

MULTI-ROBOT COOPERATIVE LOCALIZATION AND COMMUNICATION TESTBED

Yuxiang Xing (xing14)

XP Liu (xpliu2)

Sahil Jain (sahil5)

Design Document for ECE 445, Senior Design, Fall 2026

TA: Tim Jiang (chij2)

Contents

1. Introduction	3
1.1 Problem and Solution	3
1.2 Design Scope and Status.....	3
1.3 Visual Aid.....	3
1.4 High-Level Requirements	4
2. Design	4
2.1 Block Diagram	4
2.2 Physical Design and Platform Subsystem	5
2.3 Relative Localization Subsystem	5
2.4 Computer Control and Wireless Communication Subsystem	7
2.5 Custom Motor Power and Safety PCB	8
2.6 Independent Evaluation Subsystem.....	9
2.7 System Acceptance Test Procedures.....	10
2.8 Tolerance Analysis.....	10
3. Cost and Schedule	11
3.1 Cost Analysis	11
3.2 Schedule.....	12
4. Societal Impact Standards Ethics and Safety	13
4.1 Societal Impact.....	13
4.2 Engineering Standards and Guidance	13
4.3 Ethics and Responsible Reporting.....	14
4.4 Electrical Mechanical and Battery Safety.....	14
5. Citations	14

1. Introduction

1.1 Problem and Solution

Cooperating robots must maintain relative position while handling lost visibility and communication. We propose three identical differential-drive robots: manually guided leader A and followers B/C. Reusing phones and one computer reduces duplicated onboard computing compared with our earlier proposal. The contribution is a measurable integration of AprilTag localization [4], local motor control, and fault handling, not a new localization algorithm.

Phone video reaches a shared computer over Wi-Fi. The computer estimates A from AprilTags and commands follower offsets $B = (-0.75, +0.30)$ m and $C = (-0.75, -0.30)$ m in A's frame (x forward, y left). Each robot uses an ESP32-S3-DevKitC-1-N8R8 on a custom carrier for wheel control and local stopping. A separate reference camera scores performance without feeding control.

1.2 Design Scope and Status

Operate on a flat 3×3 m indoor field with controlled lighting. Cap all wheel speeds at 0.10 m/s; A travels at 0.06 m/s straight and 0.05 m/s on curves. AprilTag vision, encoders, and a front ToF stop sensor are baseline. Two UWB ports per board support a four-module/two-robot experiment; heading accuracy is not guaranteed. One detachable OV5640 camera is a prototype alternative to phone video.

All performance values are design targets, not test results. Current schematic ERC reports zero violations; the 150×110 mm PCB draft still has 239 unrouted connections and an unresolved fuse footprint. Power modules, battery plates, phone timing, motor loading, and coast stopping must be validated before release.

1.3 Visual Aid

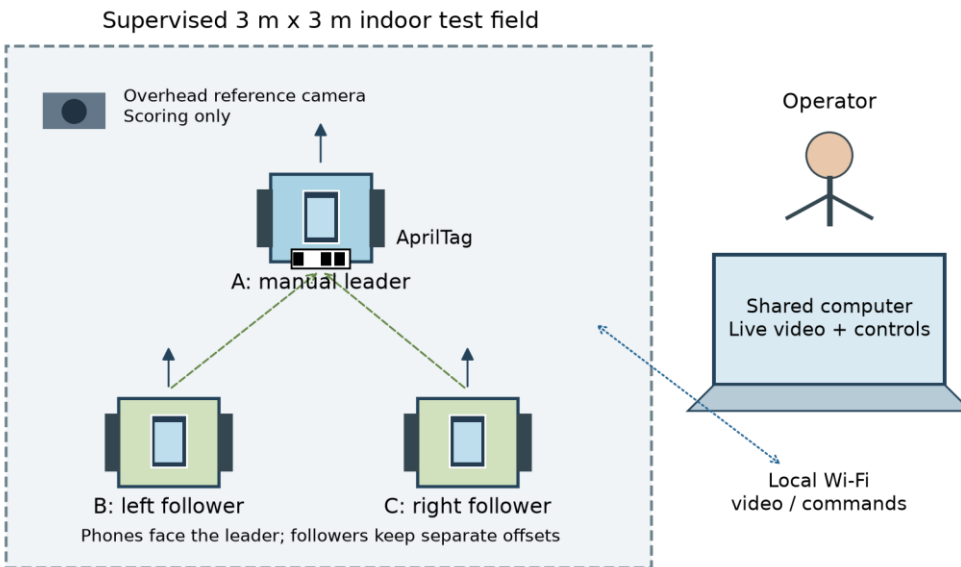


Figure 1. Intended operation. The shared computer controls the three robots; a separate reference-video data path supplies independent scoring only.

1.4 High-Level Requirements

- HLR1 — Each follower shall estimate the leader’s planar relative position within 5 cm and relative heading within 5° for at least 8 of the 10 surveyed static poses defined in Section 2.7.
- HLR2 — The complete A+B+C system shall pass at least 8 of 10 joint trials, with each follower’s target-position error at most 15 cm for at least 80% of scored moving samples after the first 2 s, and both followers within 5 cm and 5° of their targets within 30 s after A stops, remaining stopped together for at least 1 s.
- HLR3 — Following loss of required robot status, valid visual localization, or fresh computer commands, or detection of a front obstacle/sensor failure, each follower shall reach the stopped condition within 0.5 s from an initial 0.10 m/s. Each fault is tested three times per follower. Hardware disable and MCU reset must satisfy the same stopping limit.

“Stopped” means independently measured translation ≤ 0.01 m/s and rotation $\leq 2^\circ$ /s continuously for 0.2 s. The stop time is the beginning of that interval. A joint trial also requires no contact, no boundary exit, and no side exchange. Measurement uncertainty is handled conservatively in Section 2.7.

2. Design

2.1 Block Diagram

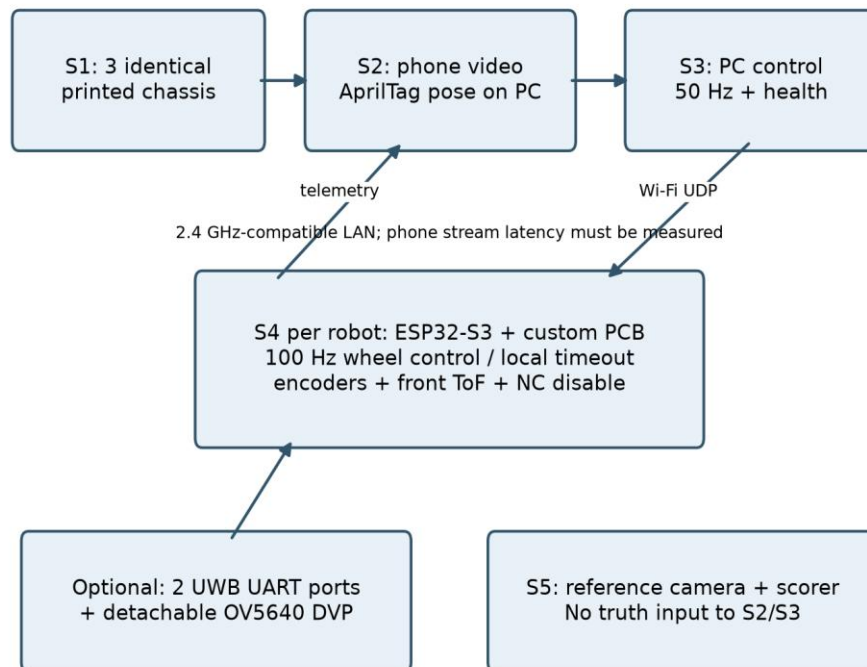


Figure 2. Modular system architecture. Arrow labels identify data, power, and safety interfaces. S1–S5 map directly to Sections 2.2–2.7.

S1 provides common mechanics; S2 computes calibrated phone-based pose; S3 performs computer-based control and health supervision; S4 supplies local wheel control, sensing, and disable circuits; S5 independently scores results. A/B/C share electronics with separate IDs and calibration. S2/S3 never consume S5 ground truth.

2.2 Physical Design and Platform Subsystem

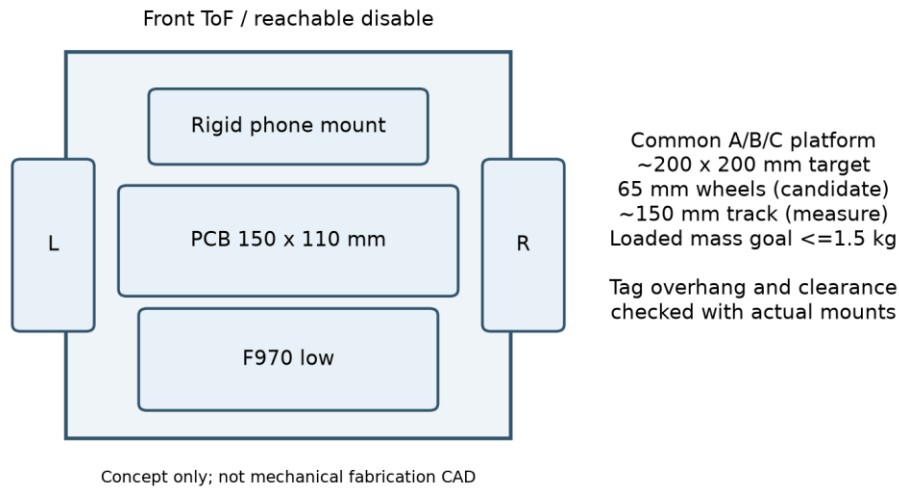


Figure 3. Proposed 200×200 mm packaging envelope. Dimensions are targets to verify with the actual phone, battery plate, motor shafts, and wheel hubs.

Target approximately 200×200 mm chassis/wheel footprint, ≤ 1.5 kg loaded mass, 65 mm wheels, and 150 mm track; measure final geometry. Mount F970 low, phone rigidly with adjustable yaw, and PCB on insulated standoffs. A carries one or two rigid 160 mm tags on calibrated faces. Include mast/tag overhang in clearance checks. The 0.60 m follower separation leaves only 0.10 m edge clearance if both 0.20 m-wide robots err inward by 0.15 m; use surveyed side regions, a spotter, and stop above 0.20 m estimated target error.

Requirement and link	Verification procedure and pass condition
P1 — HLR1/2: loaded mass ≤ 1.5 kg; approximately 200×200 mm chassis target; tag-size uncertainty ≤ 0.5 mm and mount shift ≤ 1 mm.	Measure loaded geometry, tag edges and mount motion with calipers/scale; compare against every listed limit.
P2 — HLR2/3: measured wheel speed plus uncertainty shall not exceed 0.10 m/s.	Run ± 0.05 and ± 0.10 m/s over 1 m, three repeats per robot. Score video speed plus uncertainty against the cap.
P3 — HLR2: nominal swept-footprint clearance ≥ 0.10 m and visible leader tag along both routes.	Survey both full routes and tag visibility; verify manual START/STOP/FAULT before joint trials.

2.3 Relative Localization Subsystem

S2 supports HLR1/2 using available iPhone/Redmi phones. Start with fixed 720p/30 fps streaming, then require ≥ 20 valid poses/s and ≤ 100 ms accepted capture-to-publication age. Lock the calibrated lens/mode; test rolling shutter, compression, buffering, and capture timestamps. An app without a defensible capture-age bound cannot meet the freshness requirement. Aim follower cameras approximately 22° inward and verify visibility over both routes.

Use tag36h11 IDs 0/1, with 160 mm measured between detection corners. Calibrate intrinsics/distortion from ≥ 20 checkerboard views and check ≥ 10 held-out views. Record camera-to-axle and tag-to-leader transforms; do not reuse calibration images as independent truth.

Let $T(i,j)$ transform coordinates from frame j to frame i . With follower frame F , camera C , tag T , and leader A , compute $T(F,A) = T(F,C) \cdot T(C,T) \cdot \text{inverse}[T(A,T)]$. Extract planar translation $q = (q_x, q_y)$ and yaw ψ from $R(F,A)$. Convert the camera's optical axes explicitly into the robot convention x forward, y left, z up. For offset r_i , the target expressed in F is $e_i = q + R(\psi)r_i$. The heading error is $\text{wrap}(\psi)$ in $(-\pi, \pi]$. All log angles are radians; displayed results use degrees.

Reject wrong IDs, nonpositive depth, clipped corners, reprojection RMS >1 pixel, ambiguous pose solutions, or capture age >100 ms. If both tags are visible, reject disagreement >3 cm or $>3^\circ$. Wheel odometry may predict between frames but never renew vision freshness; 150 ms visual age requires SAFE_STOP.

Interface	Design definition
Phone $\rightarrow$ computer	Compressed video over LAN; capture timestamps/age bound validated experimentally. Fixed calibrated mode, newest-frame processing; ≥ 20 valid poses/s and ≤ 100 ms accepted age.
Encoders $\rightarrow$ ESP32 $\rightarrow$ computer	5 V encoder signals through SN74LVC125 at 3.3 V; quadrature counts in 50 Hz UDP telemetry. No baseline IMU.
S2 $\rightarrow$ S3	Robot ID, capture and receive times, q_x/q_y [m], yaw [rad], validity, tag ID, reprojection RMS. Predictions never refresh the vision timestamp.
Short prediction	Propagate using wheel odometry between images; stale vision at 150 ms requests SAFE_STOP. Clock uncertainty is included in freshness.
Front ToF $\rightarrow$ ESP32	Pololu 3692 VL53L4CD carrier on I ² C; request 50 Hz and verify actual rate. Initially stop forward motion at distance ≤ 150 mm or invalid/stale data >100 ms. Calibrate sensor-to-bumper offset and check the stopping margin on real targets.
UWB $\rightarrow$ dual UART bridge	Two MAUWBM 3.3 V UART modules per experimental robot, 115200 baud. SC16IS752 communicates over I ² C. Reset low ≥ 3 s; record firmware. Four modules equip two robots only.
Detachable camera $\rightarrow$ ESP32	Waveshare OV5640 Board (A), 18-pin DVP, 3.3 V carrier supply. Short straight-through cable initially ≤ 10 cm; no hot-plug. Same MCU runs motor control; load/latency tests gate camera use.
Requirement and link	Verification procedure and pass condition
L1 — HLR1: each follower shall pass $\geq 8/10$ static poses; each passing pose has $\geq 90\%$ valid samples and 95th-percentile errors plus uncertainty ≤ 5 cm and $\leq 5^\circ$.	Record 5 s at each of the ten poses (§2.7), mirrored for C. Include invalid samples and report all pose errors and valid fractions.
L2 — HLR2/3: ≥ 20 valid updates/s in every complete 1 s window; accepted capture-to-publication age ≤ 100 ms.	Log a 60 s moving run with both phones active; check every 1 s window and accepted frame age; count drops/rejections.
L3 — Final-position budget: tag-size uncertainty ≤ 0.5 mm; transform translation uncertainty ≤ 5 mm; held-out reprojection RMS ≤ 0.5 pixel.	Measure tag/extrinsic geometry; evaluate held-out checkerboard views and the integrated final-position budget.
L4 — HLR3: complete visual loss shall cause physical stopping plus timing uncertainty within 0.50 s.	At 0.10 m/s obscure all leader tags, three trials per follower. Film fault and motion; verify freshness expires and stop meets the limit.

Requirement and link	Verification procedure and pass condition
L5 — HLR3: reject all 10 injections per invalid-data class; rejected data shall not renew the 150 ms visual freshness timer.	Wheels raised: inject each wrong-ID, stale, clipped or conflicting-pose case ten times; verify rejection and timeout.

2.4 Computer Control and Wireless Communication Subsystem

The computer runs control and robot-health supervision at 50 Hz; ESP32 wheel control runs at 100 Hz. FOLLOW requires fresh A/peer telemetry and vision. After A stops, RENDEZVOUS corrects position then heading; hold the target for 1 s to COMPLETE. Faults override all states and latch SAFE_STOP. Arm only after 1 s healthy inputs plus explicit operator action; reconnection alone cannot restart motion.

Use the pose transform in §2.3 to obtain target error e and relative yaw ψ . Differentiate leader pose over 0.20 s, compensating follower odometry, for optional target-velocity feedforward u^* . Disable noisy feedforward. Define look-ahead error $e\ell = e + \ell[R(\psi)(1,0)^T - (1,0)^T]$, $\ell = 0.10$ m. Use $u = u^* + \omega A J\ell R(\psi)(1,0)^T + 0.6e\ell$, $v = u_x$ and $\omega = u_y/\ell$, where J rotates 90° .

Wheel requests are $v_L = v - b\omega/2$ and $v_R = v + b\omega/2$ using measured track b . Scale together to respect 0.10 m/s; limit $|\omega| \leq 0.5$ rad/s and normal acceleration ≤ 0.20 m/s². For rendezvous, use position-then-heading control at ≤ 0.05 m/s; internal settle targets are 1 cm/1°, with 1.5 cm hysteresis and a 30 s timeout. Independent ground truth determines acceptance.

Use a private local hotspot or borrowed access point. ESP32-S3 requires 2.4 GHz 802.11b/g/n [7]; Wi-Fi 6 does not guarantee latency. UDP commands/telemetry run at 50 Hz, with robot ID, session, sequence, timestamps, state/faults, wheel requests/counts and sensor data. Reject malformed, wrong-session, duplicate, reordered, or out-of-range commands; bound computer-MCU clock error to 10 ms.

Use 32-byte command and telemetry records. Commands include CRC16-CCITT and a ≤ 100 ms issue-time lease; followers additionally require vision age ≤ 150 ms. A is exempt from vision gating in manual mode. Stale packets cannot renew motion. Three robots generate 9,600 payload bytes/s at 50 Hz in both directions; two provisional 4 Mbit/s phone streams dominate demand. Drop old frames and prevent the network thread from renewing a frozen control decision.

Requirement and link	Verification procedure and pass condition
C1 — HLR2/3: all 12 state-transition cases shall follow Section 2.4; faults take priority and reconnection alone never enables motion.	Replay start-without-vision, missing-peer, valid-start, A-stop, settle, drift, timeout, peer-fault, stale-vision, stale-command, reconnect and reset.
C2 — HLR3: each required-telemetry loss shall cause stopping plus uncertainty ≤ 0.50 s; 100 duplicate/reordered packets shall not renew freshness.	Cut each required telemetry source, three runs per follower. Inject 100 duplicates/reordered/delayed packets; verify no freshness renewal.
C3 — HLR3: all 100 injections per malformed/stale command class shall be rejected; command loss shall cause stopping plus uncertainty ≤ 0.50 s.	Inject 100 bad-CRC, truncated, wrong-session, stale, duplicate and out-of-range commands per class. Cut commands in motion; freeze vision while networking continues.
C4 — HLR2: at least 8/10 whole-system trials shall meet every following, final-pose, timing, and no-contact condition.	Run ten alternating straight/curved trials (§2.7), freezing calibration/gains. Score both robots jointly, retaining all failures.

2.5 Custom Motor Power and Safety PCB

S4 supports HLR2/3 with an official N8R8 DevKit, two DRV8874PWPR drivers, SN74LVC125 encoder conditioning, SC16IS752 dual UART, ADS1015 monitoring, AP2112K peripheral/camera supplies, and a SN74LVC1G74 safety latch. The custom PCB integrates driver, protection, monitoring and latch circuits; DevKit and buck modules are commercial subsystems. The six-sheet pin-level schematic is supplied separately as Robot_V1_schematic_v0.2.pdf.

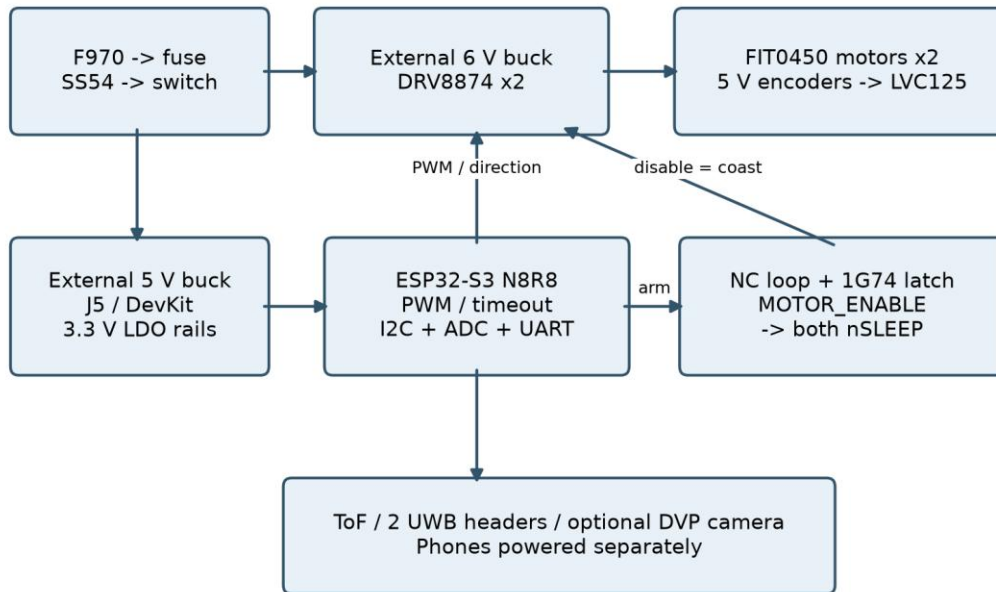


Figure 4. Power and safety architecture matching the current schematic. Opening the NC loop clears the latch and pulls both driver nSLEEP inputs low: this disables drive and coasts, rather than actively braking.

Reuse three F970 packs and compatible chargers: approximately 7.2–7.4 V nominal, 8.4 V maximum. Verify exact capacity, condition, protection and discharge rating. A proper NP-F plate feeds fuse F1, SS54 reverse protection and the main switch. Fuse/connector ratings and buck SKUs await load tests. No onboard charging or bare-contact clips; first power-up uses a current-limited bench supply.

Provide external 6 V motor (target ≥ 4 A) and 5 V logic (≥ 2 A) bucks; verify regulation over 7.2–8.4 V battery input after protection drop. Separate 3.3 V AP2112K rails initially budget 200 mA each; verify peak load and (5–3.3)I dissipation. Remove J5 when USB powers the DevKit. Phones use their own batteries. Runtime target is ≥ 1 h; estimate only after measuring usable battery Wh and average load W.

FIT0450 motors [11] are 6 V, 160 rpm, 120:1, with 0.0196 N·m rated torque and 2.8 A stall current. Six motors serve three robots; buy two first. A 65 mm wheel needs 29.4 rpm at 0.10 m/s. For $m=1.5$ kg, $a=0.20$ m/s² and rolling coefficient 0.03, torque per wheel $\approx (ma+0.03mg)\cdot 0.0325/2=0.0120$ N·m. The modest margin requires loaded start/turn tests and matching wheel hubs.

Run PI wheel control at 100 Hz and PWM at 20 kHz with anti-windup. Measure decoded encoder counts per output revolution; distance/count = $\pi D/N_{\text{decoded}}$. SN74LVC125 converts encoder signals from 5 V to 3.3 V. Both PWMs are direct MCU outputs; right direction uses SC16IS752 GPIO3, so stop PWM before changing direction over I²C.

J11's NC loop connects RUN_REQUEST to SAFE_CLEAR_N. Opening it asynchronously clears the SN74LVC1G74 latch; MOTOR_ENABLE then pulls both driver nSLEEP pins low. RUN_REQUEST defaults low on reset and

rearming needs an explicit arm edge. Timeout, required ToF failure, undervoltage or driver fault disables drive. This is coast, not active braking: actual stopping must meet HLR3.

ADS1015 senses BAT_SW through 100 k Ω /33 k Ω (8.4 V $\rightarrow$ 2.084 V). Initially latch a fault below BAT_SW=6.8 V for 100 ms; confirm against pack and regulator limits. DRV8874 nominal current limit is 1.65/(455 μ A/A $\times$ 2.49 k Ω)=1.46 A [6]; verify 1.2–1.8 A and sufficient starting torque.

Requirement and link	Verification procedure and pass condition
E1 — HLR1–3: 6 V, 5 V and 3.3 V rails shall stay within $\pm 5\%$, with ≤ 100 mV peak-to-peak ripple and no reset over specified load tests.	At battery input 7.2/7.8/8.4 V, step 6 V load 0.2–3 A, 5 V load 0.1–1.5 A and each 3.3 V rail to 200 mA. Scope motor-start/radio/camera peaks and verify dropout.
E2 — HLR2: after 0.5 s settling, absolute wheel-speed error ≤ 0.01 m/s for $\geq 95\%$ of samples.	Request ± 0.03 , ± 0.06 and calibrated maximum m/s for 5 s, three repeats. Compare independent speed and encoder logs; verify signs and unequal wheel commands.
E3 — HLR3: command expiry shall disable drive within 0.11 s of the last valid lease; physical stop plus uncertainty ≤ 0.50 s.	Cut computer commands under video/I ² C load. Scope TP5 and nSLEEP, and film stops; three trials per follower.
E4 — HLR3: opening J11 shall drive both nSLEEP pins low within 10 ms, independently of PWM; physical stop plus uncertainty ≤ 0.50 s.	Force PWM high with wheels raised, then open J11. Scope nSLEEP; repeat moving tests three times per follower and verify no automatic rearm.
E5 — HLR3: bus ADC error ≤ 0.15 V; motor current regulation 1.2–1.8 A; BAT_SW <6.8 V for 100 ms shall latch a stop.	With current-limited bench power, reverse input, sweep BAT_SW below threshold, compare ADC to DMM at three voltages, and safely measure restrained-motor regulation.
E6 — HLR2: accessible surfaces $\leq 50^\circ\text{C}$ and measured case hotspots $\leq 70^\circ\text{C}$ during specified thermal tests, with no reset or driver thermal fault.	Run loaded robot 15 min and rail full-load 10 min; measure accessible/case temperatures; require no reset/thermal fault.
E7 — HLR3: MCU reset shall disable drive, stop motion plus uncertainty within 0.50 s, and remain IDLE after reboot.	Reset MCU at 0.10 m/s three times per follower; scope drive outputs and film coasting. Fail requires redesign before scored motion.

Before fabrication: choose F1, bucks and NP-F plates; check DevKit headers, DRV8874 exposed pad, camera orientation, power copper, antenna keepouts and mechanical fit; complete routing and clean DRC; obtain peer review. UWB MAUWBM modules [13] use 2.2 mm half-hole pads and need a separate adapter. Four modules test two robots. With 0.15 m baseline and illustrative 0.05 m range error, angular uncertainty scales as $\sqrt{2 \cdot 0.05/0.15} \approx 27^\circ$; retain range-only use if heading is unreliable.

2.6 Independent Evaluation Subsystem

S5 supports HLR1–3 using an independent $\geq 1080\text{p}/60$ fps overhead camera, surveyed robot markers, lens calibration, and height correction. Check ≥ 12 withheld positions and ≥ 6 headings. Propagated relative/target uncertainty must be ≤ 1 cm and $\leq 1^\circ$, not merely each robot’s individual position error. Use ≥ 120 fps side video for stops with timing uncertainty ≤ 0.02 s. Reference data never enters control.

At time t , compute $\hat{r}_i = R(-\theta A)(p_i - p_A)$, target error $E_i = \|\hat{r}_i - r_i^*\|$ and heading error $H_i = |\text{wrap}(\theta_i - \theta A)|$. Align clocks using a logged visible LED flash, check ≤ 0.02 s residual, and retain video, calibration, software version, state/fault timestamps, commands and telemetry. Missing controller samples and aborted runs count as failures; replace only documented instrument failures.

Requirement and link	Verification procedure and pass condition
V1 — HLR1–3: propagated reference uncertainty shall be ≤ 1 cm and $\leq 1^\circ$; timing alignment residual ≤ 0.02 s; reference trajectories shall not feed control.	Survey withheld poses/headings and propagate uncertainty through the target transform. Verify clock alignment and no ground-truth input to control.
V2 — HLR1–3: every synthetic scorer case shall match hand-calculated counts, durations and pass/fail results.	Compare scorer outputs with hand-computed synthetic trajectories including gaps, invalid frames, side swaps and stops.

2.7 System Acceptance Test Procedures

HLR1: use the ten surveyed poses below for B and mirrored y/yaw for C. Hold each 5 s and score ≥ 100 scheduled samples; require $\geq 90\%$ valid output and 95th-percentile errors plus uncertainty ≤ 5 cm/ 5° . At least 8/10 poses must pass per follower.

Pose	x [m]	y [m]	$\Delta\theta$ [°]	Pose	x [m]	y [m]	$\Delta\theta$ [°]
1	-0.50	0.00	0	6	-0.75	+0.30	-15
2	-0.65	+0.20	0	7	-0.75	+0.30	+30
3	-0.75	+0.30	0	8	-0.75	+0.30	-30
4	-0.95	+0.20	0	9	-0.60	+0.30	+15
5	-0.75	+0.30	+15	10	-0.90	+0.30	-15

HLR2: five 1 m straight runs and five 1 m arcs of radius 2 m, alternating with frozen gains. Start followers within 3 cm/ 3° of targets; keep swept footprints ≥ 0.20 m from field edges. Score at 20 Hz after the first 2 s of motion, with ≥ 5 s scored motion. Apply all HLR2 bounds to both followers jointly, adding reference uncertainty to errors. No contact, boundary exit, side swap or operator intervention is allowed.

HLR3: three repetitions per follower for each of eight faults: A telemetry loss, peer telemetry loss, total tag occlusion, computer command loss, front obstacle, ToF invalidity/loss, NC switch opening, and MCU reset (48 runs). Start at measured 0.10 m/s. Time from the visible physical fault event; every stop plus uncertainty must be ≤ 0.50 s.

2.8 Tolerance Analysis

The critical interface is pose error propagated into final positioning; confirm this selection with the TA. Values below are proposed allocations, not measured accuracy [8].

Offset magnitude $r = \sqrt{0.75^2 + 0.30^2} = 0.8078$ m. Heading error shifts the target by $2r \sin(|\delta\psi|/2)$: at 5° , this is 70.5 mm, already larger than the final 50 mm limit. Thus HLR1 alone is insufficient. The final approach needs ≤ 15 mm translation and $\leq 1^\circ$ yaw, with the following conservative budget.

Worst-case contribution	Proposed allocation
Relative translation error, including camera/tag calibration	15 mm
Leader yaw error 1° propagated through offset	$2(0.8078)\sin(0.5^\circ) = 14.1 \text{ mm}$
Residual closed-loop positioning error	10 mm
Independent reference uncertainty	10 mm
Conservative sum	49.1 mm < 50 mm

The 49.1 mm sum has only 0.9 mm margin. Prefer commissioning goals of 10 mm translation and 0.75° yaw (40.6 mm sum), checked at final-pose geometry. Improve tag visibility/calibration if it fails; do not silently relax HLR2.

For $z = fs/p$, illustrative $f=800$ pixels, $s=0.160$ m and $z=1$ m give $p=128$ pixels. With relative focal error 0.25%, tag-size error 0.5 mm and corner error 0.5 pixel, $|\delta z| \lesssim 1(0.0025+0.0005/0.160+0.5/128)=9.53$ mm, leaving limited extrinsic margin. Substitute actual phone calibration; this does not prove yaw accuracy.

Conservative stop delay: 150 ms freshness +20 ms control +20 ms communication +100 ms lease fallback +10 ms MCU =300 ms. Adding 20 ms timing uncertainty leaves 180 ms for coasting from 0.10 m/s. Equivalent constant deceleration must be $\geq 0.56 \text{ m/s}^2$; 0.60 m/s^2 would give 0.487 s total. Verify the actual coast trace and redesign if it fails. On the planned curve, the faster wheel needs approximately 0.0624 m/s ($b=0.15$ m), leaving 0.0376 m/s correction margin.

3. Cost and Schedule

3.1 Cost Analysis

USD costs below distinguish October 2 module reference prices from planning allowances. Phones, F970 packs/chargers and computer are reused at zero incremental cost. The \$500 target is for all three robots. No order is claimed approved or placed.

Planning labor: $\$50/\text{h} \times 2.5 \times 120 \text{ h} = \$15,000$ per member; three members total \$45,000. This is a course accounting assumption, separate from hardware cash.

3.1.2 Parts and Services

Description	Manufacturer / exact selection or allowance	Qty	Unit USD	Total USD
DevKit	Espressif ESP32-S3-DevKitC-1-N8R8; reference	3	15.00	45.00
Encoder gearmotor	DFRobot FIT0450; reference	6	7.40	44.40
Front ToF carrier	Pololu 3692; reference	3	13.95	41.85
Motor driver IC	TI DRV8874PWPR; allowance	6	4.00	24.00
PCB support electronics	SC16IS752, ADS1015, SN74LVC125/1G74, AP2112K, passives, headers; allowance	3	20.00	60.00
Bare PCB fabrication	3 installed + 2 spare boards; batch allowance	1	30.00	30.00
Buck modules	6 V and 5 V, exact SKUs pending; allowance	6	5.00	30.00
NP-F mating plates	Exact SKU pending; allowance	3	8.00	24.00

Description	Manufacturer / exact selection or allowance	Qty	Unit USD	Total USD
Disable/main switches, fuse	Exact ratings/holders pending; allowance per robot	3	8.00	24.00
Wheels/caster/hubs	Shaft fit pending; allowance per robot	3	8.00	24.00
3D printing and mounts	Phone/battery/tag brackets; total allowance	1	25.00	25.00
Harnesses/fasteners	Total allowance	1	20.00	20.00
Phones/F970/chargers/PC	Already available; incremental cost	1	0.00	0.00
Description	Manufacturer / exact selection or allowance	Qty	Unit USD	Total USD
Bench motor carriers	Pololu 4035 DRV8874; reference	2	11.94	23.88
Detachable camera	Waveshare 13926 OV5640 Board (A); reference	1	19.99	19.99
UWB modules	Makerfabs MAUWBM, STM32 AT UART version; reference	4	38.90	155.60
UWB adapters/decoupling	2.2 mm half-hole adapter not yet designed; allowance	4	3.00	12.00
Measurement instruments/AP	Borrow; availability to confirm	1	0.00	0.00
Machine-shop hours	No outsourced machining planned	0	0.00	0.00

Core \$392.25 + validation/camera/UWB \$211.47 = \$603.72 hardware subtotal. Add \$40 shipping/tax/tariff allowance and 10% contingency (\$60.37): \$704.09 cash, \$204.09 above target. Labor-inclusive total: \$45,704.09. Resolve the gap through confirmed inventory, extra funding or agreed optional-scope reduction; unconfirmed free stock is not counted.

Borrow supplies, DMM, oscilloscope, logic analyzer, electronic load, thermal probe, reference cameras/mount and AP if needed; availability remains to confirm. Zero outsourced shop hours are planned; printing/mounts are budgeted. Unavailable loan equipment requires a revised quote.

First batch, already included above: 2 N8R8 DevKits, 2 FIT0450, 1 Pololu 3692, 2 Pololu 4035, 1 Waveshare 13926 and 4 MAUWBM: \$258.22 before delivery charges. Request exact-match school stock first, then TA procurement. Confirm module revision, firmware, mating dimensions and lead time; no substitution without interface review. FIT0450 may carry a 30% supplier tariff.

3.2 Schedule

Owners: Yuxiang—mechanics/localization; XP—PCB/firmware; Sahil—computer/networking/evaluation. Cross-review interfaces. Integrate rails → disable/watchdog → one robot → A+B → qualified C → A+B+C. PCB release is conditional on tests and completed routing; dates follow [14].

Date s	Yuxiang Xing	XP Liu	Sahil Jain	Exit milestone
Oct 2	Review geometry/vision	Publish current schematic/status	Review document and sign-up	Design document + review sign-up due 23:59
Oct 3–7	Phone mode/calibration; load chassis	Bench drivers, encoder levels, latch	Stream timestamp/latency and scorer tests	Design review Oct 5–7; critical feasibility gates

Date s	Yuxiang Xing	XP Liu	Sahil Jain	Exit milestone
Oct 8 / 15	Verify wheel hubs and mounts	Close BOM, footprints, route/DRC; release only if ready	Review interfaces and logging	PCB round Oct 8, fallback Oct 15
Oct 12–14	Show calibrated phone pose	Demonstrate bench control and stop	Show packet/fault logs	Breadboard demonstration
Oct 16–28	Assemble/calibrate A and B	Board power, thermal, loop tests	A+B following and reference calibration	One complete follower passes stopping
Oct 29	Resolve packaging failures	PCB revision if necessary	Freeze core interfaces	Final reserved PCB revision round
Nov 2–4	C mechanics/calibration	C electrical qualification	Report progress and remaining risks	Progress report
Nov 5–15	Joint route clearance	Full system rail/noise checks	A+B+C, fault and scoring rehearsal	All subsystem gates reviewed
Nov 16–19	Prepare physical demonstration	Hardware readiness and spares	Mock demo and retained logs	Mock demo
Nov 20–29	Final static poses	48 fault runs; final harnesses	10 joint trials; score uncertainty	Complete retained acceptance dataset
Nov 30–Dec 2	Demonstrate platform	Demonstrate electrical design	Demonstrate results	Final demo, assigned slot
Dec 3–9	Final figures and geometry	Final schematic/BOM	Results, limitations and references	Final report due Dec 9

4. Societal Impact Standards Ethics and Safety

4.1 Societal Impact

The project provides a reproducible testbed for cooperative-robot failures and measurement. Potential inspection/transport benefits are future applications, not demonstrated outcomes. Identical modular robots and reused phones/batteries can reduce expense and waste, without a quantified environmental claim. Clear state labels and reachable stops support varied accessibility/language needs; global deployment would require additional radio and workplace review.

4.2 Engineering Standards and Guidance

IEEE 802.11 applies to commercial Wi-Fi interfaces [9]; UART/I²C/DVP and datasheets govern electrical timing and levels. Verify permitted UWB channel/firmware operation. Follow ECE 445 safety/battery guidance [1]. No UL, functional-safety, or industrial mobile-robot certification is claimed.

4.3 Ethics and Responsible Reporting

IEEE/ACM principles of protecting welfare, avoiding harm and honest reporting [2,3,10] require bounded operation, local stopping, attribution of reused software/circuits, and retention of failed trials. Record only the field with participants' agreement; limit retained video. Private Wi-Fi and session checks are not cryptographic command authentication. New concerns include buffered stale images, unexpected restart, rolling-shutter error, and regeneration during braking.

4.4 Electrical Mechanical and Battery Safety

Work under course lab rules with an operator and spotter [1]. Inspect batteries, wiring, mounts and calibration; first power from a current-limited supply with wheels raised. Before each run test the physical disable and watchdog, then explicitly rearm. Start at 0.03 m/s; A stops when either follower faults.

Hazard	Mitigation and required check
Battery short, damage, or wrong charger	Inspect each existing F970 pack and confirm compatible charger, model/capacity, condition, and protection/discharge limits. Use a correctly mating NP-F plate, fuse, and insulated wiring. No damaged/swollen/hot pack may be used. Charge attended using the existing matched charger in an approved area, with the pack removed from the robot.
Incorrect power or exposed conductors	First energize the PCB from a current-limited bench supply with motors disconnected. Check 6 V/5 V/3.3 V polarity at their destination connectors, then attach logic. Fit insulating covers, strain relief, keyed connectors, and a fuse near the pack. Disconnect power before rewiring.
Braking current and supply transients	Scope TP1 during maximum-speed stops and reversals at full battery. Verify bus peaks stay within all connected component ratings and pack charging limits. Add correctly rated suppression/capacitance or revise braking if necessary. Do not assume the regulator or pack can absorb regeneration.
Wheel pinch, cable entanglement, or collision	Raise wheels for first firmware tests. Guard pinch points; secure hair/clothing and cables. Keep people outside the 3 m field and keep clear escape space. Never restrain a powered wheel by hand. Mark side regions and keep a spotter at the stop control.
Unexpected motion or software failure	Default to IDLE with no motor permit. Test the switch and heartbeat/command watchdogs before joint testing. Latch SAFE_STOP; require explicit reset and rearm after every fault. A reset that only coasts must still pass the separate stop-distance/time test.
Hot components or unstable structure	Run E6 before extended operation; cover hot surfaces if needed. Secure battery, phone, camera mast, and overhead camera. Check fasteners and mounting stability before every run. Stop if parts loosen, become unusually hot, or produce odor/smoke.

On an ordinary fault, disable all robots, wait for motion to cease, and disconnect battery power before inspection. For smoke, overheating or fire, keep clear, alert lab staff and follow the lab emergency procedure; do not handle/recharge the pack. Correct the cause and repeat affected safety tests before resuming.

5. Citations

[1] ECE 445, University of Illinois Urbana-Champaign, "Safety Guidelines," including the linked "General Battery Safety" guidance. <https://courses.grainger.illinois.edu/ece445/guidelines/safety.asp> and <https://courses.grainger.illinois.edu/ece445/documents/GeneralBatterySafety.pdf>. Accessed Oct. 2, 2026.

[2] Association for Computing Machinery, "ACM Code of Ethics and Professional Conduct." <https://www.acm.org/code-of-ethics>. Retained from the project proposal.

[3] IEEE, "IEEE Code of Ethics." <https://www.ieee.org/about/corporate/governance/p7-8>. Retained from the project proposal.

- [4] AprilRobotics, “AprilTag 3,” implementation documentation, especially pose estimation, tag size, and coordinate systems. <https://github.com/AprilRobotics/apriltag>. Accessed Oct. 2, 2026.
- [5] Waveshare, “OV5640 Camera Board (A),” SKU 13926, product and linked interface documentation. <https://www.waveshare.com/OV5640-Camera-Board-A.htm>. Accessed Oct. 2, 2026.
- [6] Texas Instruments, “DRV8874 H-Bridge Motor Driver With Integrated Current Sense and Regulation,” datasheet. <https://www.ti.com/lit/ds/symlink/drv8874.pdf>. Accessed Oct. 2, 2026.
- [7] Espressif Systems, “ESP32-S3-DevKitC-1 v1.1 User Guide,” module options, headers, power and hardware reference. https://docs.espressif.com/projects/esp-dev-kits/en/latest/esp32s3/esp32-s3-devkitc-1/user_guide_v1.1.html. Accessed Oct. 2, 2026.
- [8] ECE 445, University of Illinois Urbana-Champaign, “Requirements and Verification” and “Tolerance Analysis Guide.” <https://courses.grainger.illinois.edu/ece445/guidelines/requirements-and-verification.asp> and <https://courses.grainger.illinois.edu/ece445/documents/tolerance-analysis-guide.pdf>. Accessed Oct. 2, 2026.
- [9] IEEE 802.11 Working Group, “Wireless LANs.” <https://www.ieee802.org/11/>. Accessed Oct. 2, 2026.
- [10] ECE 445, University of Illinois Urbana-Champaign, “Ethical Guidelines.” <https://courses.grainger.illinois.edu/ece445/guidelines/ethical-guidelines.asp>. Accessed Oct. 2, 2026.
- [11] DFRobot, “FIT0450 6V 160RPM Micro DC Geared Motor with Encoder,” specifications and wiring. https://wiki.dfrobot.com/6V_160RPM_Micro_DC_Geared_Motor_with_Encoder_SKU_FIT0450. Accessed Oct. 2, 2026.
- [12] Pololu, “VL53L4CD Time-of-Flight Distance Sensor Carrier,” product 3692, and “DRV8874 Single Brushed DC Motor Driver Carrier,” product 4035. <https://www.pololu.com/product/3692> and <https://www.pololu.com/product/4035>. Accessed Oct. 2, 2026.
- [13] Makerfabs, “MaUWB_DW3000 Chipset,” SKU MAUWBM, UART AT firmware module and linked documentation. <https://www.makerfabs.com/mauwb-dw3000-chipset.html>. Accessed Oct. 2, 2026.
- [14] ECE 445, Fall 2026 calendar and design-document guidance. <https://courses.grainger.illinois.edu/ece445/calendar.asp> and <https://courses.grainger.illinois.edu/ece445/guidelines/design-document.asp>. Accessed Oct. 2, 2026.