

HETEROGENEOUS MULTI-ROBOT COOPERATIVE LOCALIZATION AND COMMUNICATION TESTBED

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1. Introduction

1.1 Problem

Coordinated mobile robots must estimate relative position and heading, exchange task and health information, and move together without physical contact. These capabilities are important in applications such as warehouse transport, inspection, search-and-rescue, agriculture, and service robotics, where multiple robots can divide work while maintaining safe spatial relationships. The engineering challenge is not only making an individual robot move, but ensuring that sensing, communication, control, and fault handling remain reliable when several robots operate at once.

This project studies a controlled laboratory version of that problem: one tracked leader (A) and two differential-drive followers (B and C). Each follower independently estimates the leader's relative pose using AprilTags, follows at low speed, and settles into a distinct position after the leader stops. The project deliberately excludes autonomous route planning, narrow-aisle coordination, arbitrary initial poses, and general obstacle avoidance so that the team can quantitatively evaluate simultaneous localization, following, rendezvous, and fail-safe stopping. The proposed test area is a flat 3 m × 3 m indoor field with controlled lighting and two approximately 1 m routes. The leader is manually guided at no more than 0.10 m/s.

Societal relevance is primarily connected to public safety and welfare. A multi-robot system that loses localization or communication can create collision hazards, so safety behavior must be designed rather than added after the motion controller. The project also has economic and environmental relevance: coordinated robots can reduce duplicated motion and enable multiple robots to share sensing and task information, while the use of small electric platforms provides a bounded environment for studying energy use, control efficiency, and safe automation. These benefits are potential applications rather than claims that the student prototype is ready for deployment.

1.2 Solution

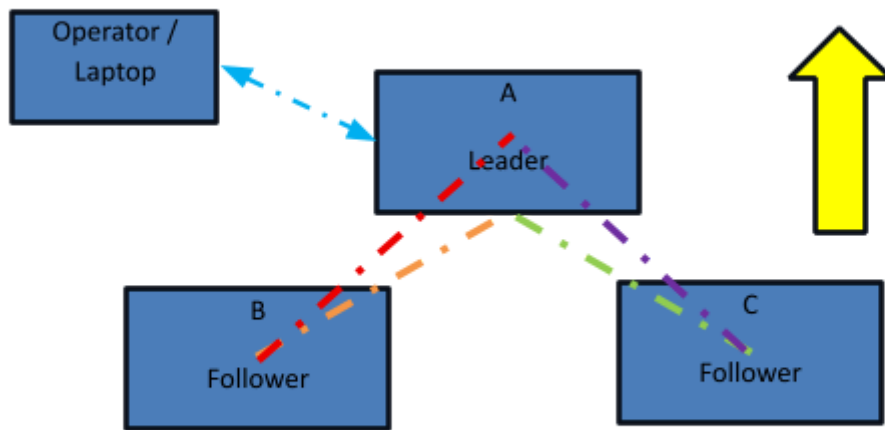
The proposed solution is a three-robot formation system in which A provides the moving reference, and B and C independently maintain fixed rear-left and rear-right target offsets. The proposed offsets, expressed in A's reference frame with x forward and y left, are $B = (-0.75 \text{ m}, +0.30 \text{ m})$ and $C = (-0.75 \text{ m}, -0.30 \text{ m})$, with both followers aligned to A's heading. AprilTags are rigidly mounted to A so each follower can measure the leader's relative position and heading with its own onboard camera. UWB receivers may be used for the same purpose, and a motion sensor may be used to avoid collision.

Each follower processes images on a Raspberry Pi 5, uses encoder/IMU information for short-term motion estimation, and runs a shared state machine with IDLE, FOLLOW, RENDEZVOUS, SETTLE, COMPLETE, and SAFE_STOP states. The Pi sends bounded left- and right-wheel speed commands to a custom motor/power/safety PCB. An ESP32-S3 on the PCB handles encoder acquisition, local wheel-speed control, watchdog functions, current/bus-voltage monitoring, motor-drive control, and a physical motor-disable input. Wi-Fi is limited to robot IDs, sequence numbers, and heartbeat/task-health state; localization and wheel control remain onboard. If localization becomes invalid (both april tag and UWB loses connection), a required heartbeat becomes stale, a Pi command times out, or a peer reports

a fault, the affected follower enters SAFE_STOP. After A stops, both followers settle at their assigned poses and remain stopped.

1.3 Visual Aid: How the System is Used

Figure 1 shows the system from the operator's point of view rather than decomposing the electronics into internal blocks. The dotted connections represent wireless communication and evaluation-only sensing.



Direction of motion

Wi-Fi com.

Overhead camera

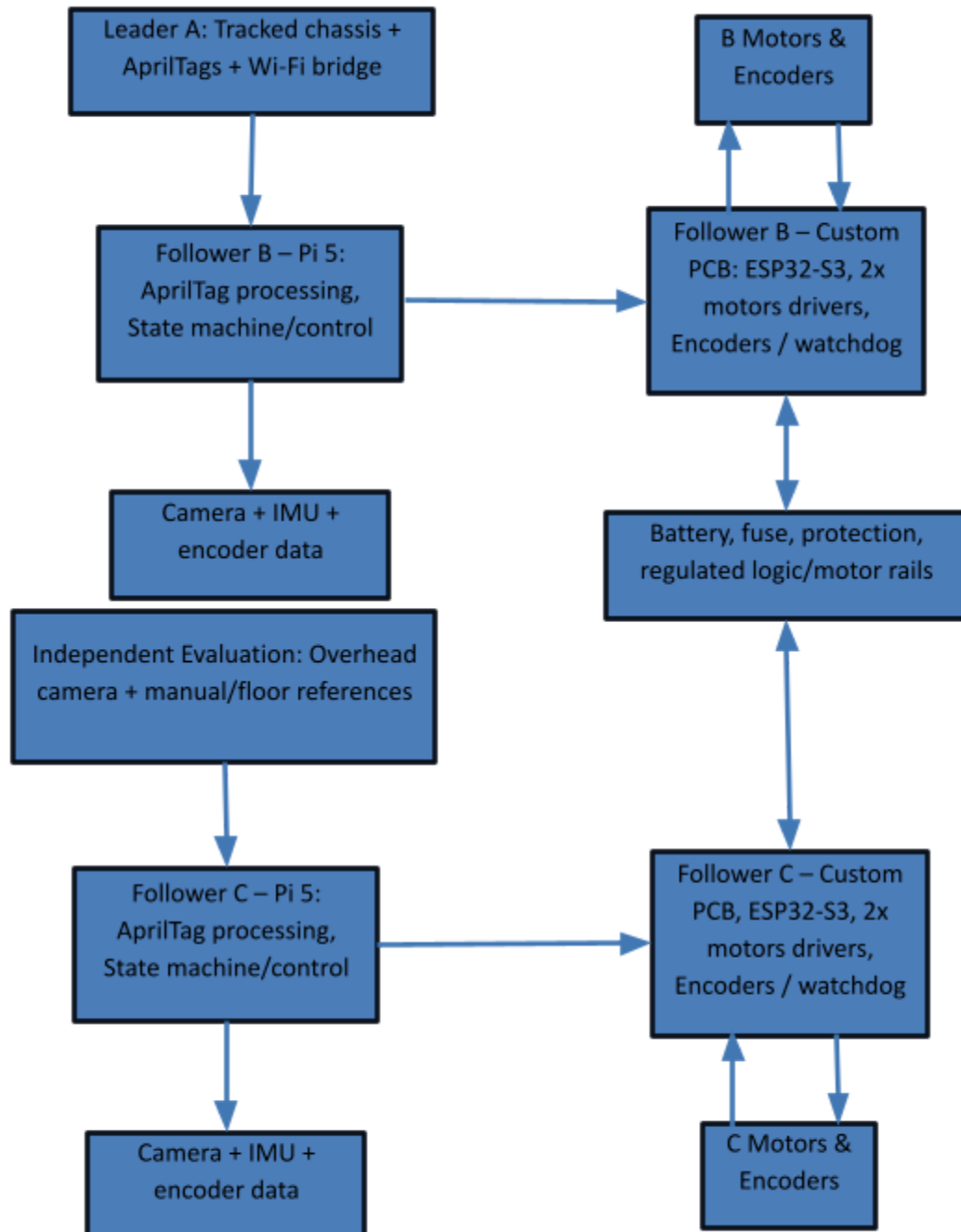
Figure 1 Visual aid showing the three-robot operating environment and external interactions.

1.4 High-Level Requirements

- Each follower shall estimate the leader's planar relative position within 5 cm and relative heading within 5° at at least 8 of 10 surveyed static poses for each follower.
- The complete A+B+C system shall pass at least 8 of 10 joint following trials, with each follower maintaining no more than 15 cm target-separation error in at least 80% of evaluated samples after the first 2 s of motion and both followers settling within 5 cm and 5° of their target poses within 30 s after the leader stops.
- Each follower shall enter a stopped condition within 0.5 s after loss of any required heartbeat, valid AprilTag localization, or Pi-to-PCB command at the maximum test speed of 0.10 m/s, with all three fault types passing three repetitions per follower.

2 Design

2.1 Block Diagram



Encoder feedback
RWM / drive
Encoder feedback
Power
Power
Sensor data
Sensor data
Wi-Fi task/health
Wheel-speed cmd
Wheel-speed cmd
Evaluation only

Figure 2 System block diagram showing sensing, computing, custom PCB control, power, and evaluation interfaces.

2.2 Subsystem Overview

Subsystem 1 — Leader and Follower Platforms

The existing tracked leader A provides the moving reference and carries the AprilTag assembly and proposed Wi-Fi heartbeat/task-state bridge. Followers B and C use identical differential-drive chassis with encoder-equipped brushed DC gearmotors. B and C use the same PCB and software architecture, with only robot ID, calibration values, and target offsets changed. This common architecture reduces duplicated design work and makes the second follower an integration of a validated design rather than a separate electrical design.

Subsystem 2 — AprilTag Relative Localization

Each follower uses one Raspberry Pi global-shutter camera to observe rigidly mounted AprilTags on A. The camera-to-follower and tag-to-leader transforms are calibrated before scored trials. Quadrature encoders and a BNO085 IMU provide short-term motion estimates between visual updates. AprilTags remain the primary relative-pose reference; UWB and LiDAR are not required for the core demonstration.

Subsystem 3 — Onboard Control and Communication

A Raspberry Pi 5 on each follower performs image processing, relative-pose estimation, the follower state machine, and high-level wheel-speed commands. Wi-Fi carries only robot ID, sequence number, and task/health state. The local PCB watchdog independently supervises commands from the Pi, so stopping does not depend on a laptop or on successful delivery of a remote stop message.

Subsystem 4 — Shared Custom Motor, Power, and Safety PCB

The main circuit-level deliverable is one PCB design used on both followers. The proposed board contains an ESP32-S3, two brushed-DC motor-driver channels, current/bus-voltage monitoring, encoder input conditioning, battery protection, regulated logic/computer power, a physical motor-disable input, a local command watchdog, and defined Pi/sensor connectors. Exact motor, battery, and regulator ratings remain subject to measured load characterization.

Subsystem 5 — Test Field and Independent Evaluation

A flat 3 m × 3 m field provides one straight and one gently curved route. An overhead camera and floor/manual references independently measure trajectories and final poses. Evaluation measurements do not feed the controller, preventing the test instrumentation from masking failures in onboard localization or control.

2.3 Subsystem Requirements

Subsystem 1 — Platforms

- Leader A shall carry rigid AprilTag targets whose dimensions and transforms are measured before scored trials.
- Followers B and C shall support differential-drive motion and encoder feedback.
- Both followers shall remain within the validated 0.10 m/s core speed envelope.

Subsystem 2 — Localization

- Each follower shall provide relative position and heading estimates referenced to defined robot reference points.
- The camera/tag geometry shall be calibrated before scoring and held fixed across trials.
- Loss of valid AprilTag localization shall request SAFE_STOP rather than attempting unconstrained recovery.

Subsystem 3 — Control and Communication

- The Pi shall generate bounded left/right wheel-speed requests and implement the defined state machine.
- Wi-Fi messages shall include robot ID, sequence number, and task/health state so stale messages can be detected locally.
- Each follower shall stop on a local Pi-command timeout without requiring laptop intervention.

Subsystem 4 — Custom PCB

- The PCB shall provide two independently controlled motor channels and encoder acquisition.
- The PCB shall include battery fuse/reverse-polarity protection, regulated logic power, current/bus-voltage monitoring, and a physical motor-disable input.
- The local watchdog and motor-disable path shall remain capable of stopping drive actuation when higher-level software or communication fails.

Subsystem 5 — Evaluation

- The field shall maintain direct tag visibility, separate approach regions, and physical clearance for the tested routes.

- Independent measurements shall be sufficiently accurate to distinguish the 5 cm/5° final-pose requirements.
- Logs shall record relative-pose error, following error, final-pose error, joint-trial outcome, and communication/stop events without feeding these measurements back into control.

2.4 Tolerance Analysis

The most important feasibility risk is the fail-safe stopping requirement because the system must stop within 0.5 s after a relevant fault at the maximum follower speed of 0.10 m/s. At the worst-case test speed, if a follower could continue at constant speed for the entire 0.5 s, it would travel $0.10 \times 0.50 = 0.050$ m, or 5 cm. Therefore, a zero-delay idealized stop requires an average deceleration of at least $0.10/0.50 = 0.20$ m/s².

A conservative design check includes 0.20 s of combined sensing, software, communication, and watchdog response before braking begins. The remaining 0.30 s then requires an average deceleration of at least $0.10/0.30 = 0.333$ m/s². The corresponding stopping distance is approximately $d = v \cdot t_{\text{delay}} + v^2/(2a) = (0.10)(0.20) + (0.10^2)/(2 \cdot 0.333) \approx 0.035$ m, or 3.5 cm. This is feasible if motor/load characterization demonstrates at least 0.333 m/s² average deceleration under the tested load. The team will measure actual response latency and deceleration with wheels lifted and then on the test field. If measured performance is insufficient, the team will reduce the validated operating speed or improve the local watchdog/drive-disable response before scored trials. This analysis does not assume a specific motor torque until the selected motors and battery are characterized.

3. Ethics, Safety and Societal Impact

3.1 Ethics

The project follows the engineering principle that public safety takes priority over demonstration performance. The IEEE Code of Ethics emphasizes responsibility for safety, health, and welfare and requires engineers to be honest about technical claims and limitations. The project therefore will not describe the prototype as a general-purpose autonomous multi-robot system: the validated scope is limited to low-speed operation, controlled lighting, specified routes, surveyed starting regions, and known target geometry.

The computing portion also follows the ACM Code of Ethics, which emphasizes the public good and calls for thorough, objective evaluation of computer systems and their possible risks. The team will preserve trial logs, report failed trials rather than selectively presenting successful demonstrations, document calibration changes before scoring, and distinguish independent evaluation measurements from controller inputs.

Ethical risks also arise from accidental or intentional misuse. Because the robots can move without continuous wheel commands from a laptop, a failure in the local control chain could otherwise create an unexpected motion hazard. The design addresses this through local watchdogs, physical motor-disable inputs, bounded speed, restricted routes, and SAFE_STOP behavior. The team will not intentionally defeat these mechanisms during normal operation.

4. Verification Plan

Localization: Ten surveyed static poses per follower, covering 0.5–1.0 m separation and relative heading within $\pm 30^\circ$. Pass: ≤ 5 cm position and $\leq 5^\circ$ heading on at least 8/10 poses.

Simultaneous Following: Ten joint trials, five per route. Pass: at least 8/10 trials; after 2 s, target-separation error ≤ 15 cm for at least 80% of evaluated samples, with both followers remaining on their assigned sides.

Rendezvous: After A stops, both followers must settle within 30 s to ≤ 5 cm position and $\leq 5^\circ$ heading error and remain stopped simultaneously for at least 1 s.

Fault Stopping: For each follower, test Wi-Fi heartbeat loss, AprilTag localization loss, and Pi-to-PCB command loss three times. Pass: stop within 0.5 s for every repetition, plus successful physical motor-disable tests and peer-fault stop behavior.

5. Scope and Deliverables

The final deliverable is one existing tracked leader and two custom-controlled followers demonstrating simultaneous AprilTag-based relative localization, low-speed following, settling at separate relative poses, and local fail-safe stopping. The team will first validate the shared follower PCB and local stop functions, then integrate A+B, then add C using the same validated design, and finally conduct simultaneous B/C trials. Optional UWB, LiDAR/ToF, altered lighting, additional initial poses, and obstacle experiments will be attempted only after the core acceptance criteria are satisfied.

References

[1] ECE 445, University of Illinois Urbana-Champaign, “Safety Guidelines.

”<https://courses.grainger.illinois.edu/ece445/guidelines/safety.asp>

[2] ACM, “ACM Code of Ethics and Professional Conduct.” <https://www.acm.org/code-of-ethics>

[3] IEEE, “IEEE Code of Ethics.” <https://www.ieee.org/about/corporate/governance/p7-8>