ECE 445 Spring 2026

Design Document

Circular Antweight Battlebot

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Contents

1. INTRODUCTION

1.1 Problem and Solution

Antweight (<= 2 lb) combat robots must remain mobile, controllable, and safe while enduring repeated impacts, motor stalls, and power transients during a two-minute match. In practice, many small combat robots lose matches not because their weapon concept is weak, but because they get stuck on opponents or arena walls, lose traction while pushing, or suffer electrical brownouts that reset the controller and drop the radio link. These failures also create safety risks during testing because an uncontrolled robot can move unpredictably.

Our solution is a circular, low-profile 'UFO-shaped' antweight battlebot that prioritizes positional control and robustness. A protected differential drivetrain (two recessed wheels) reduces exposed corners and snag points, improving survivability. A front motorized shovel/lifter provides an active mechanism to get under opponents, lift or destabilize them, and enable pushing or pinning. The robot is controlled from a PC over Wi-Fi using an onboard custom PCB (ESP32 + motor drivers). Safety is enforced with layered shutdown: a manual kill switch that removes motor power, firmware link-loss failsafe, and hardware-level fault/enable gating to quickly disable motors in overcurrent or stall conditions.

1.2 Visual Aid

Figure 1 illustrates how the system is used. The operator runs a controller application on a PC and sends commands over Wi-Fi to the battlebot. The robot executes drive and weapon commands while reporting link/fault status via LEDs and optional telemetry.

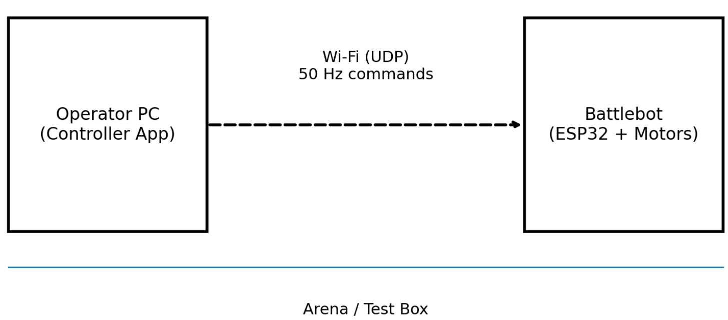

Figure 1. System use context (operator PC controlling the robot over Wi-Fi).

Figures 2a and 2b show the current mechanical concept used for packaging and integration planning.

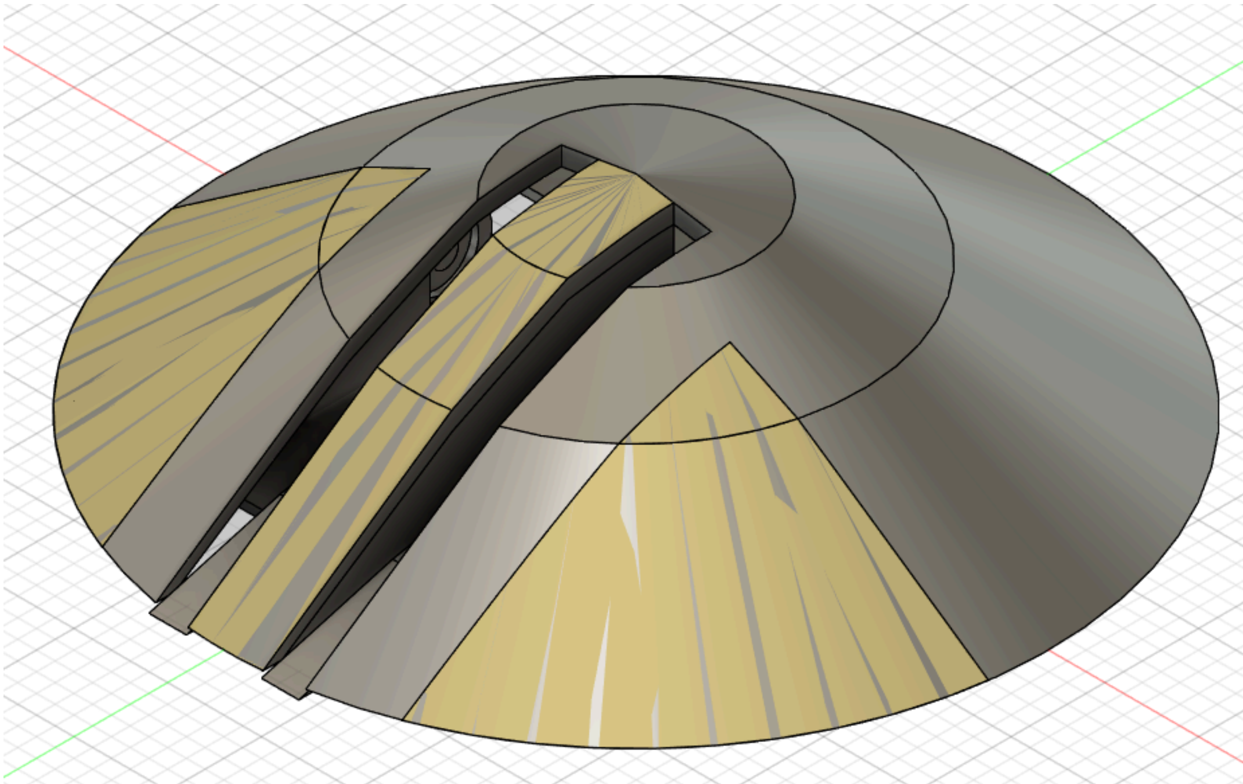

Figure 2a. Concept CAD render (top/isometric view).

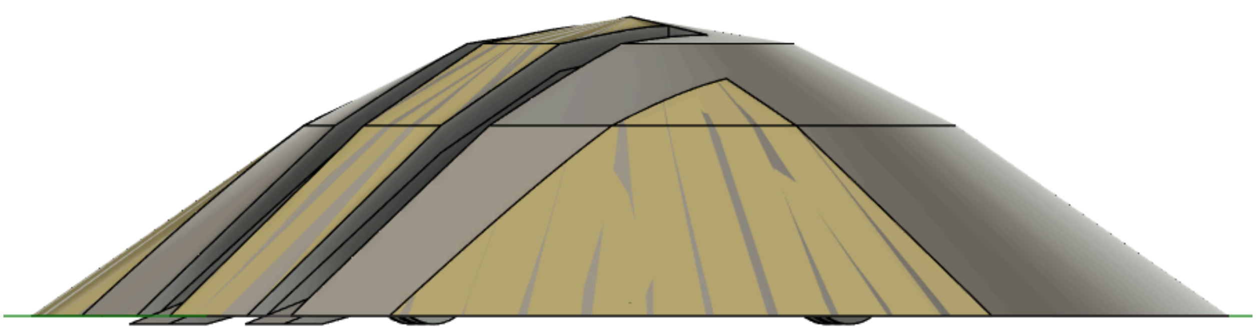

Figure 2b. Concept CAD render (side view).

1.3 High-Level Requirements

1. HLR1 (Weapon effectiveness): The shovel/lifter must raise a 0.9 kg (2 lb) test block by >= 40 mm within <= 2.0 s and hold it for >= 5 s without mechanism damage or controller reset.

2. HLR2 (Teleoperation responsiveness): The robot must be controllable from a PC over Wi-Fi using the onboard custom PCB and respond to operator commands with average end-to-end latency <= 150 ms during a 2-5 minute driving test.

3. HLR3 (Safety shutdown): The robot must support a manual kill switch and must automatically disable all motion within <= 2.0 s after RF link loss; faults (overcurrent/stall) must also disable affected actuators without requiring firmware intervention.

4. HLR4 (Mobility under load): The drivetrain must reach >= 0.4 m/s unloaded on arena-like flooring and must push a 1.0 kg test sled for >= 2 s without logic brownout.

2. DESIGN

2.1 System Block Diagram

Figure 3 provides the modular system block diagram. Subsystems are designed to be implemented and tested independently and then integrated: (1) Control & Communication, (2) Power & Safety, (3) Drive, and (4) Weapon.

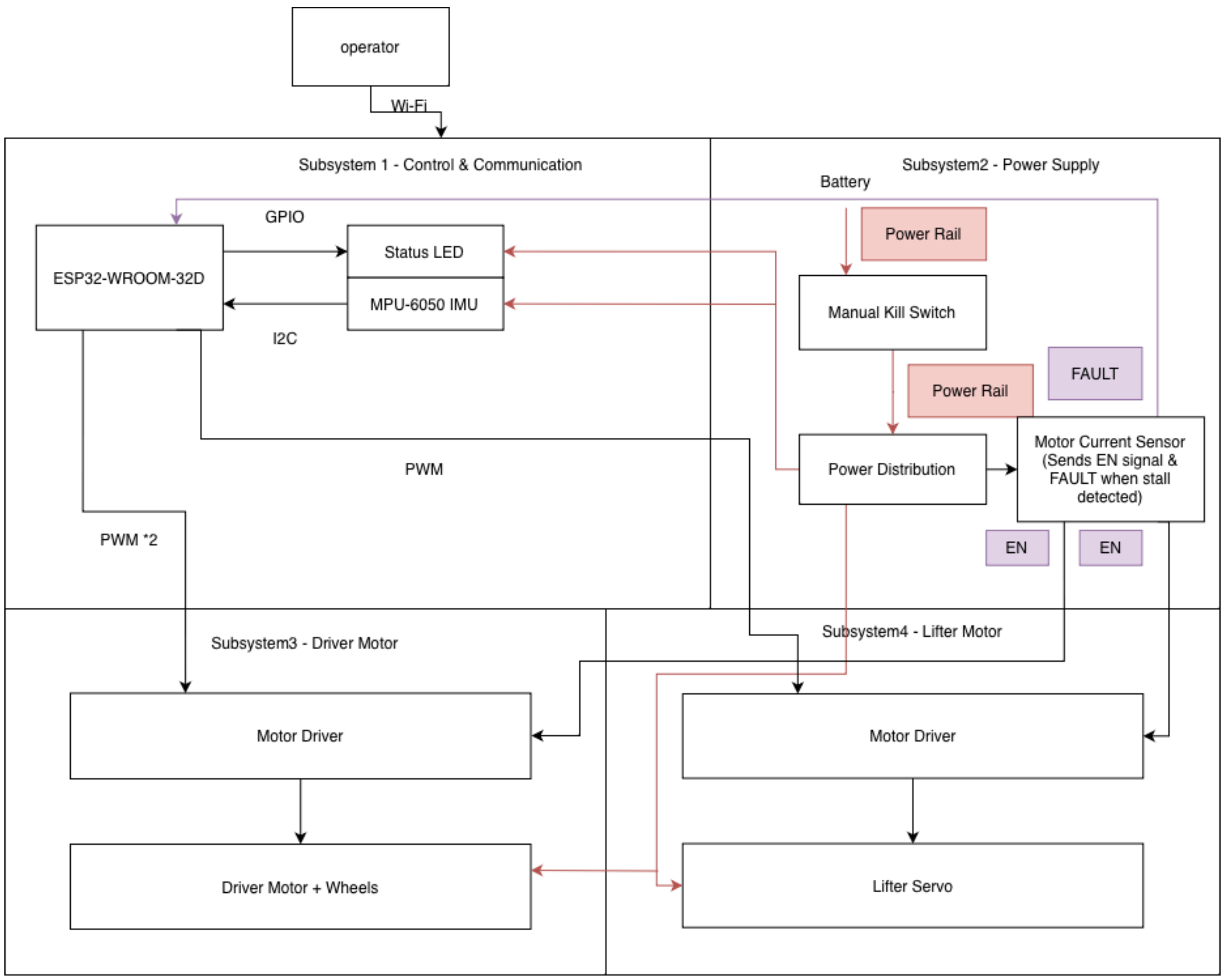

Figure 3. System-level block diagram (subsystems and critical interfaces).

Critical subsystems: The ESP32 receives commands from the operator and generates PWM outputs for the motor drivers and servo. The power subsystem routes battery power through a manual kill switch and regulated rails for logic and servo power. Fault/enable (FAULT/EN) signals provide a hardware safety layer that can disable motor drivers rapidly in abnormal conditions.

2.2 Physical Design

The robot chassis is a circular shell with a shallow dome profile and a front wedge/shovel opening. The drivetrain wheels are recessed into side pockets to reduce direct impacts. The battery and PCB are mounted near the center of mass to reduce yaw inertia and improve stability during pushing. A removable top lid provides access to the kill switch, battery connector, and programming header.

Nominal physical targets (to be finalized in CAD): diameter 120-140 mm; height <= 45 mm; ground clearance 1-2 mm at the wedge lip; wedge angle 15-25 degrees; wheel diameter 45-55 mm. The shovel leading edge uses hard stops to prevent over-travel and includes reinforcement (metal insert or thickened print) to reduce chipping.

2.3 Subsystem 1 - Control & Communication

Purpose and contribution to HLRs: This subsystem implements teleoperation (HLR2) and enforces link-loss shutdown behavior (HLR3). It also provides status visibility (armed/link/fault) to support safe testing.

2.3.1 Hardware design

Microcontroller: ESP32-WROOM-32D module on the custom PCB. The ESP32 runs at 3.3 V and provides Wi-Fi, GPIO, PWM, and I2C. We include a UART programming header and a reset/boot interface for firmware loading.

Sensors: MPU-6050 IMU via I2C (400 kHz fast mode). IMU data (>= 50 Hz) supports optional impact logging and orientation telemetry.

Indicators: Three external LEDs (Power/Armed, Link, Fault) driven by GPIO through current-limiting resistors.

2.3.2 Interfaces (quantitative)

Power input: 3.3 V logic rail, 3.3 V +/- 5%, peak ESP32 current budget 500 mA (includes Wi-Fi TX peaks).

Wi-Fi link: UDP control packets at 50 Hz (20 ms period). Packet loss tolerance: up to 5 consecutive packets before failsafe triggers.

Motor control outputs: (a) two PWM + DIR pairs for left/right drive H-bridges; PWM frequency 20 kHz target (inaudible), 8-10 bit duty resolution. (b) 50 Hz servo pulse output (1.0-2.0 ms) for weapon servo.

I2C: 400 kHz; pullups sized for < 300 ns rise time with estimated bus capacitance <= 100 pF (target 2.2 kΩ to 4.7 kΩ).

Fault inputs: active-low FAULT line(s) from motor driver(s) sampled by GPIO interrupt; forces immediate output disabled.

2.3.3 Firmware architecture and safety logic

Firmware runs a fixed-rate 50 Hz control loop:

1. Receive and parse UDP packets (drive throttle, turn, weapon command, arm bit, sequence number).
2. Apply command limiting (slew rate, max duty).
3. Update PWM outputs to motor drivers and servo.
4. Update LEDs and telemetry.

Failsafes:

1. Link-loss: if no valid packet with a new sequence number is received for 2.0 s, set motor PWM=0, assert brake/coast as configured, and command weapon servo to safe position. Remain disabled until the operator re-arms.
2. Fault: on FAULT interrupt, immediately set all actuator outputs to safe state and latch fault until manual reset.
3. Brownout robustness: brownout detector remains enabled; the power design targets >= 3.1 V minimum on the 3.3 V rail during worst-case loads.

2.4 Subsystem 2 - Power Supply & Safety

Purpose and contribution to HLRs: This subsystem enables reliable operation under peak loads (HLR4) while enforcing safety shutdown (HLR3). It provides stable regulated rails for logic and servo, and it ensures faults/stalls cannot cause prolonged heating.

2.4.1 Power architecture

Battery: 3S LiPo (11.1 V nominal, 12.6 V full, ~9.0 V under heavy load). The pack connects through an XT30 or JST-VH connector.

Manual kill switch: single-action mechanical switch that removes motor power (VMOTOR) and de-energizes actuators.

Regulation: A 3 A buck converter generates a 5.0 V rail for the weapon servo and auxiliary loads. A 3.3 V regulator supplies the ESP32 and sensors. Bulk capacitance is placed at the battery input and near the ESP32 (>= 1000 uF low-ESR electrolytic/tantalum plus 0.1 uF ceramics).

Protection: Motor drivers provide overcurrent protection and FAULT outputs. An additional system-level fuse (polyfuse or blade fuse) limits catastrophic wiring faults.

2.4.2 Quantitative requirements and interfaces

VBAT: 3S LiPo, 9.0 V to 12.6 V operating range (target).

VMOTOR rail: VBAT after kill switch, continuous current >= 10 A, peak >= 20 A (<= 1 s), wiring sized accordingly.

5V rail: 5.0 V +/- 5%, continuous >= 3.0 A (servo stall + margin).

3.3V rail: 3.3 V +/- 5%, continuous >= 0.7 A (ESP32 Wi-Fi peaks + sensors + LEDs).

Kill switch action: disables all motion within 0.5 s of actuation (electrical) and is externally accessible.

Fault response: Motor driver overcurrent/thermal fault must disable its output within <= 50 ms and assert FAULT to ESP32.

2.4.3 Key design decisions

3S LiPo provides sufficient voltage headroom for motor performance while allowing efficient buck regulation to 5 V and 3.3 V. Separating servo power (5 V rail) from logic (3.3 V rail) reduces conducted noise and prevents servo stall current from sagging the MCU rail. Bulk capacitance near the ESP32 and careful ground routing (star connection between high-current return and logic return) mitigate brownout during fast load steps.

2.5 Subsystem 3 - Drive (Motor Driver + Motors + Wheels)

Purpose and contribution to HLRs: This subsystem provides mobility and pushing power (HLR4) and must remain controllable under load (HLR2). A protected differential drive reduces mechanical damage risk during collisions.

2.5.1 Motor and wheel selection

We selected two brushed DC micro metal gearmotors (Pololu-class) with a gear ratio around 100:1 and a high-power 6 V motor option. This provides a tradeoff between top speed and stall torque suitable for a 2 lb robot. Wheel radius is approximately 22-25 mm. Wheel material is high-traction TPU or rubber tread on a 3D-printed hub to maximize pushing force.

2.5.2 Motor driver selection and interface

Each drive motor is controlled by a dedicated H-bridge driver IC with integrated protection and fault reporting (e.g., TI DRV8871). Inputs: PWM and DIR from ESP32. Outputs: bidirectional motor current on VMOTOR. The driver exposes a FAULT output to the ESP32 and enforces internal current limiting to reduce stall heating.

2.5.3 Quantitative requirements

Speed: >= 0.4 m/s unloaded on an arena-like surface (measured over 1 m run).

Push test: push a 1.0 kg sled for >= 2 s without ESP32 reset or link drop.

Driver electrical: >= 3 A continuous per channel, >= 5 A peak <= 1 s; PWM >= 1 kHz, target 20 kHz.

Mechanical: wheels recessed; drivetrain must survive direct impact equivalent to a 2 lb robot collision at 1 m/s without motor shaft bending.

2.6 Subsystem 4 - Weapon (Shovel/Lifter Actuation)

Purpose and contribution to HLRs: The shovel/lifter is the active mechanism used to get under and destabilize opponents (HLR1). It must be strong enough to lift a 2 lb block with margin and safe under jams (HLR3).

2.6.1 Mechanical mechanism

The weapon consists of a front wedge lip and an actuated shovel plate connected through a short linkage. The mechanism is designed for limited travel (0-45 degrees) with hard stops to prevent over-rotation.

2.6.2 Actuator selection and interface

Actuator: high-torque metal-gear servo (MG996R-class) powered from the 5 V rail. Control is a standard 50 Hz servo PWM signal from the ESP32. Servo power wiring uses a dedicated ground return to the 5 V regulator and includes local decoupling (>= 470 uF) near the servo connector to reduce voltage sag.

2.6.3 Quantitative requirements

Lift test: raise 0.9 kg block by >= 40 mm within <= 2.0 s; hold >= 5 s.

Thermal/duty: sustain >= 30% duty cycle in a 2-minute match without thermal shutdown.

Jam safety: if shovel is stalled, current limit or fault must prevent continuous stall > 0.5 s.

2.7 Requirements and Verification (R&V) Table

Table 1 maps high-level and subsystem requirements to objective verification procedures. Verification methods: T = test/measurement, A = analysis/calculation, I = inspection.

ID	Requirement	Verification	Procedure / Setup	Pass Criteria	Evidence
HLR1	HLR1 (Weapon effectiveness): The shovel/lifter must raise a 0.9 kg (2 lb) test block by >= 40 mm within <= 2.0 s and hold it for >= 5 s without mechanism	T	Lift 0.9 kg block using weapon from rest; measure lift height and time; hold position 5 s.	>= 40 mm in <= 2.0 s; hold >= 5 s; no reset	Video + measurements

	damage or controller reset.				
HLR2	HLR2 (Teleoperation responsiveness): The robot must be controllable from a PC over Wi-Fi using the onboard custom PCB and respond to operator commands with average end-to-end latency <= 150 ms during a 2-5 minute driving test.	T	PC sends timestamped commands at 50 Hz; ESP32 echoes seq/timestamp; measure input-to-PWM update latency over 5 min.	Average <= 150 ms; no > 500 ms spikes	Log file + plot
HLR3	HLR3 (Safety shutdown): The robot must support a manual kill switch and must automatically disable all motion within <= 2.0 s after RF link loss; faults (overcurrent/stall) must also disable affected actuators without requiring firmware intervention.	T	Drop Wi-Fi link; measure time until PWM=0 and motors stop. Test kill switch.	Auto stop <= 2.0 s; kill switch stop <= 0.5 s	Video + oscilloscope
HLR4	HLR4 (Mobility under load): The drivetrain must reach >= 0.4 m/s unloaded on arena-like flooring and must push a 1.0 kg test sled for >= 2 s without logic brownout.	T	Speed run over 1 m; push 1.0 kg sled for >= 2 s while monitoring 3.3 V rail.	Speed >= 0.4 m/s; no reset; 3.3 V stays >= 3.1 V	Video + DMM/Scope
S1-1	Control loop updates motor outputs at >= 50 Hz.	T	Instrument firmware with GPIO toggle each loop; measure frequency.	>= 50 Hz	Scope capture
S2-1	5 V rail regulation within +/-5% under 0-3 A load step.	T	Electronic load steps 0.5 A to 2.5 A; measure droop/settle.	4.75-5.25 V; settle < 200 ms	Scope capture
S2-2	Drive motor overcurrent fault	T	Command stall (wheel blocked); measure FAULT	<= 50 ms	Scope capture

	disables output within <= 50 ms.		edge to PWM disable.		
S3-1	Motor driver supports >= 3 A continuous per drive motor.	A/I	Use datasheet rating and PCB thermal layout inspection; confirm copper area and airflow.	Meets rating with margin	Datasheet + PCB screenshot
S4-1	Servo torque margin >= 1.5x for lift requirement.	A	Compute required torque from arm length/load; compare to servo stall torque at voltage.	>= 1.5x	Calc sheet

2.8 Tolerance Analysis

2.8.1 Drive System

In this section we analyze the tolerance of ‘pushing a 1kg sled’. We estimate the friction constant to be worst case 0.7, thus calculation below:

$F_{required} = \mu \times m \times g = 6.87N$

Available motor torque (worst case):

1. Battery voltage under load: 9.0V (from 11.1V nominal, 3S LiPo sag)
2. Rated torque at 12V: 2.5 kg-cm
3. Torque at 9V: 2.5 × (9/12) = 1.875 kg-cm
4. With -15% motor tolerance: 1.875 × 0.85 = 1.594 kg-cm
5. Convert to N-m: 1.594 kg-cm × 0.0981 = 0.156 N-m

Wheel radius (Nominal):

1. 22.5 mm - With +0.5mm tolerance: 23.0 mm = 0.023 m
2. Force per motor: $F_{motor} = T / r = 0.156 / 0.023 = 6.78$ N

Total force (2 motors): $F_{total} = 2 \times 6.78 = 13.56$ N > 6.87 N required

2.8.2 Weapon System

In this section we calculate the necessary torque to lift 0.9kg at 120mm arm (height extended to 60mm so enough margin for 40mm requirement):

Worst case conditions:

1. Arm length: 120mm + 1mm (tolerance) = 121mm = 12.1cm
2. Lift angle: 30°
3. Load: 0.9kg
4. Servo voltage: 5.5V (battery sag)

$T_{required} = m \times L \times g \times \sin(\theta) = 0.9kg \times 12.1cm \times \sin(30°) = 0.9 \times 12.1 \times 0.5 = 5.45$ kg-cm

Servo torque available (worst case):

1. MG996R at 6V nominal: 11 kg-cm
2. At 5.5V: ~11 × (5.5/6) = 10.1 kg-cm
3. With -10% tolerance: 10.1 × 0.9 = 9.09 kg-cm

Safety margin = $T_{available} / T_{required} = 9.09 / 5.45 = 1.67$

2.8.3 Power System

In this section we'll discuss the risk of brownout when all motors/servo in stall condition. Such a condition brings max current thus lowest voltage that might cause ESP32 to shut down.

Current draw analysis (worst case):

1. 2× N20 motors stalling: 2 × 1.2A = 2.4A
2. MG996R servo stalling: 2.5A
3. ESP32-S3 + MPU-6050 + LEDs: 0.35A
4. Total current: $I_{total} = 5.25A$

Battery performance under load:

1. Maximum discharge of 3s LiPo: 450mAh × 45C = 20.25A
2. Internal resistance: $R_{batt} \approx 150m\Omega$

3. Voltage sag: $V_{sag} = I \times R = 5.25A \times 0.15\Omega = 0.79V$
4. Battery voltage under load: 11.1V - 0.79V = 10.31V

Buck converter to 3.3V logic rail: - Input voltage: 9.61V

1. Output voltage nominal: 3.3V
2. With -5% tolerance: 3.3V × 0.95 = 3.135V

ESP32 datasheet brownout threshold voltage is 2.8V, so we have 0.335V voltage margin, pretty close but still tolerance. We propose adding a 1000μF or larger capacitor near ESP32 to handle load fluctuations.

3. Cost and Schedule

3.1 Cost Analysis

Labor cost is estimated per course guideline: ($/hour) x 2.5 x hours to complete = TOTAL.

Team member	Assumed salary ($/hr)	Estimated hours	Multiplier	Labor total ($)
Junyan Bai	45	150	2.5	16,875
Yuxuan Guo	45	150	2.5	16,875

Total estimated labor: $33,750 (labor only; excludes parts).

3.1.1 Parts and services

Table 2 lists the expected non-standard parts and estimated costs. Costs are estimates based on typical distributor/retail pricing and will be updated with final part selection and purchasing receipts.

Item	Manufacturer / Source	Part # / Spec	Qty	Unit cost ($)	Ext cost ($)	Notes
Wi-Fi MCU module	Espressif / DigiKey	ESP32-WROOM-32D	1	7.19	7.19	Module mounted on custom PCB
IMU	SparkFun breakout (alt: bare QFN)	MPU-6050 (SEN-11028)	1	32.5	32.5	May be replaced by bare QFN on PCB
Drive motor	DWEII	DC 6V 500RPM Speed Reduction Motor N20 3mm Shaft Mini Metal Gearwheel Gear Motor	2	23.95	47.9	Final ratio TBD
Motor driver IC	Texas Instruments / DigiKey	DRV8871	2	2.73	5.46	One per drive motor
Weapon servo	TowerPro / HobbyKing	MG996R	1	9.0	9.0	Also considering FS5115M-FB which has

						angle feedback, more friendly for stall detection
Battery	Gens Ace	3S 450 mAh 45C LiPo	1	16.99	16.99	11.1 V nominal
5 V buck regulator	TI	TPS5430 (or equiv.)	1	3.0	3.0	On PCB; cost estimate
3.3 V regulator	AMS	AMS1117-3.3 (or equiv.)	1	0.5	0.5	On PCB; cost estimate
Kill switch	COTS	Mini slide or toggle switch, >= 20 A	1	5.0	5.0	Externally accessible
Wiring/connectors	COTS	XT30/JST, 16-22 AWG wire, heatshrink	1	10.0	10.0	Assorted
Fasteners	COTS	M2/M3 screws, nylocks, threadlocker	1	8.0	8.0	Assorted
3D printing filament	COTS	PETG/PLA+ 1 kg	1	25.0	25.0	Shared across prints
PCB fabrication	PCB house	2-layer, 1 oz copper, 100x100 mm	1	25.0	25.0	Estimate incl. shipping

Estimated parts/services subtotal: $195.54 (excluding tax/shipping variance).

3.2 Schedule

Table 3 provides a week-by-week schedule for design finalization, purchasing, fabrication, assembly, integration, and testing. Weeks are relative and should be aligned to the course calendar.

Week	**Milestone / tasks**	**Owner**	**Deliverable**
Wk 1	Freeze mechanical layout; finalize motor/servo selection; finalize PCB I/O list.	Both	Final CAD + BOM v1

Wk 2	PCB schematic + layout; DRC; order PCB; order long-lead parts (motors, battery).	Yuxuan	Gerbers + purchase orders
Wk 3	3D print chassis revisions; assemble drivetrain mounts; build test jig for lift.	Junyan	Chassis rev A + jig
Wk 4	Assemble PCB; bring up 3.3 V/5 V rails; flash firmware; Wi-Fi link test.	Yuxuan	PCB bring-up checklist
Wk 5	Integrate motors + drivers; closed-loop drive tuning; verify link-loss and kill switch.	Both	Drive subsystem test report
Wk 6	Integrate weapon mechanism; tune servo motion; lift test with 2 lb block.	Junyan	Weapon test report
Wk 7	Full system integration; endurance tests; fault injection (stall) tests.	Both	Integration test report
Wk 8	Refine mechanical robustness; add guards/hard stops; finalize documentation.	Both	Design doc + safety checklist
Wk 9	Mock competition runs; fix issues; final demo preparation.	Both	Demo-ready robot

4. Discussion of Societal Impact, Engineering Standards, Ethics, and Safety Considerations

4.1 Societal, economic, environmental, and global impact

Societal/public welfare: Although combat robotics is an entertainment application, the engineering practices used here (failsafes, fault detection, robust power design, and transparent testing) directly map to safer embedded and robotic systems.

Economic: The project emphasizes realistic design tradeoffs under strict size/weight/cost constraints.

Environmental: We reduce waste by iterating CAD before printing, reusing fasteners/electronics across revisions, and following proper battery disposal procedures for damaged LiPo packs.

Global/cultural: Combat robotics is an international community; documenting safety procedures and sharing reproducible designs supports responsible engineering norms.

4.2 Applicable engineering standards

This project references standards and guidance in the following areas:

1. Professional ethics: IEEE Code of Ethics and ACM Code of Ethics.
2. Battery safety: University battery handling guidance (charging, storage, disposal).
3. Electrical practices: good engineering practice for low-voltage DC systems (wiring gauge, fusing, insulation, strain relief).

4.3 Ethics

In alignment with IEEE/ACM ethics principles, we prioritize safety, honest reporting of limitations, and responsible operation. We will test only in controlled environments, avoid overstating performance claims, and document failures and mitigations. We also ensure that safety features (kill switch, link-loss shutdown, fault protection) are functional before any high-power testing.

4.4 Safety considerations and mitigations

Key hazards include unintended motion (wireless control), pinch points at the weapon linkage, wiring overheating under stall current, and LiPo battery fire risk. Mitigations:

1. Operational: clear arming procedure (controller/app on first; robot powered last), testing in a contained box, and keeping hands clear of the front mechanism.
2. Electrical: manual kill switch, firmware link-loss failsafe, driver-level current limiting and fault shutdown, appropriate wire gauge, strain relief, and insulating covers over exposed conductors.
3. Battery: only use a LiPo-rated balance charger, charge in a fire-resistant area (LiPo bag/metal box), never charge unattended, store at reduced state of charge, and retire packs that show swelling or damage.

5. REFERENCES

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