• Communications and local power integrity: CAN 500 kbps (or RS-485 250–500 kbps) with heartbeat every 50 ms; 3 missed heartbeats ⇒ safe state; no missed deadlines during 100 mA D3V3 load steps and heavy CAN traffic.	• Pull the link; verify safe state after three missed heartbeats. • Superimpose 100 mA load steps on D3V3 while saturating CAN; check for zero missed deadlines.

2.5 Tolerance Analysis

One possible aspect of the design that directly affects the outcome would be structural integrity. To suffer a load from a high toque scenario, the choice of skeleton material should be precise and careful. The clutch at elbow and servo drive train is of vital significance. In any case these clutch fails to suffer high load scenario, the exoskeleton would fail, and even post safety risk on the user. Therefore, it is critical to evaluate the performance of the dog clutch made from PA-CF filament.

Suppose now the loading scenario is a 10 kg weight, and the joint state is at $\pi/2$, where the upper limb is vertical and the lower limb is horizontal to the ground. The torque at the joint is given by:

$$T_{\text{req}} = mgr = 10 \times 9.81 \times 0.40 \approx 39.2 \text{ N} \cdot \text{m}. \tag{20}$$

To include margin, all calculations below use

$$T = 50 \text{ N} \cdot \text{m} = 50{,}000 \text{ N} \cdot \text{mm}. \tag{21}$$

The clutch has $n = 4$ dogs engaged at mean radius $r_c = 20$ mm. Each dog therefore carries the tangential force

$$F = \frac{T}{n\, r_c} = \frac{50{,}000}{4 \times 20} \approx 625 \text{ N}. \tag{22}$$

Each dog looks like a "+" and is approximated at the root by a rectangular section with radial depth $h = 5$ mm, circumferential thickness $t = 13$ mm, and axial width $b = 11$ mm (the weakest path for bending). Fillets are present but small, so we later apply a modest notch factor.

Bending at the tooth root ($\sigma = Mc/I$). Treat the dog as a short cantilever with lever arm $\approx h/2$:

$$M = F\,\frac{h}{2}, \qquad I = \frac{bh^3}{12}, \qquad c = \frac{h}{2}, \qquad \sigma_{\max} = \frac{Mc}{I}. \tag{23}$$

Substituting $b = 11$, $h = 5$ and $F = 625$ N,

$$M = 625 \times 2.5 = 1562.5 \text{ N} \cdot \text{mm}, \qquad I = \frac{11 \times 5^3}{12} = 114.58 \text{ mm}^4, \tag{24}$$

$$\sigma_{\max} = \frac{1562.5 \times 2.5}{114.58} \approx 34.1 \text{ MPa}. \tag{25}$$

Because the + geometry introduces a root notch, apply a conservative $K_t \approx 1.6$ (small fillet). The effective bending stress is

$$\sigma_{\text{eff}} = K_t\, \sigma_{\max} \approx 1.6 \times 34.1 \approx 54.6 \text{ MPa}. \tag{26}$$

Transverse shear at the root ($\tau = \frac{VQ}{It}$). For a rectangular section the peak shear is well approximated by $\tau_{\max} = \frac{3V}{2A}$ with $A = bh$:

$$\tau_{\max} \approx \frac{1.5\,F}{bh} = \frac{1.5 \times 625}{11 \times 5} \approx 17.0 \text{ MPa}. \tag{27}$$

Including a mild shear notch factor $K_{t,\tau} \approx 1.2$,

$$\tau_{\text{eff}} \approx 1.2 \times 17.0 \approx 20.4 \text{ MPa}. \tag{28}$$

Torsion of the clutch ring/hub ($\tau = T\rho/J$). With outer/inner radii $R_o = 20$ mm and $R_i = 12$ mm,

$$J = \frac{\pi}{2}\left(R_o^4 - R_i^4\right) \approx 2.18 \times 10^5 \text{ mm}^4, \qquad \tau_{\text{ring}} = \frac{TR_o}{J} \approx \frac{50{,}000 \times 20}{2.18 \times 10^5} \approx 4.6 \text{ MPa}. \tag{29}$$

Safety factors (PA6–CF). Bambu Lab Datasheet strengths: bending (XY, dry) $\approx$ 151 MPa; bending (XY, wet) $\approx$ 95 MPa; layer (Z, dry) $\approx$ 80 MPa; layer (Z, wet) $\approx$ 45 MPa. A conservative shear allowable is $\tau_{\text{allow}} \approx 0.6\,\sigma_{\text{allow}}$. Using the effective stresses above:

$$\text{SF}_{\text{bend,XY,dry}} = \frac{151}{54.6} \approx 2.77, \qquad \text{SF}_{\text{bend,XY,wet}} = \frac{95}{54.6} \approx 1.74, \tag{30}$$

$$\text{SF}_{\text{shear,XY,dry}} = \frac{0.6 \times 151}{20.4} \approx 4.4, \qquad \text{SF}_{\text{shear,XY,wet}} = \frac{0.6 \times 95}{20.4} \approx 2.8, \tag{31}$$

$$\text{SF}_{\text{ring torsion}} = \frac{0.6 \times 151}{4.6} \approx 19.7 \quad \text{(very high)}. \tag{32}$$

If printed in the weak Z orientation, the bending safety factor becomes

$$\text{SF}_{\text{bend,Z,dry}} = \frac{80}{54.6} \approx 1.47, \qquad \text{SF}_{\text{bend,Z,wet}} = \frac{45}{54.6} \approx 0.82, \tag{33}$$

which is unacceptable for wet/humid service.

In summary, with four dogs of size $h = 5$ mm, $t = 13$ mm, $b = 11$ mm at $r_c = 20$ mm, the PA6–CF clutch meets strength with a comfortable safety factor when printed so that the tooth root carries load in the XY plane.

3 Cost and Schedule

3.1 Cost Analysis

- **Labor:** The average starting salary for UIUC ECE graduates is estimated to be $95,000/year or $45/hour. The cost of labor is estimated by 2.5 x weekly hours x hourly wage x 10 weeks.
  - Alan: Estimated 20 hours per week. 2.5 x 8 x 45 x 10 = $22,500.
  - Rubin: Estimated 8 hours per week. 2.5 x 8 x 45 x 10 = $9,000.
  - David: Estimated 6 hours per week. 2.5 x 6 x 45 x 10 = $6,750.
- **Parts:**

Part	Description	Manufacturer	Quantity	Unit Cost in USD
RS700 V2	High Torque BLDC	Nsdrc Scaleparts	1	124.99
MN5006	UAV Motor	T-Motor	1	84.99
XINGYHENG	Power Converter	Xingyheng	1	12.99
None	Cooler	Devmo	1	13.99
None	Power Converter	DROK	1	15.99
63-37	Solder Wire	MAIYUM	1	8.99
XT60	Plug Connector	elechawk	1	8.99
SQESC 2670	Motor Speed Controller	SEQURE	1	45.58
MG90S	Motor kit	Miuzei	1	23.99
WH148	Rotary Potentiometer	Comimark	1	6.99
None	ESC Motor Plug	Ruikarhop	1	16.99
None	Metric Knurled Nuts	Hanglife	1	19.99
None	Screw Assortment	MYwish	1	9.99
PA6-CF	Filament	Bambu Lab	2kg	79.99
PETG-CF	Filaments	Bambu Lab	2kg	31.99
PAHT-CF	Filaments	Bambu Lab	1kg	94.99
PET-CF	Filaments	Bambu Lab	1kg	84.99
LAUNCHXL-F280049C	LaunchPad kit	Texas Instruments	1	39.00
Total				837.40

Table 5: Bill of Materials

Development is still in progress, and any new parts introduced will be reported in future reports.

3.2 Schedule

The project responsibilities are distributed as follows: Alan is developing the mechanical system; Rubin is handling software development; and David is in charge of power and subsystem integration.

Timeline	Alan	Rubin	David
Late August	Beginning of semester		
Mid September	Start working on project		
10/8	Produce 3D exoskeleton		
10/16	Signal PCB	Work on software	Power PCB
10/27	continue exoskeleton structure	Research EMG	Solder, test PCBs
11/3		Finalize EMG code	Revise PCB
11/10	Revision	Revision	Integrate subsystems
11/17		Finish development for Mock demo	
11/24		Fall break, address unforeseen challenges	
12/1		Final revision for final demo	
12/10	Final reports	Final reports	Final reports
12/11	Lab Notebook	Lab Notebook	Lab Notebook

Table 6: Planned timeline of progress

4 Ethics and Safety

4.1 Battery & Electrical

Hazards: Battery & circuit failure.

Mitigations: Battery pack with BMS monitoring output power, overcharge/overdischarge, thermal runaway, and reduce/shutdown output when battery failure is detected. Install fuses in the main circuit to cut off the power source when the current exceeds the safety threshold due to a short circuit or malfunction.

Hazards: Thermal runaway / burns from hot circuit, drivers, motors.

Mitigations: Thermostats on circuit, drivers, motors; software monitoring & hardware thermal cutoff (bimetal/thermal fuse) to reduce or halt output when overheating.

Hazards: Exposed conductors.
Mitigations: Insulated plating around circuits, wires, and motors.

4.2 Control/Fail-Safe Electronics

Hazards: Excessive torque/velocity.
Mitigations: Hardware limiter on actuator and motor output; Emergency-Stop button that cuts actuator and motor power.

Hazards: Bad sensor data / EMG input misinterpretation.
Mitigations: Filter noisy inputs, emergency stop when null/erratic input detected.

Hazards: Software bugs.
Mitigations: Torque/velocity hard limits enforced in hardware;

4.3 Mechanical/Lifting Scenarios

Hazards: Entrapment when jammed.
Mitigations: Manual clutch disengagement switch, exposed bolts on joints that can be loosen to disassemble with simple tools.

Hazards: Over-extension / sudden drop on power loss.
Mitigations: Passive counterbalance or elastic element to limit impulse; normally engaged friction brake/damper that defaults to safe resistive descent when power is lost;

4.4 EMG Sensing

Hazards: Poor electrode placement or loose leads causing false commands.
Mitigations: Use standard skin prep (shave, alcohol wipe, dry), strain–relief tape on leads, and clear placement marks (20,mm spacing along muscle fibers). Add startup checks for signal quality (baseline noise, impedance) and block control if quality is low.

Hazards: Skin irritation from pads or paste.
Mitigations: Prefer hypoallergenic pads; limit session length; rotate sites; provide cleaning instructions. Stop use if redness or pain occurs.

Hazards: Crosstalk between muscles leading to wrong angle predictions.
Mitigations: Place electrodes over muscle bellies (biceps/triceps) and away from tendons; use differential pickup and proper band-pass filtering; add a low-confidence "hold" mode when signals conflict.

4.5 EMG Analog Front-End

Hazards: Electrical shock or unsafe leakage to the body.
Mitigations: Keep the EMG front-end isolated or battery-powered; use high-value input resistors and series protection;

Hazards: Saturation/clipping of the amplifier.
Mitigations: Gain staging with headroom; envelope detection with defined dynamic range; firmware clamps out-of-range values and flags the condition.

4.6 EMG Data, Training, and Model

Hazards: Training data that does not represent real use (bad labels, short sessions).

Mitigations: Collect PC-based "free-run" sessions covering the full elbow range, speeds, and loads; synchronize EMG envelopes and potentiometer angle; inspect logs for gaps; split into train/validation/test; document the data set.

Hazards: Privacy and data handling.

Mitigations: Store recordings locally, anonymize filenames, and delete raw sessions after training unless the user consents to retention; version the exported weights and scalers.

Hazards: Model overfitting or drift after electrode re-placement.

Mitigations: Keep a small MLP; use cross-validation and early stopping; include a quick startup calibration (rest + brief contractions) that rescales inputs; allow easy PC retraining and re-flashing of weights.

4.7 EMG Controls and Fail-Safes

Hazards: EMG misinterpretation causing unintended motion.

Mitigations: Require concurrent agreement between biceps/triceps channels (antagonist check); gate commands by a confidence metric; when confidence is low, hold last safe angle. Provide a big, latching Emergency-Stop that removes actuator power.

Hazards: Sudden jumps in predicted angle.

Mitigations: Low-pass filter and slew-rate limit the model output; clamp commands to a safe angle window; blend toward current angle when both channels fall near zero.

Hazards: Software faults in feature extraction or inference.

Mitigations: Watchdog timer; range checks on ADC and outputs; NaN/Inf guards; revert to a safe fallback (manual potentiometer control or fixed neutral angle) on any fault.

Hazards: Latency causing instability.

Mitigations: Fixed processing window (e.g., 50,ms), deterministic scheduling, and profiling; if loop time is exceeded, degrade to slower, safe assistance levels.

4.8 Tampering and Misuse

Hazards: Program/parameters modified or corrupted

Mitigations: Flash the control firmware to ROM so it cannot be altered in the field.

Hazards: Fail-Safe defeated, mechanical/battery/electronics systems tampered.

Mitigations: On power-up, run a built-in self test before enabling motion, checking peripheral connections, fail-safe, battery health, cross-check sensor readings with actuator outputs.

Hazards: Abuse and Misuse

Mitigations: Labeling weight capability and limits, provide safety training manual to users.

Hazards: Day-to-day variability (sweat, fatigue, pad shift).

Mitigations: Brief per-session calibration to set rest and max voluntary contraction; store normalization parameters; prompt the user to re-calibrate if baselines drift.

Hazards: Misuse (pads swapped, wrong sites).

Mitigations: Color-code leads and provide a simple placement card; firmware verifies expected pattern during a guided check (flex $\rightarrow$ biceps rises, triceps falls). If pattern fails, refuse to start.