ECE 445 Project Proposal

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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

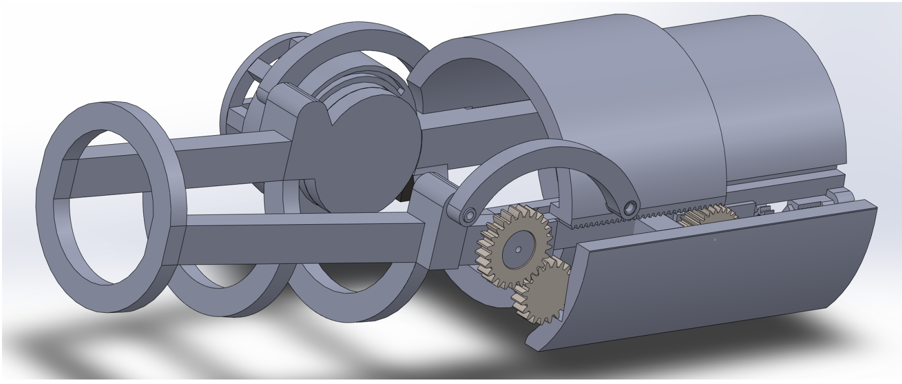

Figure 1: CAD model of in-progress design

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 $\geq 60°/\text{s}$, 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

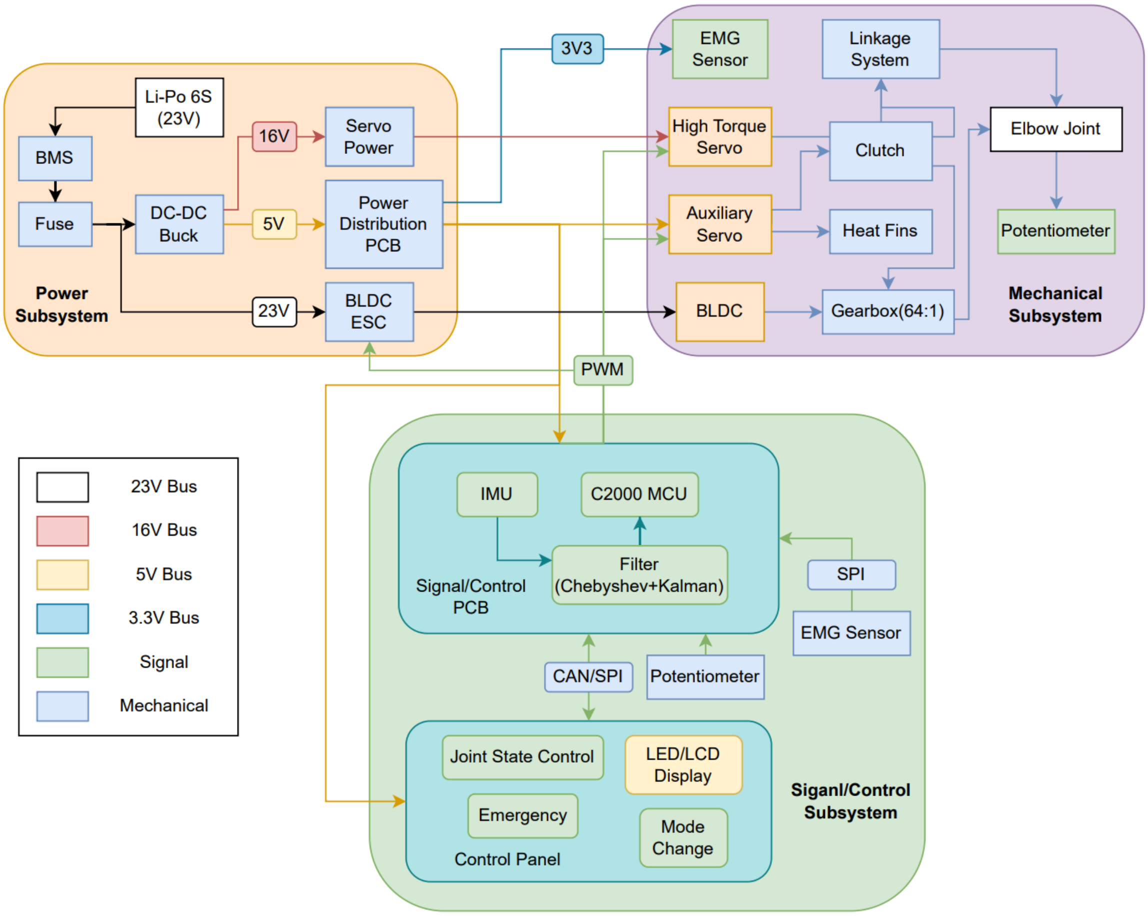

Figure 2: Block Diagram

2.2 Subsystem Overview

2.2.1 Mechanical Subsystem

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

2.2.2 Power Subsystem

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)—each with its own fuse. This power distribution prevents motor/servo transients from sagging the control circuits. A 6-cell Li-Po pack (25.2–19.0 V) feeds a BMS, creating a protected 23 V bus that connects to the BLDC and two isolated DC-DC branches: 16 V SERVO for the high-torque servo motor and 5 V LOGIC for electronics. The 5 V rail enters the Power Distribution PCB and is converted locally to 3.3 V on the signal board.

2.2.3 Signal/Control Subsystem

6 EMG Sensors will be placed on Anterior deltoid, Middle deltoid, Posterior deltoid, Biceps brachii, Triceps brachii, Brachioradialis, to read muscle movement from the user and communicate to the Control PCB via SPI. IMUs and potentiometers will be used to assess the angle of joints and velocity of the movement as feedback to the control system. Inputs from EMGs, IMUs, and potentiometers will be filtered by a Chebyshev band-pass and Kalman fusion filter to filter off noises before passed to the control algorithms. A C2000 MCU is used to processes inputs and runs estimation of target angle, and computes the outputs to servos and motors in control algorithms to drive the exoskeleton to the target position. 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.

2.3 Subsystem Requirements

2.3.1 Power Subsystem (Battery, BMS, Fusing, DC–DC, Distribution)

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 Actuation & Mechanical Subsystem (BLDC + Gearbox + Dog Clutch; Servo + Linkage; Joint; Structure)

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 $\geq$ 20 A); 16V SERVO (continuous $\geq$ 10 A, peak $\geq$ 20 A).
- **Signals:** ESC PWM (1000–2000 Hz), servo PWM (3.3 V logic), clutch enable GPIO.
- **Sensing:** Elbow potentiometer → 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 $\geq 120°$/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).

2.3.3 Signal/Control Subsystem (MCU, Sensors, EMG, HMI/Comms, Safety)

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 ≤ 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.

Interfaces.

- **Power:** 5 V input from power PCB; local 3.3 V generation. A3V3 noise $< 50\ \mu V_{rms}$; 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 ≤ 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 ≥ 1 kS/s; RC $f_c = 50$–200 Hz; absolute error $\leq \pm 2°$ over 0–90°.
  - **IMU:** SPI or $I^2C \geq 400$ kHz; gyro/accel ODR ≥ 1 kHz; fusion output at 200 Hz.
- **Actuation outputs:** ESC PWM (1–2 ms pulses @ 50–400 Hz) with command-to-update delay ≤ 2 ms; servo PWM (3.3 V logic) with jitter $< 50\ \mu$s; clutch enable GPIO with debounce and interlock.
- **HMI/Comms:** CAN 500 kbps (or RS-485 250–500 kbps); heartbeat every 50 ms; 120 Ω termination at bus ends; all frames include CRC and sequence counters.
- **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 ≤ 150 ms end-to-end; main control loop ≥ 500 Hz with worst-case jitter < 1 ms; PWM outputs update within ≤ 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 $\leq 5°$/s; engagement/disengagement completes in ≤ 200 ms; peak elbow-torque ripple during engagement $\leq 15\%$ of steady assist.
- **State estimation accuracy:** elbow angle RMS error $\leq 2°$ over 0–90°; IMU drift held $< 1°$/min during static holds via fusion.
- **Comms robustness:** loss of 3 consecutive heartbeats (≥ 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 $< 50\ \mu\text{V}_{\text{rms}}$ 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 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:

$$T_{\text{req}} = mgr = 10 \times 9.81 \times 0.40 \approx 39.2\ \text{N}\cdot\text{m}. \tag{1}$$

To include margin, all calculations below use

$$T = 50\ \text{N}\cdot\text{m} = 50{,}000\ \text{N}\cdot\text{mm}. \tag{2}$$

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

$$F = \frac{T}{n\,r_c} = \frac{50{,}000}{4 \times 20} \approx 625\ \text{N}. \tag{3}$$

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 $\approx h/2$:

$$M = F\,\frac{h}{2}, \qquad I = \frac{bh^3}{12}, \qquad c = \frac{h}{2}, \qquad \sigma_{\max} = \frac{Mc}{I}. \tag{4}$$

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

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

$$\sigma_{\max} = \frac{1562.5 \times 2.5}{114.58} \approx 34.1\ \text{MPa}. \tag{6}$$

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

$$\sigma_{\text{eff}} = K_t\,\sigma_{\max} \approx 1.6 \times 34.1 \approx 54.6\ \text{MPa}. \tag{7}$$

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 $A = bh$:

$$\tau_{\max} \approx \frac{1.5\,F}{bh} = \frac{1.5 \times 625}{11 \times 5} \approx 17.0\ \text{MPa}. \tag{8}$$

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

$$\tau_{\text{eff}} \approx 1.2 \times 17.0 \approx 20.4\ \text{MPa}. \tag{9}$$

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

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

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:

$$\mathrm{SF}_{\text{bend,XY,dry}} = \frac{151}{54.6} \approx 2.77, \qquad \mathrm{SF}_{\text{bend,XY,wet}} = \frac{95}{54.6} \approx 1.74, \tag{11}$$

$$\mathrm{SF}_{\text{shear,XY,dry}} = \frac{0.6 \times 151}{20.4} \approx 4.4, \qquad \mathrm{SF}_{\text{shear,XY,wet}} = \frac{0.6 \times 95}{20.4} \approx 2.8, \tag{12}$$

$$\mathrm{SF}_{\text{ring torsion}} = \frac{0.6 \times 151}{4.6} \approx 19.7 \quad \text{(very high)}. \tag{13}$$

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

$$\mathrm{SF}_{\text{bend,Z,dry}} = \frac{80}{54.6} \approx 1.47, \qquad \mathrm{SF}_{\text{bend,Z,wet}} = \frac{45}{54.6} \approx 0.82, \tag{14}$$

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 Ethics and Safety

3.1 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.

3.2 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;

3.3 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;

3.4 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.