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ECE 445

Proposal Document

Introduction

Problem: One to two paragraphs detailing the problem statement. Include any relevant references to justify the existence or importance of the problem.

The proliferation of wireless local area networks is fundamental to the operation of modern homes, offices, and industrial environments, supporting everything from personal communication to a vast ecosystem of IoT devices. However, the performance of these networks is highly susceptible to the physical environment, with signal strength often varying dramatically due to architectural features, furniture, and interference. The process of identifying and mitigating areas of poor coverage, or "dead zones," is crucial for network optimization but typically relies on a manual survey [3]. This method involves an individual walking through a space with a signal-measuring device, which is a process that is not only time-consuming and laborious but also yields inconsistent, low-resolution data. This leaves the placement of routers and access points to guesswork rather than analysis [1].

This project directly addresses the inefficiencies and inaccuracies of manual WiFi mapping by developing an autonomous mobile robot capable of generating a signal strength map of an indoor environment. By integrating a LIDAR sensor with a SLAM algorithm, the system can build an accurate 2D representation of an area and then navigate it autonomously along a calculated path. As the robot traverses the space, it continuously records the WiFi Received Signal Strength Indicator with an ESP32 module and correlates it with its precise location data. The final dataset enables the creation of a detailed heat map, providing a clear visualization of the WiFi coverage. This automated approach eliminates the manual labor and inconsistency of traditional methods, offering a powerful tool for users to diagnose connectivity issues and effectively optimize wireless infrastructure [2].

Solution: One to two paragraphs describing the solution. Give a high-level idea of what your solution is, then delve into detail as to how it is implemented. You do not have to commit to a particular implementation at this point, but your description should be explicit and concrete.

Our solution is an RC car designed to systematically map the WiFi signal strength within an indoor environment and generate a visual heat map. The system is built on a custom RC car platform featuring omnidirectional wheels, which allow for movement in any direction. The car is equipped with a LIDAR sensor for spatial awareness, an ESP32 microcontroller to serve as the low-level hardware controller, and a Raspberry Pi single-board computer to act as the "brain" for

SLAM and the path planning algorithm. All onboard electronics, including power distribution from a LiPo battery and signal routing, will be integrated via a custom designed PCB. The system's operation is divided into two distinct phases: a short initial manual-control phase to allow the Raspberry Pi to build a 2D map of the environment, followed by a very long methodical autonomous phase to collect WiFi signal data across the entire room [3].

The implementation hinges on a clear and robust communication hierarchy. During the initial mapping phase, a user will control the vehicle from a custom GUI on a host computer, sending command packets via Bluetooth to the ESP32 which will interface with a four-channel motor controller. Simultaneously, the ESP32 will continuously process the raw data stream from the LIDAR sensor and relay parsed distance and angle information to the Raspberry Pi over a UART connection. The Raspberry Pi will then use a well-established SLAM algorithm to construct the 2D map in real-time.

Once the user engages the autonomous mode via the GUI, the Raspberry Pi finalizes the map and utilizes a path-planning algorithm, such as calculating the most efficient trajectory to cover the entire known area. It then begins sending a sequence of simple directional commands to the ESP32. As the ESP32 executes these movement commands, its onboard WiFi module is tasked with continuously scanning for the network's Received Signal Strength Indicator simultaneously correlating it with a (x, x) coordinate given by SLAM. After the planned path is complete, the ESP32 transmits the collection of coordinate and RSSI data points back to the host computer, which then renders the final heat map visualization for the user.

Visual Aid: A pictorial representation of your project that puts your solution in context. Include other external systems relevant to your project (e.g. if your solution connects to a phone via Bluetooth, draw a dotted line between your device and the phone). Note that this is not a block diagram and should explain how the solution is used, not a breakdown of inner components.

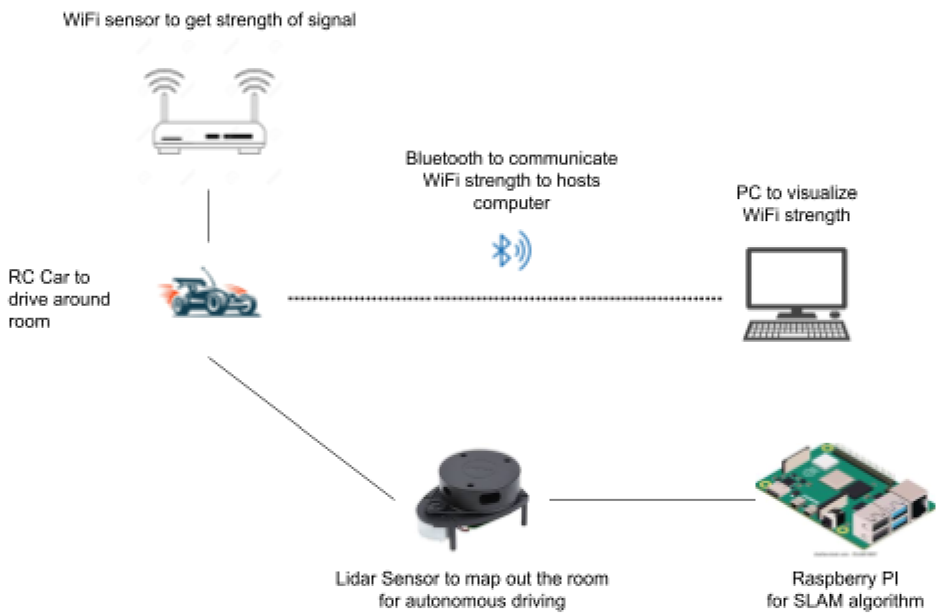

Diagram 1

High-level requirements list: A list of three quantitative characteristics that this project must exhibit in order to solve the problem. Each high-level requirement must be stated in complete sentences and displayed as a bulleted list. Avoid mentioning "cost" as a high level requirement.

- A user must be able to manually drive the car from the host computer using Bluetooth.
- The car must drive a planned route and use its LIDAR sensor to build a 2D map.
- The car must measure WiFi signal strength at various locations to create a heat map.

Design

Block Diagram: Break your design down into blocks and assign these blocks into subsystems. Label voltages and data connections. Your microcontroller can live in multiple subsystems if you wish, as in the example below.

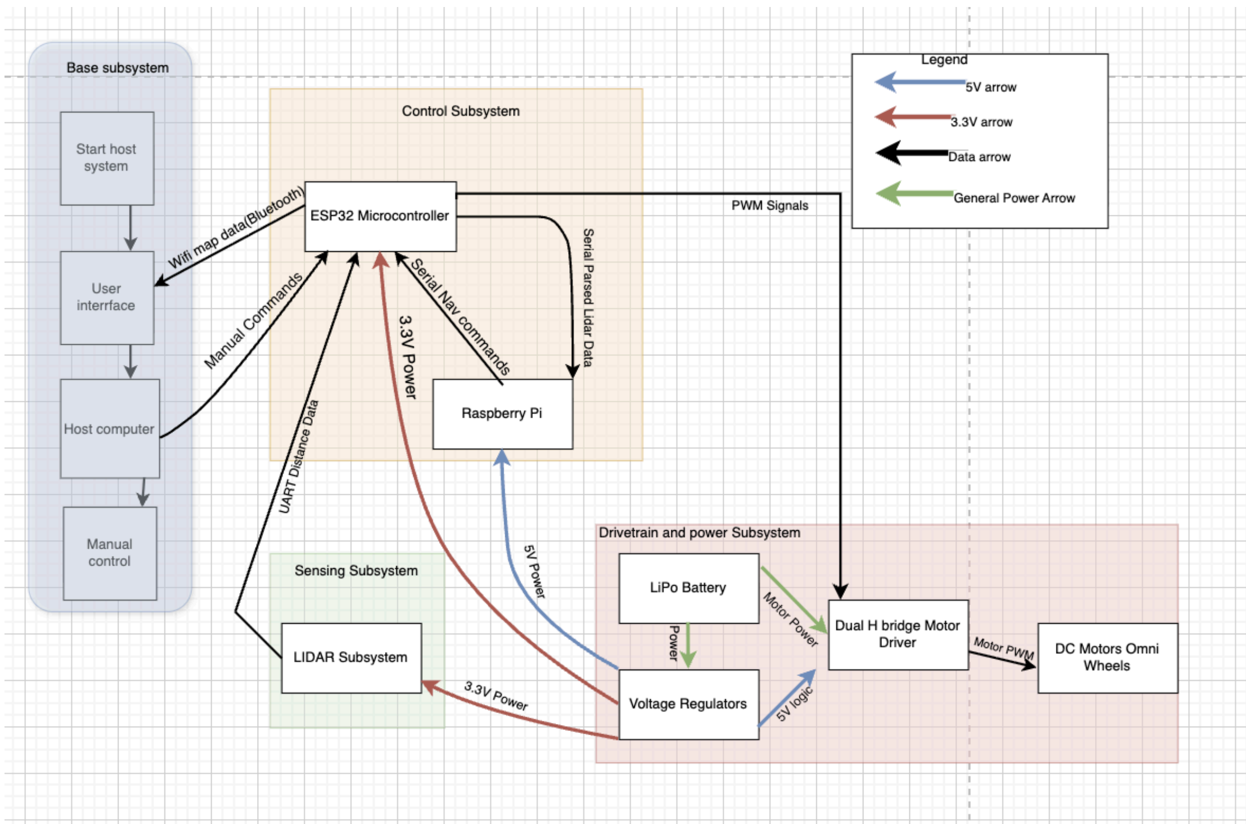

Diagram 2 [4]

Subsystem Overview: A brief description of the function of each subsystem in the block diagram and explain how it connects with the other subsystems. Every subsystem in the block diagram should have its own paragraph.

Base Subsystem

This subsystem hosts the user interface on the host computer and is responsible for starting the system, teleoperating the vehicle during the manual-mapping phase, and displaying the final Wi-Fi heat map. Functionally, it sends manual drive commands and a start signal from the GUI over Bluetooth to the ESP32 in the Control Subsystem. It also acts as the receiver for the Wi-Fi map data the ESP32 transmits back over Bluetooth once a run is complete. In short: Base ↔ Control is a Bluetooth control/telemetry link; Base does not directly touch sensors or motors, but it initiates operation and consumes the final dataset for visualization.

Control Subsystem

This subsystem contains the ESP32 microcontroller and the Raspberry Pi. The ESP32's functions are to (1) maintain the Bluetooth link with the Base Subsystem, receive manual commands/start signals, and send Wi-Fi map data; (2) generate PWM drive signals to the dual H-bridge motor driver in the Drivetrain & Power Subsystem; (3) parse incoming LIDAR distance/angle data (UART) from the Sensing Subsystem and forward parsed data to the Raspberry Pi; and (4) indicate when the final Wi-Fi map data is ready for the Base Subsystem. The Raspberry Pi runs navigation: it ingests serial LIDAR data from the ESP32, performs mapping/localization/path planning, and returns serial navigation commands to the ESP32 for execution. Power-wise, the ESP32 receives 3.3 V and the Raspberry Pi 5 V from the Drivetrain & Power Subsystem's regulators. Thus, Control is the hub: Bluetooth to Base, UART to Sensing, PWM to Drivetrain, and regulated power in from Drivetrain & Power [4].

Sensing Subsystem
This subsystem is the LIDAR sensor, powered at 3.3 V from the Drivetrain & Power Subsystem's regulators. When the RC car is started, the Control Subsystem initializes the LIDAR, after which the sensor continuously streams UART distance/angle data to the ESP32 within the Control Subsystem. The LIDAR has no direct connection to the Base Subsystem or the motor driver; its single logical link is UART → ESP32, enabling the Raspberry Pi (via the ESP32) to build the map and produce navigation commands.

Drivetrain & Power Subsystem
A LiPo battery feeds two paths: (1) high-current motor power directly to the dual H-bridge motor driver, and (2) the voltage regulators that generate the logic rails. The motor driver receives PWM inputs from the ESP32 (Control Subsystem) and outputs the corresponding drive currents to the DC motors on the omnidirectional wheels. The regulators supply 5 V logic to the motor driver, 5 V to the Raspberry Pi, and 3.3 V to both the ESP32 and the LIDAR sensor. The system "start" action enables these regulators so all downstream electronics power up in order. In summary, Drivetrain & Power provides the power rails for Control and Sensing, accepts PWM control from Control, and converts that into mechanical motion at the wheels.

Subsystem Requirements: For each subsystem in your block diagram, you should include a highly detailed block description. Each description must include a statement indicating how the block contributes to the overall design dictated by the high-level requirements. Any interfaces with other blocks must be defined clearly and quantitatively. Include a list of requirements where if any of these requirements were removed, the subsystem would fail to function. Good example: Power Subsystem must be able to supply at least 500mA to the rest of the system continuously at 5V +/- 0.1V.

Base Station Subsystem Requirements

- Must provide a graphical user interface (GUI) for manual control of the RC car.
- Must be able to establish and maintain a stable Bluetooth connection with the ESP32.
- Must be able to send a distinct command to initiate the autonomous mapping phase.
- Must be able to receive and parse the final (x, y, RSSI) data structure from the car.

- Must render the received data as a visual heat map of the mapped area.

Control Subsystem Requirements

- The ESP32 must sample the WiFi RSSI of the target network at a regular interval.
- The ESP32 must relay raw LIDAR data to the Raspberry Pi at a rate sufficient for real-time SLAM processing.
- The Raspberry Pi must successfully execute a SLAM algorithm to generate a 2D map of the environment.
- The Raspberry Pi must be able to calculate a coverage path plan for the entire mapped area.
- The ESP32 must be able to translate high-level commands ("F", "B", etc.) from the Raspberry Pi into the appropriate PWM signals for the motor driver.
- The subsystem must accurately associate each WiFi RSSI measurement with the car's (x, y) coordinates provided by the SLAM algorithm.

Sensing Subsystem Requirements

- Must provide a 360-degree, 2D scan of the surrounding environment.
- The data output rate must be sufficient for the SLAM algorithm on the Raspberry Pi to perform real-time tracking.
- The sensor's range and accuracy must be adequate to map a typical indoor room (e.g., minimum range of 5-8 meters).
- Must operate reliably on a 3.3V power source.

Drivetrain & Power Subsystem Requirements

- The LiPo battery must have sufficient capacity to power the entire system for a minimum of 15 minutes of continuous operation.
- The voltage regulators must provide stable 5V (+/- 0.2V) and 3.3V (+/- 0.1V) supplies to all components.
- The Dual H-Bridge Motor Driver must be able to supply enough current to drive all four DC motors simultaneously under load.
- The omnidirectional wheels and motors must be able to execute forward, backward, and lateral movements as commanded.

Tolerance Analysis: Identify an aspect of your design that poses a risk to successful completion of the project. Demonstrate the feasibility of this component through mathematical analysis or simulation.

Because we have 2 chips communicating with each other, being the Raspberry pi and the ESP32, we have to make sure that the data being sent does not get lost or delayed, which could make the robot continue driving when it shouldn't. To avoid this potential issue we are going to add 2 different methods of protection. The first one is that the pi will be sending a signal 20 times a second to the ESP32 via a UART connection. The signal will include a timestamp, data to verify that it's the same so no errors (CRC-32 for error checking). If we don't receive a signal in a period of half a second, the car pauses its driving and waits. If it's longer than 2 seconds, we have a fault that we need to manually uncheck on our computer. Let's assume that the data will be sent as a 12 byte signal, with common UART speed being 115200 bits per second, so it takes around 1 ms to transmit the data, adding in a slight delay just in case puts us at 5 ms. Adding in 2 ms for the esp to read the data, giving us 8ms for the data to be sent and received, so a 50 ms buffer is very reasonable to us. Packets will be acknowledged to verify they were received.

Ethics and Safety

Assess the ethical and safety issues relevant to your project. Consider both issues arising during the development of your project and those which could arise from the accidental or intentional misuse of your project. Specific ethical issues should be discussed in the context of the IEEE and/or ACM Code of Ethics. Cite, but do not copy the Codes. Explain how you will avoid ethical breaches. Cite and discuss relevant safety and regulatory standards as they apply to your project. Review state and federal regulations, industry standards, and campus policy. Identify potential safety concerns in your project.

Our Commitment

Our team is committed to upholding the highest standards of ethical conduct and ensuring the safety of all individuals and property throughout the development and operation of this project. We will be guided by the principles outlined in the IEEE and ACM Codes of Ethics and will adhere to all relevant safety regulations and standards.
Ethical Considerations

This project, while academic in nature, involves the collection and processing of environmental data, which necessitates a careful ethical review.

Data Privacy and Security: The primary ethical concern is the project's data collection capability. The LIDAR sensor builds a detailed 2D map of a physical space, while the ESP32 logs wireless network information. In the wrong context, this could infringe on an individual's reasonable expectation of privacy. Intentional misuse could turn the device into a tool for surreptitious mapping of private spaces. This directly invokes the **ACM Code of Ethics 1.6 ("Respect privacy")** and the **IEEE Code of Ethics, Principle 1 (Integrity),** which includes the commitment to protect the privacy of others.
Mitigation Strategy: To prevent ethical breaches, this project will be conducted exclusively in controlled, non-sensitive university lab environments with the full consent of all persons present. The data collected (maps and RSSI values) will be used solely for academic purposes, will not be associated with any personal information, and will be securely deleted from all systems upon project completion. Data transfer from the car to the host computer will be handled responsibly to minimize the risk of interception [3].

Potential for Malicious Use: The hardware platform could be modified for malicious purposes. For example, the WiFi-enabled ESP32 could be reprogrammed from a passive signal-strength measurement tool into an active network snooping or attack tool. This possibility requires us to consider our responsibilities under **ACM Code of Ethics 1.2 ("Avoid harm")** and **IEEE Code of Ethics, Clause IX: "to avoid injuring others, their property, reputation, or employment by false or malicious action."**
Mitigation Strategy: Our team will ensure that the developed software is strictly limited to the project's stated goals of navigation and RSSI mapping. We will not develop or distribute any software functionalities that could facilitate network intrusion or privacy violations. The project's

documentation will explicitly state its intended academic purpose and highlight the ethical considerations of its hardware capabilities.

Intellectual Honesty: The project will leverage existing open-source software (e.g., SLAM on the Raspberry Pi). We will honor licenses and **properly credit upstream contributors**, aligning with **ACM Code of Ethics 1.5** (“Respect the work required to produce new ideas, inventions, creative works, and computing artifacts”) and the **IEEE Code of Ethics, Clause VII** (“…to credit properly the contributions of others”).
Mitigation Strategy: Our team will diligently track the use of all third-party libraries and code. We will provide clear and accurate attribution for all open-source software used in our project reports, documentation, and presentations.

Safety Analysis

A thorough safety analysis has been conducted to identify and mitigate potential hazards associated with the project's hardware and operation.
Electrical Safety: The primary electrical hazard stems from the use of a Lithium Polymer (LiPo) battery to power the device. LiPo batteries can pose a significant fire risk if they are punctured, short-circuited, or improperly charged. The custom PCB, which handles power distribution and signal routing, must be designed to prevent short circuits.

- **Standards and Regulations:** We will ensure all electronic components are CE/UL certified where applicable. The wireless transmitters (ESP32, Raspberry Pi) are subject to FCC Part 15 regulations, and we will use pre-certified modules to ensure compliance.
- **Mitigation Strategy:** A dedicated LiPo battery charger with cell-balancing and overcharge protection will be used at all times. The battery will be physically secured within the RC car's chassis to protect it from impact. The custom PCB design will include short-circuit protection (fuses) and will be thoroughly reviewed for proper component spacing and trace routing before fabrication.

Mechanical Safety: The project is a mobile autonomous robot. Although small, it has the potential to collide with people or fragile objects, posing a minor physical hazard and a risk of property damage.

- **Mitigation Strategy:** The car's autonomous operational speed will be deliberately limited in software to a slow walking pace. All testing and operation will occur in a designated, controlled lab area, cleared of obstacles and unnecessary personnel. The system will include a clear and accessible emergency stop mechanism, likely implemented through the Bluetooth control interface on the host computer.

Laser Safety: The LIDAR sensor uses a laser to map its surroundings. Direct exposure to a high-power laser can cause severe eye damage.

- **Standards and Regulations:** Laser safety is governed by the international standard IEC 60825-1.
- **Mitigation Strategy:** We will ensure the selected LIDAR unit is a Class 1 laser product, which is eye-safe under all normal conditions of use. We will verify this classification on the component's official datasheet before integration and operation.

Campus Policy Compliance: As this is a university project, we are bound by the safety protocols of the University of Illinois at Urbana-Champaign and the Electrical and Computer Engineering department.

- **Mitigation Strategy:** All project work will be conducted in authorized lab spaces and in full compliance with university and departmental safety guidelines. We will consult with our faculty advisor and lab technicians to ensure all procedures, particularly those related to battery charging and autonomous vehicle testing, are approved and follow established protocols.

Acknowledgement & Citations

The authors acknowledge that Google's Gemini and OpenAI's ChatGPT were used for inspiration and to help flesh out initial ideas for this project.

[1] Haptic Networks. (n.d.). Common Mistakes In WiFi Network Design (And How To Avoid Them). Haptic Networks. Retrieved September 13, 2025, from https://haptic-networks.com/wifi/common-mistakes-in-wifi-network-design-and-how-to-avoid-them/

[2] Cisco Systems, "Understand Site Survey Guidelines for WLAN Deployment," Cisco Support Documentation, updated Nov. 14, 2023. https://www.cisco.com/c/en/us/support/docs/wireless/5500-series-wireless-controllers/116057-site-survey-guidelines-wlan-00.html

[3] Google, Gemini. [Online]. Available: https://gemini.google.com. Accessed: Sept. 19, 2025.

[4] OpenAI, ChatGPT. [Online]. Available: https://chatgpt.com/. Accessed: Sept. 19, 2025.