TURF

Turf Upkeep & Robotic Fieldcare

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1. Executive Summary

The TURF Autonomous Lawnmower project focuses on designing a compact, affordable, and fully autonomous mowing platform capable of operating safely within user-defined boundaries. During Senior Design I, the team developed the foundational architecture for a robotic mower that integrates embedded control, wireless localization, motor actuation, power electronics, and sensor-based obstacle detection. The system is centered on an ESP32 microcontroller, supported by UWB ranging modules for position tracking and ultrasonic sensors for short-range obstacle detection. Differential drive motors provide mobility, while a dedicated blade motor handles cutting operations. All subsystems are powered by a 12-volt $LiFePO_4$ battery, with a multi-stage regulation system using a variety of buck converters to deliver stable 12 V, 5 V, and 3.3 V rails.

Throughout SD1, significant effort was devoted to researching hardware options, defining system requirements, and constructing the electrical and mechanical framework for the prototype. The team completed detailed analysis of the power system, selected appropriate motors and drivers, and designed the initial PCB that integrates control logic, regulators, sensors, and safety interfaces. Individual components were tested for functionality, including motor control, voltage regulation, and UWB ranging performance, establishing confidence in the chosen architecture. Mechanical design work included early chassis layout, mounting considerations, and subsystem placement to support upcoming assembly.

This report summarizes the SD1 progress, including the project description, research foundation, design decisions, power system architecture, hardware/software design, and administrative planning. The work completed provides a strong basis for SD2, where the team will fabricate the full prototype, integrate all subsystems, perform field testing, refine navigation algorithms, and complete the final demonstration of the TURF autonomous mowing platform.

Beyond the core hardware development, the team also made substantial progress on the high-level operational framework and autonomy strategy. A complete software architecture was drafted to define how the mower will transition between configuration, localization, navigation, safety monitoring, and return-to-dock behavior. The companion mobile application was designed to provide anchor-coordinate entry, mowing-area definition, real-time monitoring, and emergency-stop capability. This dual-system approach, pairing onboard embedded control with a lightweight user interface, establishes a clean division between user configuration and autonomous computation, simplifying both usability and system integration.

Considerable analysis was also dedicated to evaluating localization methods suitable for outdoor, GPS-denied environments. Ultra-wideband ranging was selected for its robustness, repeatability, and compatibility with the ESP32 platform. Early testing confirmed that the DW1000 modules provide consistent short-range distance measurements, enabling reliable trilateration when paired with well-placed anchors. The team investigated filtering approaches, anchor placement strategies, and update-rate trade-offs, laying the groundwork for the real-time position estimation that will be implemented in SD2.

Risk assessment and mitigation planning were key elements of the SD1 effort. The team identified potential hazards related to battery systems, motor control, blade operation, and outdoor environmental conditions. As a result, safety mechanisms including emergency stop interfaces, boundary enforcement logic, and optional tilt/lift sensing were incorporated into the hardware and software design from the outset. These considerations ensure that the platform will meet safety expectations during field operation and final demonstration.

Additionally, project management structure and deliverables for SD2 were formally outlined. Milestones were established for mechanical assembly, printed circuit board assembly, firmware integration, and outdoor testing. Procurement planning ensures that all major components will be sourced early to avoid lead-time delays during Spring semester integration. Team roles were clarified for electrical, software, mechanical, and testing responsibilities, improving workflow efficiency and accountability.

Collectively, the work completed in Senior Design I provides a strong and coherent foundation for successful system integration in Senior Design II. With the architecture defined, components selected, and preliminary testing complete, the team is well-positioned to transition from research and planning to full prototype construction, refinement, and performance validation. The upcoming phase will focus on achieving stable localization, robust path following, reliable docking behavior, and a polished demonstration of the TURF autonomous lawnmower system.

2. Project Description

2.1. Motivation and Background

There is an increasing demand for automated solutions to household and commercial lawn care. While there are many robotic lawn mowers on the market, existing models remain limited in capability, often relying on expensive boundary installations or requiring frequent user intervention. Additionally, many are cost-prohibitive for average homeowners and small businesses. We seek to address these challenges by developing a low-cost autonomous lawn mower capable of navigating defined boundaries with minimal setup and operating safely and independently in outdoor environments. By integrating GPS-based or wireless perimeter enforcement and obstacle detection the system will provide a versatile platform for small-scale land management. This, along with a modular design and potential for automated docking, will allow the mower to function reliably without constant user interaction.

The motivation for this project lies in the broad range of individuals and industries that rely on regular grounds maintenance. Homeowners often spend significant time and resources mowing their lawns, while landscaping companies face rising labor costs and inefficiencies in routine maintenance. Beyond residential use, commercial and municipal applications exist in maintaining schoolyards, parks, athletic fields, and office campuses where consistent lawn care is essential for safety and aesthetics. A compact, low-cost, and customizable autonomous mower will create an alternative to expensive commercial systems and allow a wider range of users to access robotic lawn care technology.

Potential applications of our proposed design extend beyond simple lawn mowing. As autonomy and sensor technologies continue to improve, the rover could be adapted for related outdoor tasks such as garden maintenance, targeted watering or fertilization, and even environmental monitoring. By focusing on modularity and open-source design, our project seeks to fill a gap in the market for affordable, adaptable, and safe robotic lawn care systems that can scale from personal use to broader community applications.

2.2. Goals and Objectives

2.2.1. Goals

Basic Goals:

- Develop an autonomous rover capable of navigating within a pre-programmed lawn area.
- Implement path following and boundary enforcement
- Enable obstacle detection and emergency stop for safety.

Advanced Goals:

- Incorporate efficient path planning to optimize mowing coverage.
- Integrate real-time monitoring through a mobile/web interface (battery, status, and location).
- Implement automatic docking and charging functionality.
- Modularize the design to allow interchangeable tools (e.g., mower deck, trimmer head, or utility attachment).

Stretch Goals:

- Add computer vision for object detection and dynamic avoidance of pets, people, or foreign objects.
- Enable smart scheduling and weather-aware operation (pause/resume during rain).
- Add AI-based object recognition to allow cataloging of observed wildlife.
- Incorporate mapping features to log coverage areas for multi-session mowing.

2.2.2. Objectives

Basic Objectives:

- Design and fabricate a durable, weather-resistant housing for electronics and cutting mechanism.
- Implement localization using UWB TOF (Ultra-Wide Band Time-of-Flight).
- Implement control system for propulsion, steering, and mowing motor.
- Demonstrate at least 10 minutes of untethered autonomous mowing within a defined test plot.
- Use ultrasonic rangefinder to stop before obstacles.

Advanced Objectives:

- Implement optimized path coverage algorithms to minimize missed or repeated areas.
- Build and demonstrate an automatic docking/charging station for the mower.
- Implement a mowing schedule (i.e. once a week the mower mows the backyard on its own)

Stretch Objectives:

- Incorporate rain and weather detection to suspend mowing in unsafe conditions.
- Use computer vision (OpenCV) to detect people, pets, or foreign objects in the mowing area, and automatically modify path.

2.3. Requirement Specifications

Table 1: Requirement Specifications

Marketing Requirements	Engineering Requirements	Justification
The mower should be able to autonomously cover an entire home lawn.	Must implement a row-by-row coverage algorithm (boustrophedon pattern), with ≤10 cm overlap between passes	Ensures full and efficient lawn coverage without leaving uncut strips.
The mower should be able to navigate accurately across the lawn.	Position estimation error ≤20 cm relative to field anchors using UWB TOF localization	Accurate localization is necessary to keep mowing rows straight and consistent.
The mower should be energy efficient to maximize runtime.	Single charge operation time ≥30 minutes; system enters sleep mode when idle.	Allows TURF to complete a standard suburban lawn in one session. Sleep mode conserves energy when idle.
The mower should be safe to operate around people and obstacles.	Must detect obstacles ≥1 m away and stop within ≤0.5 m of obstacle.	Safety for humans, animals, and equipment is critical for adoption.
The mower should be easy to recharge and maintain.	Automated docking station for charging and clippings disposal; recharge time ≤10 hours.	Simplifies operation and maintenance for groundskeepers.

The mower should be affordable for small organizations (schools, clubs), and households.	Estimated BOM <$500 for prototype.	Ensures feasibility for small institutions and households with limited budgets.

Achieving these specifications is important to ensure the functionality of our system and its ability to complete tasks. Three specifications that we will be able to demonstrate in testing are the positional error, obstacle recognition, and automated docking and charge time as these are quantifiable measurements.

2.3.1.

During Senior Design 2, it was determined that it was not possible to demonstrate recharging speed during a live demo due to time constraints. Instead, an alternative requirement was demonstrated. The robot was shown to be able to stop within 0.5 seconds of an emergency stop function being triggered in the mobile application. The ultimate specifications are outlined in Table 2: Updated Requirement Specifications.

Table 2: Updated Requirement Specifications

Marketing Requirements	Engineering Requirements	Justification
The mower should be able to navigate accurately across the lawn.	Position estimation error ≤20 cm relative to field anchors using UWB TOF localization	Accurate localization is necessary to keep mowing rows straight and consistent.
The mower should be safe to operate around people and obstacles.	Must detect obstacles 0.5m away and stop immediately	Safety for humans, animals, and equipment is critical for adoption.
The mower should be able to connect and respond to inputs from an app.	The mower should stop within 0.5s of the emergency stop in the app.	Simplifies operation for the operator and allows for wireless communication.

2.4. Previously Existing Products

Robotic lawn mowers have become increasingly common in recent years, with major brands such as Husqvarna, Worx, and Gardena offering consumer models (Husqvarna, 2025) (Worx, 2025). Most of these systems rely on boundary wires to define the mowing area, requiring lengthy installation and limiting flexibility if the yard layout changes. More advanced models integrate GPS navigation to remove the need for wires, but these still face issues with accuracy under tree cover or near buildings.

One of the main drawbacks of existing robotic mowers is their high cost. Entry-level models typically start around $800–$1,000, while higher-end systems with GPS guidance and larger battery capacity can exceed $3,000–$5,000. These prices make them inaccessible for many homeowners despite the convenience they offer.

Our system is designed to provide similar automation benefits at a lower cost, while improving accuracy and adaptability compared to traditional boundary-wire solutions.

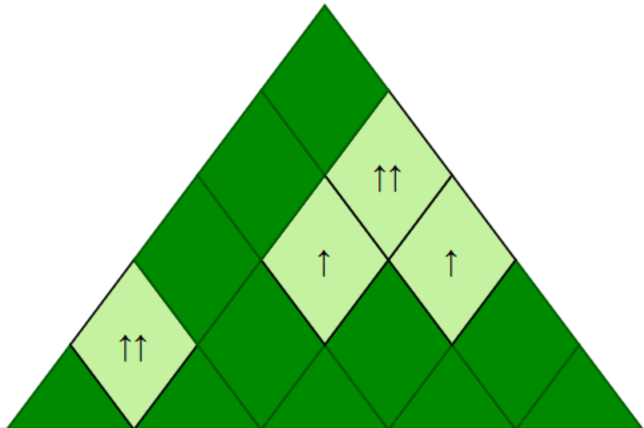
2.5. Engineering-Marketing Tradeoff Matrix

Table 3: Tradeoff Matrix

		Coverage Algorithm Accuracy (minimize overlap)	Localization Accuracy (minimize error)	Operation Time	Obstacle Detection	Docking and self-Maintenance
		−	−	+	+	+
1. Coverage	+	↑	↑	↑↑		↑↑
2. Mow Quality	+	↑	↑			↑
3. Time Efficiency	+	↑↑	↑↑			↑↑
4. Safety	+				↑↑	
5. Maintenance	−				↑	↑↑
6. Affordability (cost)	−	↓	↓	↓↓	↓	↓↓

2.6. House of Quality

Table 4: House of Quality



		Coverage Algorithm Complexity	Localization Accuracy	Operating Time	Obstacle Detection	Docking and self-Maintenance
		−	−	+	+	+
1. Coverage	+	↑	↑	↑↑		↑↑
2. Mow Quality	+	↑	↑			↑
3. Time Efficiency	+	↑↑	↑↑			↑↑
4. Safety	+				↑↑	
5. Maintenance	−				↑	↑↑
6. Affordability (cost)	−	↓	↓	↓↓	↓	↓↓
Engineering Targets		≤10 cm overlap	≤20 cm error	≥30 min	≥1 m	0

2.7. Hardware Diagram

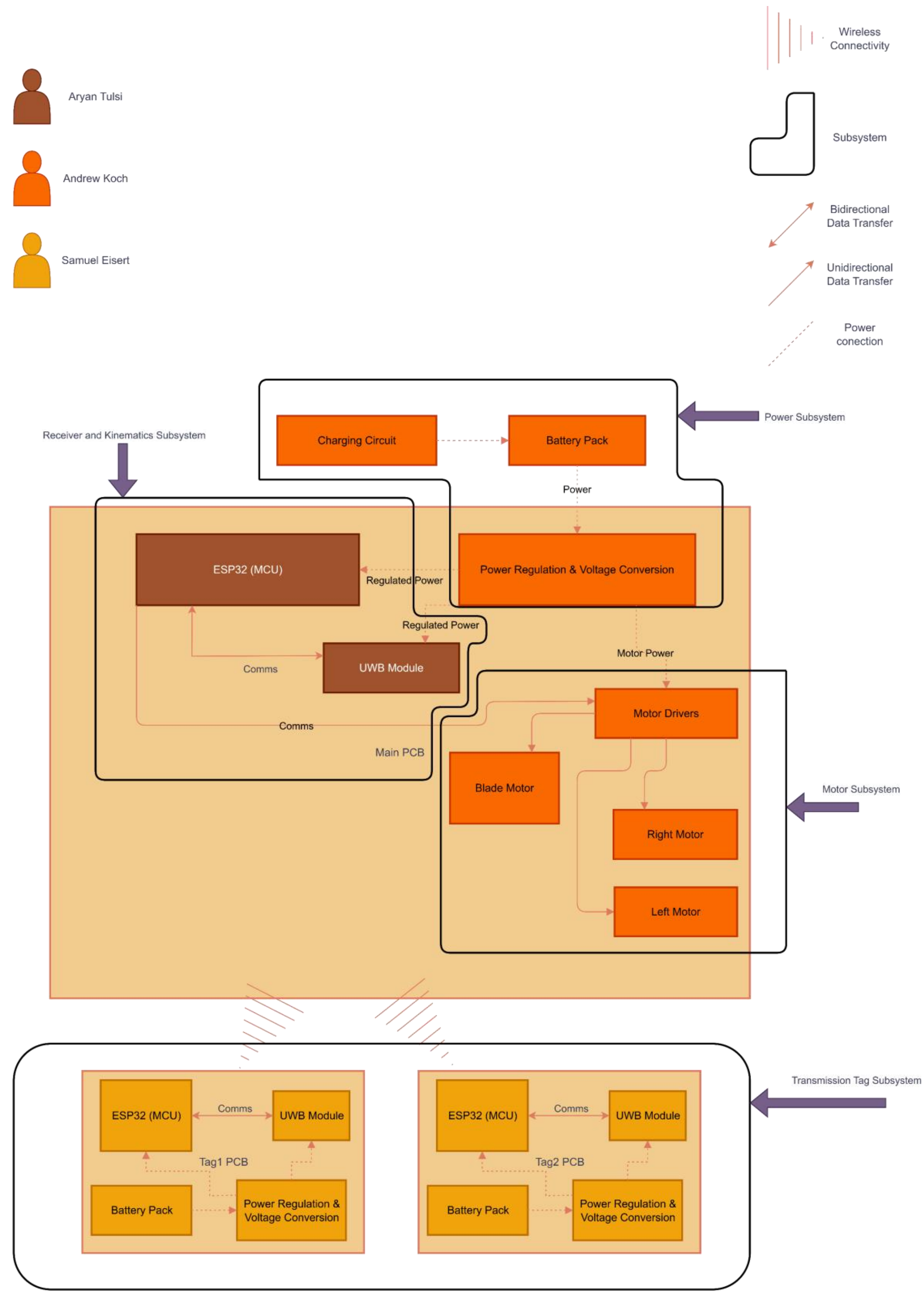


Figure 1: Hardware Diagram

The TURF system hardware shown in Figure 1: Hardware Diagram, is divided into 4 main subsystems. The main mower PCB contains the Power, Receiver and Kinematics, and Motor subsystems. The anchor tag PCBs used for localization are considered their own subsystem.

At the core of the mower is the Main PCB, which integrates several critical components. An ESP32 microcontroller serves as the central processor, handling communication, localization, and control logic. A dedicated UWB module provides time-of-flight ranging capabilities to enable accurate localization relative to the external anchor tags. The PCB also includes motor driver circuits, which receive velocity commands from the ESP32 and regulate power delivery to the wheel motors and blade motor. Power is managed through a regulation and voltage conversion stage, which ensures that the ESP32, UWB module, and drivers receive stable, appropriate supply rails.

Externally connected to the PCB are the battery pack and the charging circuit, which together provide energy storage and replenishment. The battery supplies power through the regulation stage, while the charging circuit manages safe recharging during docking. The regulated outputs supply the ESP32, UWB module, and motor drivers.

In addition to the main mower board, the system includes two independent Tag PCBs placed at fixed locations in the environment. Each tag contains its own ESP32, a UWB module, a battery pack, and a power regulation stage. These tags communicate with the mower’s UWB module to exchange ranging pulses, allowing the mower to calculate its two-dimensional position. The tags are battery powered and are designed to operate with low-duty cycles, conserving energy by sleeping when the mower is inactive.

2.8. Software Diagram

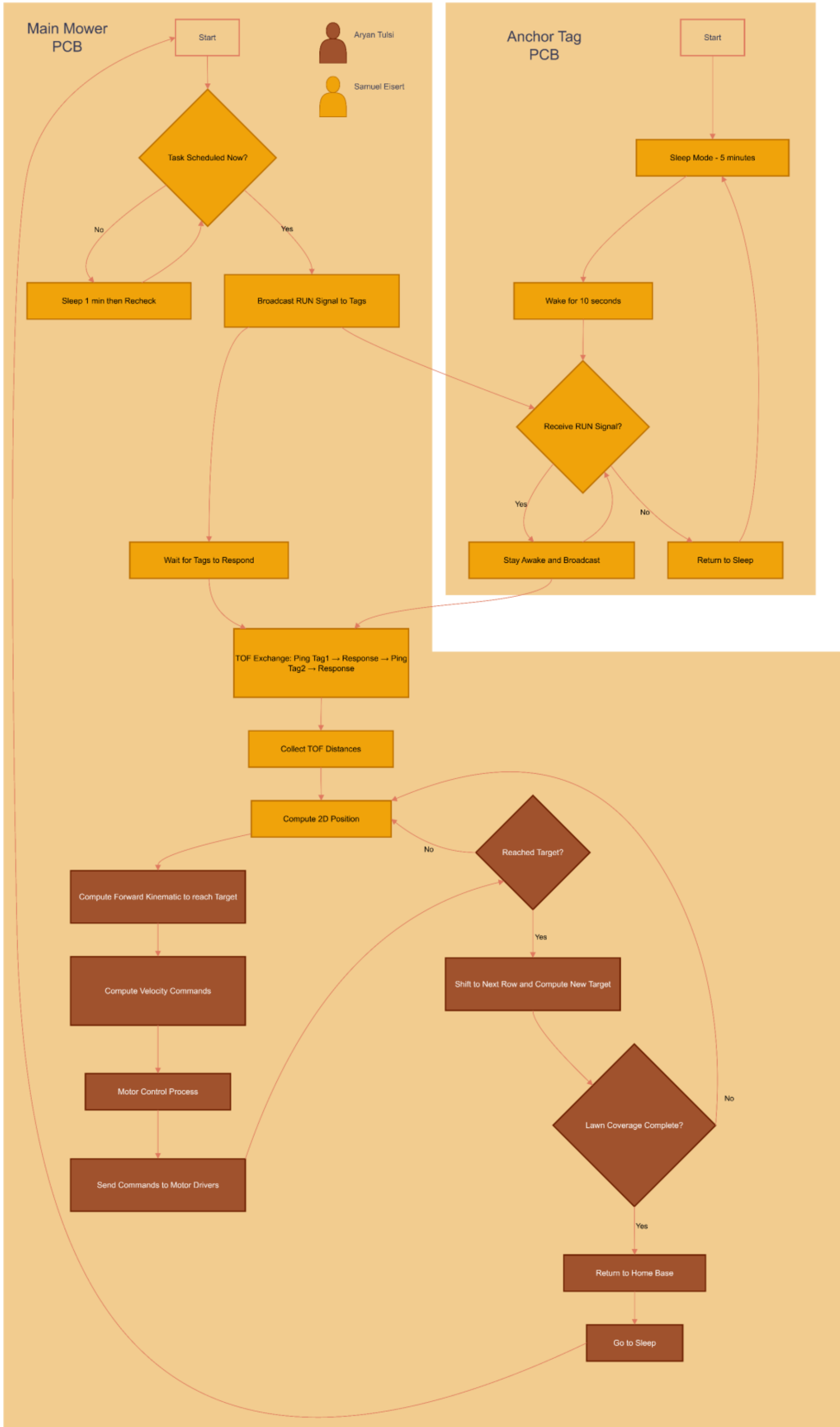


Figure 2: Software Diagram

The TURF system software shown in Figure 2: Software Diagram, is divided into two cooperating components: the **anchor tags** and the **mower controller**.

The **anchor tags**, which are battery-powered, operate in a low-power cycle to conserve energy. Each tag remains in sleep mode for five minutes and then wakes for a ten-second listening period. During this window, the tags check for a RUN signal broadcast from the mower. If no signal is detected, they return to sleep; if the mower is active, they remain awake and continue broadcasting until the mower stops. This strategy balances responsiveness with extended battery life.

The **mower software** manages task scheduling, localization, navigation, and coverage. At startup, the mower checks whether a task is scheduled for the current time. If no task is present, it enters a one-minute sleep interval before rechecking. When a task is due, the mower broadcasts a RUN signal to wake the tags and waits for confirmation. Once communication is established, the mower initiates a time-of-flight (TOF) exchange: it sequentially pings each tag, collects the return signals, and computes its position based on the known anchor locations.

Using this localization data, the mower passes its position into the navigation process, which calculates velocity commands via the navigation stack. These commands are processed by the motor control system and translated into actuation signals for the motor drivers. The mower then advances toward its target.

At each step, the system verifies whether the target point has been reached. If not, the localization and navigation cycle repeats to refine movement until the target is achieved. Once a row is complete, the mower shifts laterally by one body width and continues in the opposite direction, following a boustrophedon coverage pattern. This process repeats until the entire lawn is covered. At the end of the task, the mower navigates back to its home base, docks for recharging and clipping disposal, and transitions into sleep mode until the next scheduled task.

2.9. Prototype Illustrations[1]

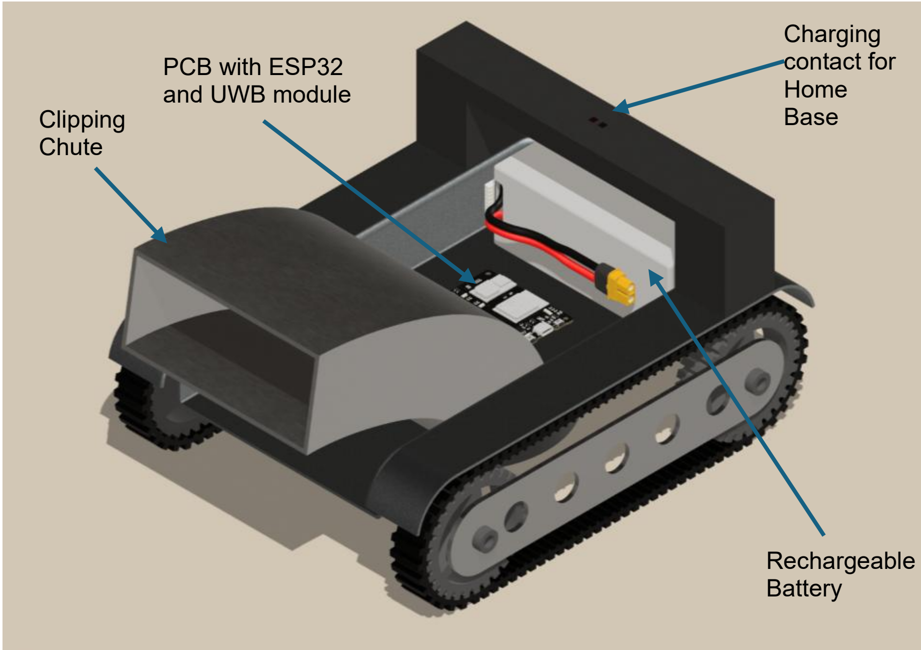


Figure 3: Top-Front-Left View

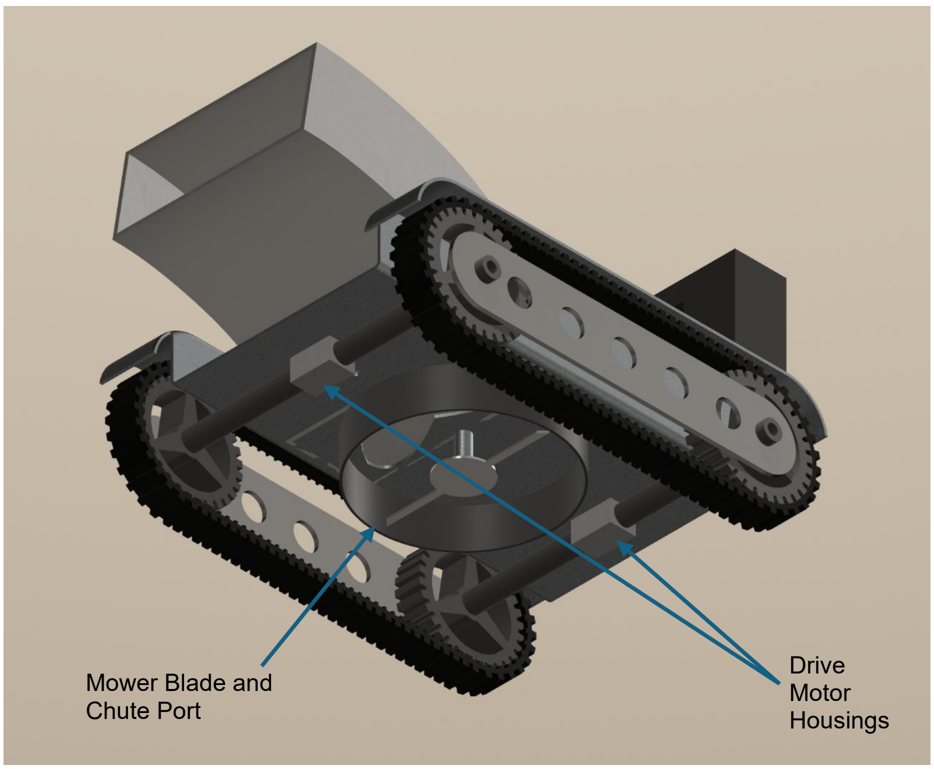


Figure 4: Bottom-Front-Left View

[1] Includes 3D models from (S, 2021) (Sains, 2022) (modified blade, 2023)

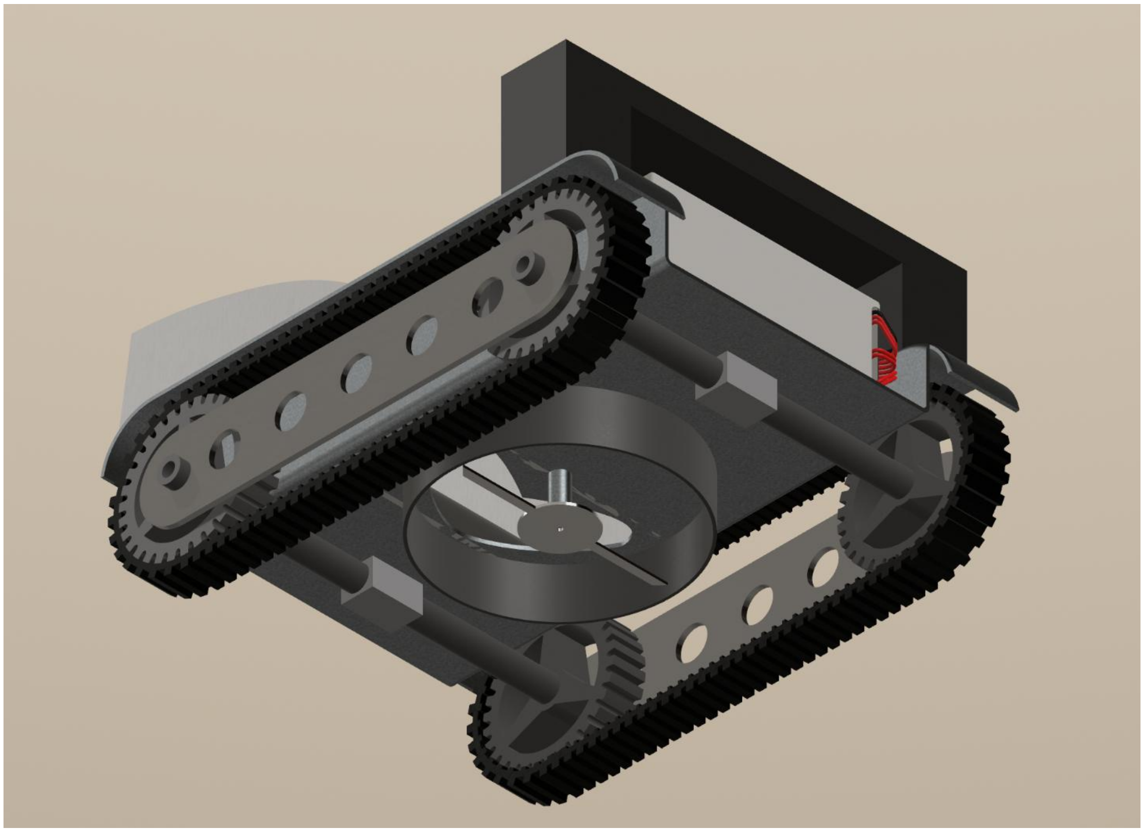


Figure 5: Bottom-Rear-Left View

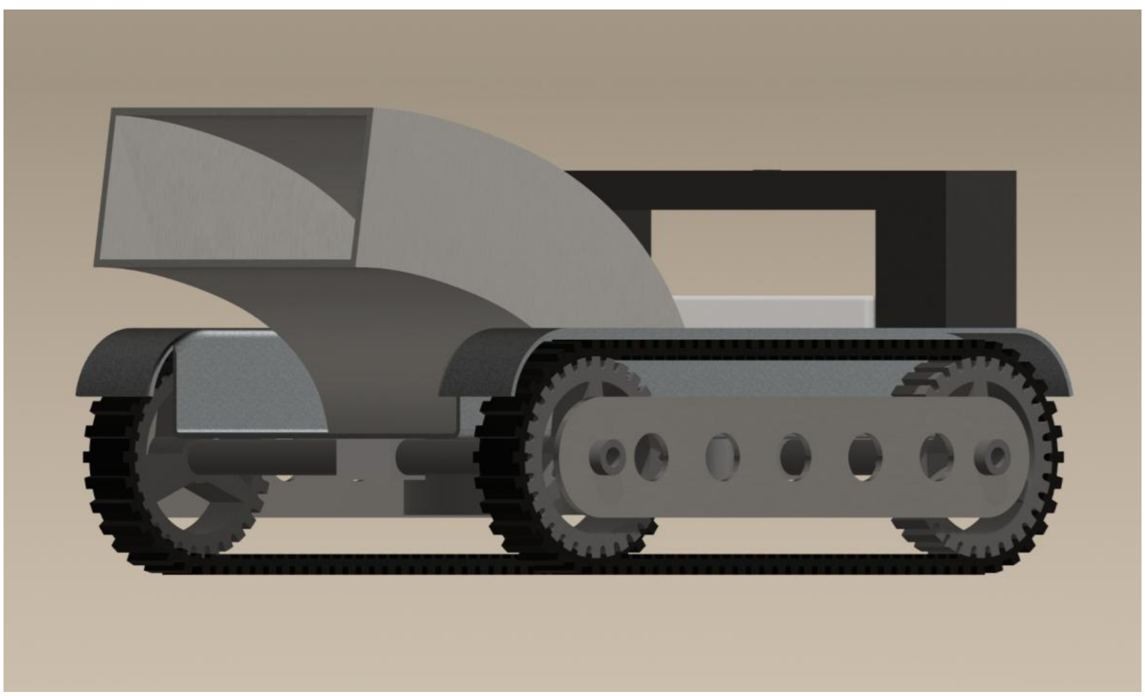


Figure 6: Front-Left View

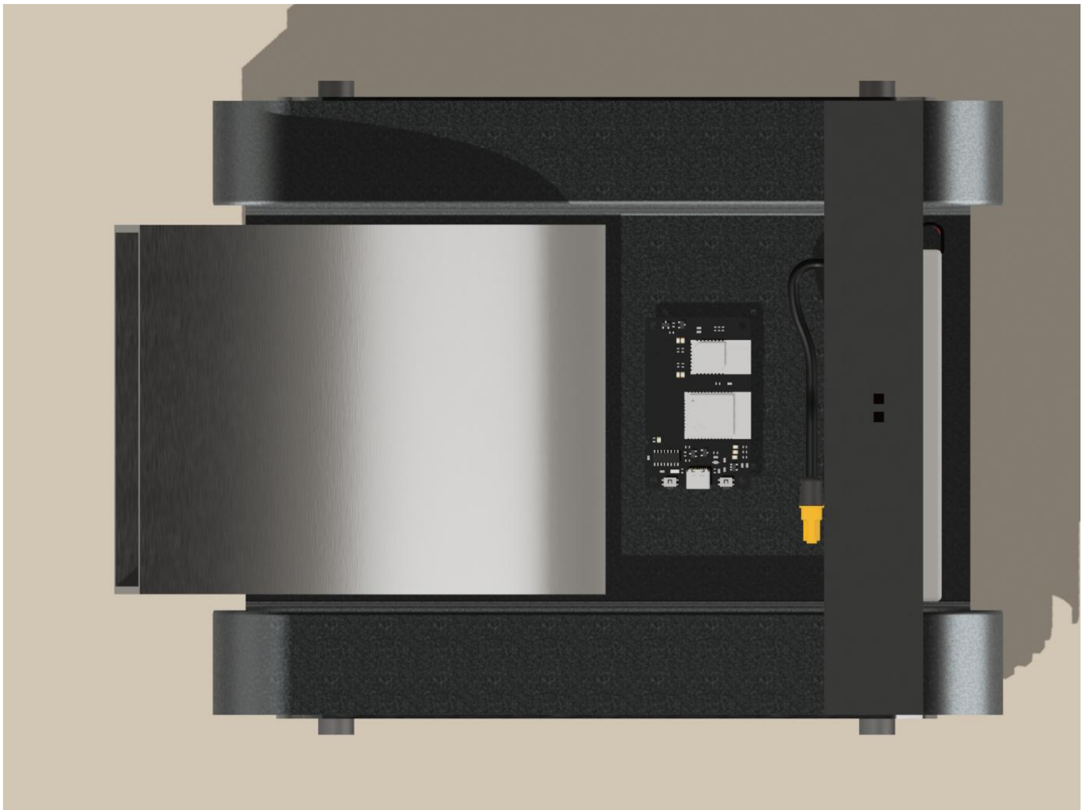


Figure 7: Top View

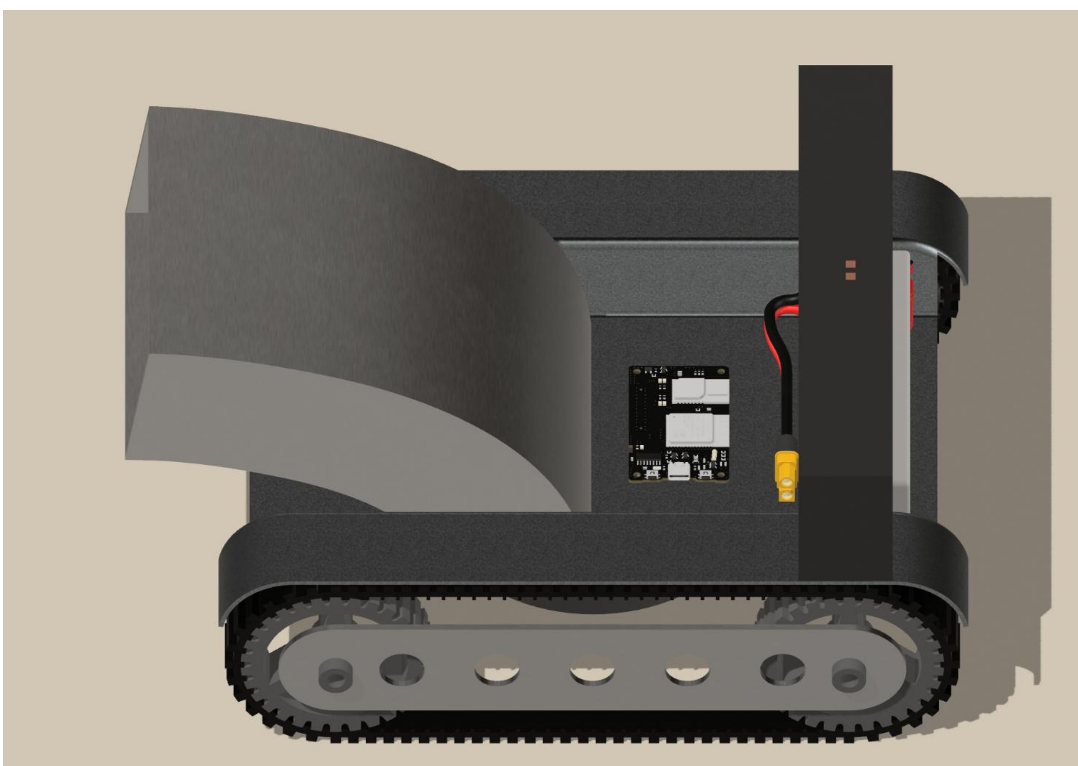


Figure 8: Top-Left View

3. Research and Investigation

3.1. Logic Processing System

3.1.1. Logic Processing System Technology Comparison

The Central Processing Unit of the TURF robot must balance cost, computational capability, power efficiency, and ecosystem support. The team considered two major system types including single board computers and microcontrollers.

Single-Board Computers (SBCs) such as the Raspberry pi family of devices are powerful and support general purpose operating systems that help to abstract away much of the scheduling complexity of a system. The team considered these as such devices would allow us to integrate more advanced software features such as image processing for object identification, which could in turn be used for safety features or lawn care suggestions.

Microcontrollers (MCUs) such as the ESP-32 family of devices are capable and energy efficient but are much less computationally capable than SBCs. Microcontrollers do not run general purpose operating systems, instead we must code on “bare metal”. Many MCUs come with support for FreeRTOS, a real time operating system that handles scheduling and concurrency. MCUs were considered because they are simpler to integrate into our hardware systems and have significantly lower costs and computational overhead.

A major factor the team took into consideration is the senior design requirement for fully integrated PCBs and the absence of solderless solutions. MCUs were the clear choice in this regard as all major systems are within one IC package. SBCs would require either using a PCB package such as the Raspberry pi Compute Unit, or creating our own custom system including RAM, Storage, Peripheral connectivity and more, which is prohibitively expensive and time consuming. MCUs also allow for good real time system building, which is essential in the TURF system. The robot control stack cannot be allowed to freeze or “lag”, as this can lead to the system veering off course during navigation, and potentially harming life in the area if safety features cannot act in a deterministic way.

Table 5: MCUs vs SBCs

Technology Type	Single-Board Computers (SBCs)	Microcontrollers (MCUs)
Example Device Family	Raspberry Pi	ESP32
Processing Capability	Very High (>1 GHz multi-core CPU)	Moderate (100–300 MHz)
Power Consumption	High (5–10 W typical)	Low (<1 W)
Operating System Support	Full OS (Linux, Windows IoT)	Bare-metal / RTOS (FreeRTOS)

Hardware Integration Complexity	High – requires external RAM, storage, and I/O support	Low – single IC integration
Cost Range (USD)	$35 – $100	$3 – $15
Real-Time Performance	Non-deterministic scheduling	Deterministic scheduling
Suitability for TURF	Powerful but complex; excessive for simple real-time tasks	**Selected – meets cost and real-time requirements**

3.1.2. Logic Processing System Part Selection (MCU)

The central processing unit (CPU) of the TURF robot serves as the brain of the system, responsible for executing control loops, managing communication interfaces, and handling sensor data. The team evaluated three candidate microcontroller units (MCUs): ESP32-WROVER-E-N16R8, ESP32-WROOM-32, and ATmega328P. The selection process focused on computational performance, memory capacity, power efficiency, cost, and ecosystem maturity.

The **ESP32-WROVER-E-N16R8** is a high-performance dual-core microcontroller that integrates both Wi-Fi and Bluetooth connectivity along with 16 MB of flash and 8 MB of PSRAM. Its expanded PSRAM enables the execution of memory-intensive tasks such as localization processing and data buffering without the need for external components. The dual-core Xtensa architecture supports real-time control while maintaining communication tasks concurrently under FreeRTOS. This module provides the best balance between power and flexibility for the TURF platform.

The **ESP32-WROOM-32**, while architecturally similar to the WROVER variant, lacks the additional PSRAM and therefore offers reduced capacity for parallel operations or large data structures. It remains suitable for lighter embedded applications or simpler IoT systems but may face memory limitations when handling multiple real-time tasks or localization computations.

The **ATmega328P**, used in older Arduino boards such as the Arduino Uno, offers simplicity and extremely low power consumption but has limited computational and memory resources (32 KB flash and 2 KB SRAM). It lacks native wireless connectivity, requiring external modules for network communication. While inexpensive and easy to program, it is inadequate for the multitasking and wireless communication demands of the TURF robot.

The ESP32-WROVER-E-N16R8 was selected for its superior processing power, generous memory capacity, and built-in wireless support, all of which enable robust multitasking under FreeRTOS. The WROOM variant was deemed a suitable backup with reduced performance margin, while the ATmega328P was eliminated due to its limited computational and connectivity capabilities.

Table 6: MCU Comparison

MCU	ESP32-WROVER-E-N16R8	ESP32-WROOM-32	ATmega328P
CPU / Clock Speed	Dual-core Xtensa @ 240 MHz	Dual-core Xtensa @ 240 MHz	8-bit AVR @ 16 MHz
Flash / RAM	16 MB Flash / 8 MB PSRAM	4 MB Flash / 520 kB SRAM	32 KB Flash / 2 KB SRAM
Wireless Connectivity	Wi-Fi + BLE	Wi-Fi + BLE	None (requires external)
RTOS Support	Native FreeRTOS	Native FreeRTOS	Limited
Approx. Cost (USD)	$7 - $8	$5–6	$2–3
Strengths	High performance, large memory, multitasking	Proven platform, inexpensive	Low cost, easy to program, mature ecosystem
Limitations	Slightly higher cost	Limited RAM; unsuitable for heavy concurrent tasks	Insufficient performance, no wireless
Suitability for TURF	**Selected – meets all performance and integration needs**	Acceptable fallback option	Unsuitable

3.2. Localization System

3.2.1. Localization System Technology Comparison

Accurate localization is fundamental to the TURF robot's ability to autonomously navigate and perform precise operations within a defined boundary. The team evaluated three common localization technologies: Dead Reckoning, Global Navigation Satellite System (GNSS) also known as Global Positioning System (GPS), and Ultra-Wideband (UWB). Each approach offers distinct trade-offs in precision, reliability, and system complexity.

Dead reckoning estimates position by integrating motion data from onboard sensors such as wheel encoders and inertial measurement units (IMUs). While simple to implement, it accumulates error over time due to slippage, drift, or small sensor inaccuracies. As a result, dead reckoning is be st suited for short, intermediate localization between reliable external references rather than as a standalone navigation system.

GNSS provides global positioning and is widely used for outdoor devices. It excels in open environments where satellite visibility is best making it a natural choice for a free-range robot. However, standard consumer-grade GPS modules offer positional accuracy of at best 1-3 meters. This is insufficient for the TURF robot where centimeter level precision is necessary for quality mowing. The GNSS systems explored could be enhanced using calibration systems and real-time error connection using internet connected databases from receiver manufacturers, but this introduces cost and complexity beyond the scope of the TURF system.

Ultra-Wideband (UWB) localization provides high-precision ranging by measuring the time of flight of short radio pulses (Bluetooth) between anchors, location fixed devices with known coordinates, and tags, the mobile component which in this case will be in the TURF robot. For 2D localization, 3 anchors must be in range of the tag for triangulation, and this offers accuracy of <10cm. Accuracy can be improved with the use of more anchors. UWB requires a controlled environment with fixed anchor points in line of sight, but offers deterministic, accurate, and repeatable localization suitable for bounded areas like TURF will operate in.

While dead reckoning and GNSS each provide valuable data, neither alone meets the precision and reliability requirements of the TURF platform. To achieve robust localization, UWB will serve as the primary positioning system, while dead reckoning will act as a supportive subsystem to maintain relative motion tracking when UWB anchors temporarily fall out of range. This hybrid approach ensures continuous position awareness and estimation even when line-of-sight is broken between UWB anchors and the tag.

Future iterations of the TURF system may include multi-sensor localization and autonomous calibration methods to enhance localization performance. Combining UWB with GNSS or computer vision could increase performance and allow for global referencing in larger unbounded environments. However, for the current prototype, the UWB anchor network provides the ideal balance between precision and cost.

Table 7: Localization System Comparison

Parameter	**Dead Reckoning**	**GNSS / GPS**	**Ultra-Wideband (UWB)**
Principle of Operation	Integrates encoder and IMU motion data	Satellite based	Time-of-Flight ranging between fixed anchors and mobile tag
Accuracy	Low (drift accumulates over time)	Moderate (1–3 m typical)	High (<10 cm typical)
Infrastructure Requirement	None	None (requires satellite access)	Requires ≥ 3 anchors within range for triangulation
Cost Level	Low	Medium	Medium–High (cost increases with larger areas and more anchors)
Strengths	Simple implementation; low hardware overhead	Wide coverage; global positioning	Centimeter-level precision; reliable short-range positioning
Limitations	Cumulative error; unreliable for long durations	Not precise enough for lawn boundaries	Limited range; requires fixed anchor network

Suitability for TURF	Supplementary only (for short-term estimation)	Unsuitable for fine-grained navigation	**Selected – provides required precision for confined fields**

3.2.2. Localization System Part Selection (UWB)

Accurate ranging is essential to the TURF robot's localization subsystem. The UWB ICs will be responsible for measuring precise distances between the robot's onboard tag and stationary anchors. Two transceiver ICs from Qorvo were evaluated for this role: the DW1000 series and the DW3000 series. Both devices support time-of-flight (ToF) ranging, but they differ in terms of accuracy, power efficiency, and ecosystem maturity.

The DW100 is a low-power UWB transceiver-receiver chip, supporting six RF bands from 3.5 GHz to 6.5GHz. It achieves ranging precision of approximately ± 10cm under ideal conditions while remaining IEEE802.15.4-2011 UWB compliant. It communicates over SPI and supports data rates up to 6.8 Mbps. Its proven reliability and extensive open-source support make it a low-risk and appealing choice for rapid development of the TURF platform. The DW1000 has been deployed in many commercial systems and academic scenarios, meaning reference designs, software implementations, and driver libraries are readily available. This maturity shortens development time and ensures stable performance for the TURF system's first iteration.

The DW3000 is Qorvo's next generation UWB platform. It adds support for IEEE802.15.4z, has improved interference resilience, and additional frequency channels for better compliance across regions The DW3000 supports having many more UWB chips active in the system and may be more suitable for swarm implementations for large bounded areas.. The DW3000 also reduces power consumption and in practice slightly improves ranging accuracy compared to the DW1000. As a newer device, it suffers from less community support and fewer example integrations. It also has a slightly higher cost.

Given the TURF robot's design priorities; availability, cost, and ease of integration; the DW1000 was selected. Its proven hardware design, active developer community, and existing open-source drivers provide a reliable foundation for the robot's localization system, while still achieving the precision required for sub-10 cm positioning accuracy.

Table 8: DW1000 vs DW1000

IC	Standard	Accuracy	Power	Cost	Ecosystem Maturity	Suitability
DW1000	IEEE 802.15.4-2011 UWB	10cm	Low	$9	HIgh	**Selected – best cost and community support**

DW3000	IEEE 802.15.4z UWB	10cm (greater interference resistance)	Very Low	$10	Low	Potential for future system upgrades / iterations

3.3. Mobility System

3.3.1. Mobility System Technology Comparison

The mobility subsystem determines how the robot traverses outdoor surfaces and maintains stability under variable terrain conditions. The team selected a tracked system for better traction and resistance to slippage on grass and uneven ground. After establishing the mechanical configuration, the team compared four motor technologies: brushed DC motors, brushless DC motors, brushed DC motors with Hall effect sensors, and stepper motors.

Brushed DC motors are a simple and common choice for compact robots. They are inexpensive and speed can be easily controlled using PWM from the microcontroller and a simple MOSFET switching circuit or affordable H-bridge motor drivers that allow for direction changes. However, they lack feedback for position and velocity, requiring external sensors for closed-loop control.

Brushless DC motors replace mechanical commutation with electronic switching offering higher efficiency, reduced maintenance, and longer lifespans. The absence of brushes makes them quieter, and they perform well under continuous operation. However, they are significantly more expensive than typical DC motors and require sophisticated driving circuits. The additional complexity makes them unsuitable for a prototype robot such as TURF.

Brushed DC motors with Hall-effect sensors augment the standard DC motor with integrated Hall sensors. The sensors produce voltage pulses as the rotor moves, which can be counted to determine the number of revolutions. This allows for closed-loop velocity control and basic odometry. These motors are slightly more expensive but improve system consistency and stability.

Stepper motors provide precise incremental motion control without requiring feedback sensors and are controlled digitally. They are common in CNC machines and printing applications where repeatability is crucial. They are, however, inefficient and deliver less torque at high speeds. Stepper motors can also slip under load and there is no built-in way to detect this. Stepper motors require specialized drivers. The inefficiency of stepper motors makes them unsuitable for a battery powered system.

For the TURF robot, the overall objective is to achieve reliable low speed traversal and precise control over direction and velocity, rather than raw speed or power. Considering cost, complexity, and control requirements, Brushed DC motors with Hall-effect sensors were chosen for the initial prototype design. They deliver sufficient torque for the tracked platform, require no complex drivers, and provide a good way to collect rotational position information to allow for closed loop control. Premade tracked DC motor chassis are readily available from online vendors for low costs and will speed development.

Table 9: Motor Comparison

Motor Type	Brushed DC Motor	Brushed DC Motor with Hall Sensors	Brushless DC (BLDC) Motor	Stepper Motor
Control Method	PWM (open-loop)	PWM + feedback	Electronic commutation	Step/direction (open-loop)
Feedback Capability	None	Velocity & direction	Integrated (electronic)	Implicit step counting
Efficiency	High	High	Very High	Low
Cost Level	Low	Medium	High	Medium–High
Control Complexity	Low	Moderate	High	High
Strengths	Simple, low cost, high torque	Enables closed-loop control	Efficient, long lifespan	Precise positioning no encoder needed
Limitations	No speed feedback; brush wear over time	Slightly higher cost and wiring complexity	Complex drivers, excessive for low-speed use	Low efficiency, higher current draw
Suitability for TURF	Good baseline but imprecise	**Selected. Cost-effective, precision**	Suitable for high-end or future expansion	Unsuitable for battery-powered mobile platforms

3.4. Motor Driver Part Selection

The motor driver ICs control the direction, speed, and braking of the TURF robot's brushed DC drive motors. These drivers act as the power interface between the low-voltage logic of the ESP32 microcontroller and the higher-current motor outputs, ensuring safe and efficient power delivery under dynamic load conditions. Two candidates were evaluated for this role: the **Texas Instruments DRV8874** and the **STMicroelectronics L6206**. Both devices provide full H-bridge configurations for bidirectional motor control, but they differ in current capability, efficiency, voltage range, and motor number.

The **DRV8874** is a modern, integrated brushed DC motor driver designed for operation from 4.5 V to 37 V, capable of delivering up to 6 A peak output current. It includes a single full H-bridge with low-resistance MOSFETs and built-in current regulation using the IPROPI feedback pin, eliminating the need for external shunt resistors. Control options include both PH/EN and PWM modes, providing flexibility for simple microcontroller interfacing. Comprehensive protections are integrated; including undervoltage lockout (UVLO), over-current protection (OCP), thermal shutdown (TSD), and charge-pump undervoltage detection with diagnostic output via an nFAULT pin. The device's wide voltage range, low heat dissipation, and minimal external component requirements make it well-suited for compact, battery-powered robotic platforms such as TURF.

The **L6206** is a dual full-bridge driver designed for controlling two DC motors or one bipolar stepper motor. It supports a broader supply range from 8 V to 52 V, with up to 2.8 A peak current per bridge. Each bridge uses DMOS transistors with integrated high-side drivers. The device relies on external current-sense resistors (RCL) for programmable current limiting, offering design flexibility at the expense of circuit simplicity. It features thermal shutdown, over-current protection, and under-voltage lockout, and can drive up to four single-direction DC motors using each half-bridge independently. While the L6206 provides more bridges per IC, it has higher conduction losses and requires more external components, making it less suitable for fast the prototyping and easy debugging the TURF team desires. The L6206 is also about two times as expensive as the DRV8874, so not much cost is saved by using one IC per pair of motors instead of one per motor as with the DRV8874.

Table 10: Motor Driver Comparison

Feature	**DRV8874**	**L6206**
Supply Voltage	4.5–37 V	8–52 V
Motor Channels	1 Full Bridge	2 Full Bridges
Peak Current	6 A	2.8 A
MOSFET Type	Integrated N-channel	Integrated DMOS
Current Sensing	Integrated (IPROPI pin)	External resistor required
Control Interface	PH/EN or PWM	IN1/IN2 logic inputs
Protections	UVLO, OCP, TSD, charge-pump UV	OCP, TSD, cross-conduction protection
Efficiency	High (low RDS(on))	Moderate (higher RDS(on))

Integration Level	High	Moderate
Ideal Use	**Selected – 9 – 12 V robotics, efficient drive**	Higher-voltage

3.5. Miscellaneous Support Circuitry

This section is an outline of other major components to be used in the tag, and receiver and kinematics subsystems.

3.5.1. AP2112 Regulator

The AP2112 Low-Dropout Regulator is used to step down the USB input voltage of 5V to a stable 3.3V rail for powering the ESP-32 and UWB chip during wired programming and debugging. This regulator was selected for its excellent load and line regulation performance (0.02 %/V typical) and low dropout voltage of approximately 250 mV at 600 mA output current. The 600mA minimum guaranteed continuous load current is sufficient for operation of the MCU and UWB circuits and the regulator requires minimal support circuitry. The AP2112 was shown in open-source designs utilizing the ESP32-WROVER and was a simple obvious choice for the team. With an output voltage accuracy of ±1.5 %, low quiescent current of 55 µA, and short-circuit and thermal protection, it ensures efficient and reliable operation of the ESP32 even under varying USB supply conditions.

3.5.2. PTS636 Switches

The PTS636 tactile switches are used for the reset and flash functions of the ESP32 module. These switches are compact, surface-mount devices with a 6.0 × 3.5 mm footprint, offering momentary SPST-NO (Single Pole, Single Throw - Normally Open) operation. Their actuation forces range between 130 gf and 320 gf depending on height, providing a crisp tactile response suitable for manual interaction during programming and debugging. The PTS636 series is rated for 12V DC and 50 mA, ensuring robust operation during repeated press cycles, and has a mechanical lifespan of up to 100,000 actuations. The switch's low profile and SMT package facilitate compact design.

3.5.3 S8050 NPN Transistor

The S8050 NPN transistor serves as a general-purpose switching device for level shifting and control functions, such as driving enable pins or handling logic interfacing between the ESP32 and peripheral components. With a collector current rating of 500 mA and a collector-emitter voltage of 25 V, it provides ample margin for low-voltage digital and analog control signals. The transistor offers a high DC current gain (h_FE) of up to 400, ensuring efficient operation in low-base-current circuits. Its small SOT-23 package allows it to be easily integrated into dense PCB layouts.

3.5.4 CP2104 USB-to-UART Bridge

The CP2104 USB-to-UART Bridge converts USB signals from a host computer into UART serial communication for programming and debugging the ESP32-WROVER module. This single-chip bridge integrates a full-speed USB 2.0 transceiver, voltage regulator, and 576-byte transmit/receive buffers, enabling reliable high-speed serial communication up to 2 Mbps. The CP2104 was chosen for its compact QFN-24 footprint (4 × 4 mm), proven driver stability, and straightforward software integration with the Arduino and ESP-IDF toolchains. This minimizes the complexity of USB communication circuitry while maintaining reliable connectivity for programming and serial monitoring.

3.5.5. Other Minor Components

All other minor passive components such as resistors and capacitors are standard and will be selected based on availability and senior design size requirements.

3.6. Power Supply

Providing the appropriate power to the TURF autonomous lawnmower is crucial, as it determines whether the entire system can function reliably under real outdoor conditions. The power subsystem must deliver stable voltage and current to a variety of components, including high-power drive and blade motors, the ESP32 microcontroller, the UWB localization modules, and various low-power sensors.

Since the mower operates autonomously and must move freely throughout the lawn without being tethered, the primary power source must be a rechargeable, mobile battery pack capable of delivering power to all subsystems simultaneously. The battery must also be safe, lightweight, and weather-resistant, making it suitable for outdoor environments where vibration, temperature, and terrain variation can affect performance.

This section discusses the different power supply requirements and options considered for the mower, including various battery chemistries (Li-ion, $LiFePO_4$, and lead-acid), as well as the voltage regulation methods used to ensure consistent power delivery to each subsystem.

3.6.1. Battery Considerations

Choosing the correct battery is one of the most critical design choices for the TURF mower because it heavily affects runtime, safety, mobility, and cost. The battery must be able to continuously provide enough energy to power both the high-voltage mechanical subsystems, namely the drive and blade motors, and the low-voltage electronics like the ESP32 microcontroller, UWB localization module, and other sensors, while staying within acceptable performance levels.

This power source must also be rechargeable, portable, and capable of withstanding outdoor environment conditions. A non-rechargeable battery would significantly limit usability, increase waste, and prevent the mower from reaching autonomy. The battery will be mounted on the lawnmower, so it needs to be able to be moved and bumped around a bit, as it is unlikely that the mowing surface will be completely uniform. The battery will also be exposed to heat, especially in Florida, so a battery that is prone to overheating would be both inefficient and unsafe for this purpose.

After analyzing the electrical power requirements for all systems it was determined that a 12V battery would be best for efficiency, weight, and voltage compatibility. This voltage can directly drive the DC motors and can easily be stepped down to supply 5V and 3.3V rails for sensors and controllers.

With this in mind, and taking into consideration that our battery needs to be rechargeable, we narrowed the battery type down to Lithium-Ion, Lithium Iron Phosphate, Sealed Lead Acid, and the possibility of a Hybrid/Solar battery pack.

1. **Lithium-Ion:** Lithium-Ion batteries are among the most commonly used rechargeable energy storage solutions across electronics, electric vehicles, and robotics. They are fairly light weight, have high energy density, and charge quickly, which are all very good for the TURF Mower. Lithium-Ion batteries store a large amount of energy relative to their size, hence the high energy density, and are able to effectively deliver power to both high and low voltage systems. Despite these advantages, our group must take care and precaution when using Lithium-Ion batteries, as they are prone to overcharging and overheating which can lead to swelling of the battery or even fire. For this reason, combined with the outdoor nature of our project, we would need to include a Battery Monitoring System to measure the voltage, temperature, charge status, and overall health of the battery as a precaution.

2. **Sealed Lead Acid:** Sealed Lead Acid batteries are one of the first and most widely used rechargeable battery types. These batteries store electricity through a chemical reaction between lead dioxide (PbO_2) and lead (Pb) plates submerged in a sulfuric acid electrolyte [S]They are commonly found in Uninterruptible Power Supplies, Emergency Lighting, and backup security systems. They are mostly used in these backup/emergency systems due to their reliability, low cost, and tolerance to overcharging. These batteries also employ a valve-regulated mechanism which prevents leakage from the cell, making them a very safe option. The downside of these batteries is their efficiency and weight. While simple, they have low-energy density as it lacks the more energy-efficient reactions found in lithium-based batteries, and they are very heavy compared to other, more modern batteries.

3. **Lithium Iron Phosphate:** Lithium Iron Phosphate **(**$LiFePO_4$) batteries are part of the newest generation of rechargeable lithium chemistry, regarded as one of the safest and most stable options for electronic and robotic systems. They have high cycle life, exceptional thermal resistance, and steady voltage output, which are all ideal traits for our project. These batteries use iron phosphate as the cathode material in conjunction with the lithium as the anode. This chemical structure provides a strong ionic bond and higher thermal decomposition temperature, which significantly improves safety and tolerance to high temperatures. As a result, Lithium Iron Phosphate batteries rarely experience swelling or combustion, and this makes them a great fit for the TURF system.

4. **Hybrid/Solar:** To enhance sustainability and allow for trickle charging, we have added a hybrid power system that supports primary DC charging from a docking station and a secondary solar input during idle periods. This would be a small monocrystalline solar panel mounted on the top platform of the mower. This would connect to the primary battery and trickle charge it depending on the amount of sunlight. This would extend battery life by reducing the number of cycles and increasing the time on a single charge.

3.6.2. Battery Selection

Each of the three battery options have unique advantages and disadvantages, and no one battery type is uniquely superior to the others. However, for our specific use case we can narrow it down by comparing key features which have the most impact on the performance on the mower. Lithium-Ion batteries typically have large storage and quick charging time, which makes them a good candidate as a battery for any general use case. However, for a device that is designed to be outdoors in the sun, Lithium Ion may not be the right choice. Safety is a big concern, and they are prone to overcharging, leaking, swelling, and even combusting. While there are ways around this, namely a battery management system, which can be used to analyze the live status and health of the battery, these solutions go against the idea of an autonomous vehicle, as it would require consistent monitoring to be deemed safe.

Sealed Lead-Acid batteries are a solid choice, and would certainly be good enough for this project. The main drawback of the Lithium Ion batteries is their lack of resistance to high temperature and overcharging, which is not a common downside associated with Sealed Lead-Acid batteries. However, they are not a great option due to their low efficiency and high weight, which may make the mower less maneuverable and make the system work harder to overcome the weight. If not for the Lithium Iron Phosphate, a Sealed Lead-Acid battery pack would be the way to go.

After examining all three battery types, we concluded that the best option for our TURF mower is a Lithium Iron Phosphate battery. They, like the others, meet the mower's requirements for stable, high and low voltage delivery, but they also offer high safety, environmental resistance, and a long lifespan. These are the most modern type of battery out of the three, and with that comes modern safety features, which can be seen in their remarkable resistance to swelling and leaking due to overheating or overcharging. This is a must have for a battery intended to be out in the sun for long periods of time. They also provide the most charge cycles out of the other choices, which reinforces our choice as the best battery for the project.

Hybrid/Solar Add-on: For our senior design project, this may be a bit out of scope as this would be something that would be added onto a completed project rather than a functioning prototype. However, we feel that it is still worth mentioning as a stretch goal, working in tandem with the main battery pack. This would enable the system to go longer without recharging and thus improve overall battery life by reducing the number of charging cycles. Future iterations of the TURF design may integrate this as part of an autonomous energy management, enabling the mower to monitor its charge status and dynamically choose between solar and dock-based charging based on power demand, sunlight availability, and task schedule. This hybrid approach aligns with the TURF project's goal of autonomy, environmental sustainability, and low maintenance operation.

Table 11: Battery Comparison

Feature	$LiFePO_4$	Lithium-Ion	Lead-Acid
Energy Density (Wh/Kg)	90-120	120-200	30-50
Charge Cycles	2,000-10,000	300-1,000	200-500
Weight	Light/Medium	Light	Heavy
Cost	$90+	$60+	$40+
Safety	Very High	Medium	High
Final Consensus	Overall best option	Good but has reliability issues	Good budget option

3.7. Power Distribution

A well-designed power distribution network is essential to ensure that all of the TURF mower's electrical subsystems receive stable and appropriate power while maintaining safety and efficiency. The power distribution system is responsible for routing energy from the 12 V $LiFePO_4$ battery pack through a series of regulators and connectors to supply both high-power loads (motors) and low-power electronics (sensors and control boards).

The distribution design follows a multi-level architecture that separates high-power and low-power circuits to maximize efficiency and minimize the chance of voltage fluctuations damaging key components. The main 12 V line provides direct current to the drive motors and blade motor, while isolated 5 V and 3.3 V rails supply power to the ESP32 microcontroller, UWB localization modules, and sensors.

Subsystem Power Allocation

The expected current and power consumption for each major component were estimated through manufacturer datasheets and results from previous experimental calculations.

Table 12: Power Consumption

Component	Qty	Voltage	Current	Total Power Consumption
Drive Motors	2	12 V	2.5 A each	60 W
Blade Motor	1	12 V	4.0 A	48 W
Motor Drivers	2	12 V	0.3 A each	7.2 W
ESP32 Controller	1	3.3 V	0.25 A	0.83 W
UWB Modules	2	3.3 V	0.2 A each	1.32 W
Ultrasonic Sensors	3	5 V	0.02 A each	0.3 W
LCD Display/LEDs	1	5 V	0.1 A	0.5 W
Safety Sensors (lift detection)	1	5 V	0.02 A	0.1 W
Total Estimated Load	X	X	X	≈118 W

3.8. Voltage Regulators

Voltage regulation is a critical part of the TURF mower's power subsystem, ensuring that every component receives stable and appropriate voltage regardless of changes in load or battery state. Because the mower's 12 V $LiFePO_4$ battery must power a combination of high-power motors and sensitive low-voltage electronics, a reliable voltage regulation network is required to maintain performance and protect the system's electronics from overvoltage, noise, or surges. It is imperative that the right regulators are used, as the devices that derive voltage from the 5V and 3.3V rails are extremely sensitive.

The TURF system uses a combination of buck (step-down) regulators to derive 5 V and 3.3 V rails from the main 12 V supply. These voltage levels are required by the ESP32 microcontroller, UWB localization modules, ultrasonic sensors, LCD interface, and other peripherals. Unlike linear regulators, which dissipate excess voltage as heat, switching regulators use high-frequency switching and energy storage components to efficiently step down voltage while minimizing power loss. This design allows the mower to operate longer on a single charge by reducing wasted energy and heat buildup.

Since the entire system is powered by a 12V battery, the regulators need to be able to accept a range of voltages ranging from approximately 10V when empty to 13V when fully charged. Having low heat generation is also a priority, as the components will already be under thermal stress due to the environment, so heat from within the system must be minimized. High efficiency is crucial as well, as more energy that is wasted through heat means less run time until the next charge.

5 V Rail: LM2596

The LM2596 is a popular switching voltage regulator designed to efficiently convert higher DC voltages up to 40 V into stable, lower output voltages such as 5 V or 3.3 V. It is widely used in robotics and embedded systems because it provides high current capacity, good efficiency, and built-in protection features in a compact and inexpensive form. For the TURF autonomous mower, the LM2596 was selected to supply the 5 V power rail, which powers the ultrasonic sensors, LCD display, safety circuits, and indicator LEDs.

Unlike linear regulators that dissipate excess voltage as heat, the LM2596 uses a switching topology based on pulse-width modulation (PWM). It rapidly switches a transistor on and off, controlling the energy stored in an inductor to maintain a constant output voltage. This design allows efficiencies of 80-85%, depending on load current and input voltage. In the TURF mower, this efficiency helps extend the runtime of the 12 V $LiFePO_4$ battery by minimizing energy wasted as heat, an essential factor in battery-powered mobile systems.

3.3 V Rail: MP1584

The MP1584 is a miniature, high-efficiency switching voltage regulator designed to convert higher DC voltages like the mower's 12 V supply into a stable low-voltage output suitable for sensitive logic circuits. In the TURF system, it is responsible for generating a clean 3.3 V rail that powers the ESP32 microcontroller, UWB localization modules, communication interfaces, and other low-current digital peripherals.

Unlike linear regulators, the MP1584 uses a synchronous switching topology, meaning it replaces the traditional Schottky diode with a low-resistance MOSFET for current rectification. This design increases conversion efficiency to up to 90–92 %, even under moderate loads, significantly reducing power loss and heat generation. The high efficiency and compact footprint make the MP1584 ideal for battery-powered robotics, where runtime and thermal stability are crucial.

12 V Rail:

The XL4015 is a high-efficiency switching regulator designed for applications that require high output current and robust voltage stability. It can deliver up to 5 A of continuous current with conversion efficiencies as high as 96 %, making it well suited for motor control, charging circuits, and other heavy-load systems. In the TURF autonomous lawnmower, the XL4015 serves as the high-current voltage regulator for the 12 V rail that powers the drive motor drivers (L298N) and the blade motor relay circuit.

While the mower's $LiFePO_4$ battery already operates at approximately 12.8 V nominal, the XL4015 acts as a regulator and stabilizer, ensuring that voltage to the motors remains consistent even as the battery discharges or when current spikes occur during heavy acceleration or thick-grass cutting. This guarantees smooth performance and protects both the motors and the electronic control modules from voltage fluctuation.

The TURF mower employs three distinct voltage regulators to efficiently distribute power across subsystems with different current, voltage, and stability requirements. Each regulator was selected based on its performance characteristics and suitability for a specific voltage domain. The LM2596 is used to supply the 5V rail for the mower's sensors, LCD, and peripheral devices. Its low cost and simple design make it ideal for powering multiple peripherals that are not highly sensitive to noise. The MP1584 generates the 3.3 V rail used by the ESP32 microcontroller and UWB localization modules.With a higher switching frequency (≈500 kHz) it delivers a clean, low-ripple output ideal for sensitive logic circuits. The XL4015 supports the mower's 12 V high-current rail, powering the drive motors, blade relay, and charging subsystem. Capable of delivering up to 5 A at efficiencies approaching 96 %, it provides strong voltage stability during heavy motor loads and doubles as a constant-current regulator for controlled battery charging. Together, these three regulators form a tiered power regulation network optimized for efficiency, thermal management, and electrical isolation. The LM2596 handles mid-level peripheral power, the MP1584 ensures clean logic voltage for the control system, and the XL4015 supplies stable current for high-demand motor and charging circuits. This combination minimizes noise interference, balances thermal load, and maximizes runtime from the 12 V $LiFePO_4$ battery.

3.9. Motor Driver Selection

The motor driver is a critical component responsible for converting low-current control signals from the ESP32 into high-current motor commands that drive the mower's left and right wheels. Selecting the correct motor driver influences torque output, efficiency, heat generation, and overall system reliability.

The team investigated several H-bridge motor drivers commonly used in small robotics, including the L298N, DRV8874, DRV8833, and TB6612FNG modules. Each design offered different advantages related to current capability, switching frequency, efficiency, and safety protections. Early prototyping was conducted using the L298N due to its availability and simplicity; however, this driver exhibited several limitations that made it unsuitable for long-term implementation in an outdoor autonomous vehicle.

3.9.1 L298N Limitations

The L298N was the first motor driver considered due to its availability and previous use in coursework. Initial bench testing confirmed that the module was simple to interface with the ESP32 and offered basic dual-H bridge functionality. However, several significant limitations emerged during further evaluation. The L298N is based on an older bipolar-junction transistor (BJT) architecture rather than modern MOSFETs. As a result, the driver exhibits a substantial voltage drop—typically two to three volts—across each half-bridge. When powered from a 12 V battery, this drop reduces the effective voltage delivered to the motors and measurably weakens their torque output. During load testing, the motors were unable to maintain the required speed when encountering grass resistance, in part due to this power loss.

In addition to reduced torque, the L298N showed poor electrical efficiency. The BJT-based design dissipates a significant portion of input power as heat, leading the module to reach high temperatures even under moderate load. This thermal behavior raised reliability concerns, as sustained high temperatures outdoors could trigger premature shutdown or damage to surrounding electronics. Furthermore, the driver lacks modern protection features such as overcurrent detection, thermal shutdown, or programmable current limiting. These omissions create safety risks when driving motors that may stall, encounter debris, or experience rapid load changes. Given these issues, the L298N was determined to be insufficient for the demands of an autonomous lawnmower expected to operate continuously in an outdoor environment.

3.9.2 DRV8874 Selection and Advantages

After assessing multiple alternatives, the DRV8874 from Texas Instruments was identified as the most suitable motor driver for the TURF mower. The DRV8874 is a modern MOSFET-based H-bridge designed specifically for medium-to-high-current brushed DC motor applications. One of its primary advantages is its ability to support up to 6 A peak current, which is essential for handling the inrush currents produced when motors start up or encounter resistance in thick grass. During testing, the DRV8874 delivered noticeably stronger and more consistent torque compared to the L298N because of its low R_DS(on) MOSFET design, which minimizes voltage drop and significantly improves efficiency.

Beyond performance improvements, the DRV8874 includes a suite of integrated protection mechanisms that substantially enhance system safety and reliability. These include overcurrent protection, thermal shutdown, undervoltage lockout, and stall detection capabilities. The device also provides diagnostic outputs such as the nFAULT pin and analog IPROPI current-sense output, both of which allow the ESP32 to detect abnormal operating conditions and respond immediately—such as by stopping the motors or entering a safe shutdown state. These protections are essential for a system operating autonomously around people, pets, and unpredictable outdoor obstacles.

Bench testing demonstrated that the DRV8874 handled sustained PWM control smoothly, produced less heat under load, and responded quickly to direction changes. Its electrical characteristics also made it suitable for integration into the custom PCB completed in Senior Design I, reducing wiring complexity and improving long-term maintainability. Taken together, the DRV8874's efficiency, protection features, diagnostic capabilities, and superior current handling made it the clear choice for the TURF autonomous lawnmower's motor control subsystem.

3.10. Localization Research (UWB Positioning)

Accurate localization is one of the most critical components of the TURF autonomous mower because it determines how precisely the robot can follow mowing paths, stay within boundaries, avoid restricted areas, and autonomously return to its charging dock. Traditional approaches such as GPS, encoders, and vision-based localization were investigated, but each had limitations when applied to residential yards and consumer-grade hardware. GPS does not provide the required accuracy for small yards, where errors of even one to two meters can cause the mower to leave the intended boundary. RTK-GPS offers improved precision but is costly and requires constant access to a correction signal, which is unreliable in areas with tree cover or obstructed sky visibility. Camera-based SLAM systems, while powerful, require high processing power, struggle in outdoor lighting variations, and are sensitive to occlusion from grass or terrain. Lidar-based SLAM provides excellent accuracy but is cost-prohibitive for a low-budget student design project.

Given these limitations, the team conducted extensive research into ultra-wideband (UWB) ranging technology as a localization method. UWB works by transmitting very short radio pulses across a wide frequency spectrum, allowing precise time-of-flight (ToF) distance measurements. Modern UWB modules such as the Decawave (now Qorvo) DWM1000 or DWM3000 offer 10–20 cm accuracy under typical outdoor conditions. This level of precision is ideal for a mower that must operate within a defined perimeter and maintain consistent mowing patterns. UWB is also less susceptible to multipath distortion than narrowband communication methods, meaning it performs more reliably around fences, walls, and natural obstacles such as bushes.

3.10.1. Anchor Node Architecture

To implement UWB localization, the system uses a simple anchor–tag configuration. The mower contains the "tag," while two fixed "anchor" modules are placed at known positions around the mowing area. Research into baseline geometry showed that anchors must be spaced several meters apart to form a stable triangulation baseline, with positions chosen to avoid sharp angles that can reduce accuracy. Anchors must also be elevated above ground level—typically 50–100 cm—to minimize ground reflections and improve line-of-sight signal propagation.

Each anchor node periodically exchanges messages with the mower's tag following a ranging protocol such as single-sided or double-sided two-way ranging (SS-TWR or DS-TWR). DS-TWR was emphasized in research due to its improved accuracy and compensation for clock drift between nodes. The mower calculates its position by combining distance measurements from multiple anchors, forming a lightweight localization solution that does not require large computational resources. This architecture is well suited to battery-powered anchors because UWB modules support low-power sleep cycles and can operate for extended periods on small LiPo packs or even USB power banks.

3.10.2. UWB Performance Considerations

Research also revealed several practical considerations relevant to the TURF mower's environment. UWB operates best with a clear line of sight; while it tolerates some obstruction, heavy foliage, metal surfaces, or very wet environments can degrade measurement accuracy. Multipath reflections may occur near fences or metal structures, though significantly less than with Wi-Fi or Bluetooth. The team incorporated these findings into anchor placement guidelines, ensuring that anchors are positioned with stable mounting, minimal environmental interference, and consistent baseline geometry. For SD2, additional calibration procedures and filtering algorithms will be implemented to improve localization stability during outdoor use.

3.11. Obstacle Detection Research

Safe autonomous operation requires the mower to detect and respond to unexpected obstacles such as rocks, toys, garden tools, pets, or small structures. The team evaluated several sensor technologies commonly used in mobile robotics to determine which solution best aligns with cost, power limitations, and outdoor performance.

While lidar and camera-based systems offer advanced obstacle detection, they introduce new challenges. Lidar sensors, although highly accurate, are too expensive for a low-budget autonomous mower and are vulnerable to contamination from grass clippings or moisture. Vision systems, such as those using stereo cameras or neural network-based classification, require significant computing resources and are highly sensitive to lighting changes, shadows, and glare. Their performance drops substantially in bright sunlight or when the camera lens becomes obstructed by dust or debris, making them unreliable in a lawnmower environment.

3.11.1 Ultrasonic Sensor Selection

After evaluating alternatives, the team selected ultrasonic distance sensors as the primary obstacle detection method for the TURF mower's first prototype. Ultrasonic modules operate by transmitting a short sound pulse and timing the echo to compute distance. These sensors are inexpensive, simple to interface with the ESP32, and effective at detecting large obstacles within a range of approximately 20–150 cm. Early bench tests confirmed consistent readings under controlled conditions, with relatively stable performance across different obstacle sizes and shapes.

Ultrasonic sensors do, however, have limitations. Outdoor wind can scatter sound waves, potentially reducing measurement accuracy. Grass and uneven terrain can absorb or deflect the ultrasonic pulse, leading to sporadic false readings. Additionally, ultrasonic detection becomes less reliable for narrow or irregularly shaped objects that reflect sound at unexpected angles. Despite these constraints, the sensors provide a reliable first layer of detection for large objects such as tree trunks, lawn furniture, and yard boundary structures. Their low cost and low power consumption make them an appropriate choice for the early stages of system development.

3.11.2 Future Improvements and Redundant Sensing Strategies

To improve robustness and safety, the team also researched supplemental sensing methods that may be integrated in SD2 or future prototypes. These include infrared time-of-flight distance sensors for close-range object detection, low-cost solid-state lidar modules for more precise depth measurements, and mechanical bumper switches that serve as a last-resort physical contact sensor. A layered sensing approach is widely used in commercial mobile robots to ensure that no single sensor failure results in unsafe operation. By making the TURF mower’s sensor subsystem modular, the design remains flexible for future expansion as budget and development time permit.

3.12. Wireless Communication and Companion App Research

Reliable communication between the mower and the user is essential for both operational control and system diagnostics. Early research focused on identifying the most suitable wireless technologies for facilitating this communication in a residential outdoor environment. The main requirements were sufficient range to reach across a typical yard, low latency for real-time control commands such as emergency stops, adequate bandwidth to stream sensor data and status updates, and low power consumption to preserve battery life. To meet these criteria, the team evaluated Wi-Fi, Bluetooth Low Energy (BLE), and proprietary RF modules to determine the best fit for the mower's needs.

Wi-Fi emerged as the strongest candidate for primary communication due to its long range, high data throughput, and ubiquitous support on smartphones. The ESP32 operates as a Wi-Fi hotspot, allowing the companion app to connect directly to the mower without requiring an external router or network infrastructure. All communication between the app and the mower is handled through a REST API using JSON-formatted messages, with the ESP32's onboard HTTP server exposing dedicated endpoints for status polling, command dispatch, and field configuration. This architecture achieved an emergency stop latency well under 50 milliseconds in testing, satisfying the real-time control requirement. BLE was evaluated for its low power consumption and simplicity, but was ultimately not incorporated into the final design, as the REST-over-Wi-Fi approach proved sufficient for all required use cases without the added complexity of a secondary protocol. Proprietary RF modules such as LoRa were similarly ruled out due to limited bandwidth and the lack of native smartphone compatibility.

In parallel with wireless research, the team investigated frameworks for developing the companion app. After evaluating both Flutter and React Native, the team selected React Native with Expo Go and EAS Build. While Flutter offered strong UI performance, React Native was chosen due to the team's prior experience and the convenience of EAS Build's cloud-based compilation pipeline, which streamlined the generation and distribution of the Android APK. The completed app connects to the mower by entering the ESP32's IP address and port, then communicates entirely through the REST API. It provides live monitoring of key system metrics including battery level, mowing progress, distance traveled, and runtime and supports control functions such as emergency stop, pause, and resume. The app also includes an area visualization screen for reviewing mowing coverage and supports uploading custom mowing patterns to the mower. During development, a Node.js test server was used to simulate the ESP32 backend, enabling full app testing without requiring physical hardware.

3.13. Autonomous Charging Dock Research

To achieve true autonomy, the mower must be capable of recharging itself without human intervention. Research into autonomous dock designs revealed several common strategies used in consumer robots, including funnel-shaped mechanical guides, infrared beacon alignment, magnetic self-centering contacts, and inductive wireless charging pads. The team examined each approach to evaluate suitability for outdoor use, cost effectiveness, robustness, and ease of implementation.

Mechanical docking frames, similar to those used by robotic vacuum cleaners, provide a straightforward and reliable solution. They rely on tapered guides that funnel the mower into the exact charging position, compensating for small alignment errors. However, the exposed metal rails common in indoor docks are susceptible to corrosion outdoors, and guide rails must be weatherproofed. Wireless induction charging systems offer high reliability and eliminate the need for exposed electrical contacts, but they significantly increase cost and have lower efficiency—especially when grass or debris partially obstructs the charging pad. This made them impractical for a student-built prototype.

Magnetically assisted charging docks were found to be the most suitable option for TURF. These designs utilize neodymium magnets embedded in both the mower and the docking station to pull the charging contacts into alignment, tolerating up to a centimeter of misalignment. Research showed that this method is commonly used in marine and harsh environment robotics due to its reliability and resistance to contamination. The charging circuit itself must follow the $LiFePO_4$ charging profile, which requires a regulated constant-current/constant-voltage (CC/CV) charger delivering approximately 14.4 V at 1–3 A. The team examined several off-the-shelf charging controller modules designed specifically for $LiFePO_4$ chemistry, and these will be integrated with reverse-polarity protection and a relay-based switching system that isolates the battery from the mower's power bus during charging.

Research also included the positioning strategy required for successful autonomous docking. Trials from commercial robotic systems indicate that placing the dock along a straight boundary segment with a clear approach path dramatically improves reliability. Additional sensors such as infrared emitters or line-following markers may be added in SD2 to improve alignment precision. The dock design will be validated through iterative physical testing once full system integration begins.

3.13. Mechanical System Research

The mechanical system forms the physical foundation of the TURF mower, affecting durability, stability, cutting performance, and safety. Research into chassis materials emphasized the importance of balancing strength, weight, environmental resistance, and manufacturability. While steel frames offer excellent rigidity, they are heavy and prone to corrosion without proper treatment. Acrylic and 3D-printed polymers provide lightweight options but suffer from brittleness and UV degradation, making them unreliable for outdoor use. Aluminum emerged as the optimal choice due to its favorable strength-to-weight ratio, natural corrosion resistance, machinability, and ability to dissipate heat from nearby electronic components. The chassis design follows a modular approach that allows rapid removal of subsystems for debugging or repairs.

Wheel and traction research focused on identifying a wheel size and tread pattern capable of maintaining grip over grass, soil, and uneven terrain. Larger wheels provide better obstacle clearance and reduce the likelihood of stalling in thick grass, while deeper tread patterns improve traction in damp or sloped environments. The team evaluated several wheel designs commonly used in hobby robotics and settled on wheels in the 65–85 mm diameter range. Shaft couplers and motor mounts were also analyzed, with emphasis on minimizing vibration and ensuring the motors maintain rigid alignment with the chassis. Research into motor placement also considered weight distribution, ensuring the mower's center of mass remains low and centered for stability during operation.

One of the most safety-critical components of the mechanical system is the cutting mechanism. The team evaluated two primary options: a traditional metal rotary blade and a flexible nylon-string trimmer head. Although rotary blades offer higher cutting efficiency, they introduce significant safety risks in a compact autonomous platform. They also require higher torque and place greater load on the battery and driver circuitry. Nylon-string trimmer systems, by contrast, are safer, lighter, and less damaging if they strike a solid object. They also reduce the chances of severe injury or property damage in the event of a malfunction. Research from consumer lawn equipment manufacturers and robotics forums supported the decision to adopt a nylon-string trimmer mechanism for the first prototype. This approach also simplifies blade replacement and reduces the torque required from the motor, improving runtime.

Research into environmental durability highlighted the need for ingress protection, debris shielding, and vibration isolation. Grass clippings and dust can interfere with sensors, accumulate around motors, or impede cooling airflow. This prompted the team to incorporate protective housings and consider splash-resistant enclosures for electronics during SD2. Additionally, foam dampening and rubber mounting grommets were identified as effective methods of reducing vibration from the drivetrain, prolonging component lifespan and improving sensor stability.

4. Standards and Design Constraints

4.1.1. IEEE 802.15.4a Ultra-Wideband (UWB) Communication Standard

The IEEE 802.15.4a standard defines the physical (PHY) layer and part of the media access control (MAC) layer for Ultra-Wideband (UWB) wireless communication. It is a supplement to the original IEEE 802.15.4 specification, which primarily targeted low-data-rate wireless personal area networks (WPANs) such as ZigBee. The 802.15.4a amendment allows for precise time-of-flight (ToF) ranging and location-awareness capabilities using impulse radio UWB (IR-UWB) technology. This allows devices to achieve centimeter-level distance measurements and robust short-range communication in environments with significant reflection and interference.

UWB operates by transmitting very short-duration pulses over a wide frequency spectrum: below 1 GHz, between 3 and 5 GHz, and between 6 and 10 GHz. Because the signal energy is spread across such a wide bandwidth, UWB systems can coexist with other narrowband wireless systems with minimal interference. The spectrally efficient standard allows for precise localization while maintaining extremely low transmission power. The IEEE 802.15.4a standard defines parameters such as pulse repetition frequency, preamble structure, scalable data rates (ranging from 110 kbps to 6.8 Mbps), channel frequencies, and timing synchronization (MATLAB).

One of the most significant advantages of UWB under this standard is its capability to provide accurate ranging and positioning even in non-line-of-sight (NLOS) environments. By measuring the time difference between transmitted and received pulses, the system can determine distance with accuracies typically within ±10 cm. This feature is fundamental to the TURF robot's localization subsystem, which relies on anchor-tag ranging to determine its position relative to fixed UWB beacons. The precise synchronization and timestamping mechanisms defined by IEEE 802.15.4a ensure repeatable and deterministic distance measurements, which are essential for safe and consistent navigation.

From a design perspective, compliance with this standard guarantees interoperability with other UWB devices and simplifies future upgrades to newer chipsets (such as migration from the DW1000 to the DW3000 family). The DW1000 transceiver used in the TURF robot is fully compliant with IEEE 802.15.4-2011 and the 802.15.4a amendment, ensuring adherence to established spectral emission limits, frame formats, and ranging protocols. This alignment provides a solid regulatory and technical foundation for the project.

In terms of system integration, IEEE 802.15.4a also supports two-way ranging (TWR) and time-difference-of-arrival (TDoA) methods, both of which can be adapted for different deployment scales. For the TURF platform, TWR is the preferred mode due to its simpler synchronization requirements and compatibility with a small anchor network. Adherence to the standard ensures consistent timing accuracy and provides a defined signal structure for precise timestamp detection within the DW1000.

Finally, compliance with the IEEE 802.15.4a standard ensures that the TURF system's UWB communication remains within regulatory limits for unlicensed spectrum operation. By following these established protocols, the design maintains safe transmit power levels and predictable signal behavior. The standard therefore provides not only the technical backbone for TURF's localization system but also ensures legal compliance, interoperability, and scalability in future design iterations.

4.1.2. IEEE 802.11 (Wi-Fi) and Bluetooth Low Energy (BLE) Standards

The IEEE 802.11 and Bluetooth Low Energy (BLE) standards define the wireless communication protocols that enable short and medium range connectivity between embedded devices, computers, and mobile systems. These standards govern the ESP32-WROVER-E microcontroller's integrated wireless features, providing the TURF system with the capability for network-based control, diagnostics, and telemetry. Both protocols operate in the 2.4 GHz band, allowing low-cost, globally unlicensed communication. Despite using the same frequency range, they differ in modulation, data rate, power consumption, and use cases, making them complementary in a hybrid embedded system design such as TURF.

The IEEE 802.11 standard, commonly known as Wi-Fi, defines medium access control (MAC) and physical (PHY) layer specifications for wireless local area networks (WLANs). Modern variants such as 802.11n and 802.11ac offer data rates from tens to hundreds of megabits per second. In the context of TURF, Wi-Fi is used primarily for high-bandwidth data transmission, such as uploading system logs, debugging, or remote configuration over a wireless link. The ESP32 implements a full TCP/IP stack compliant with IEEE 802.11b/g/n, providing connectivity through an existing router or direct access point operation. This will allow the team to interface with the robot through standard network protocols for monitoring and control.

Complementing Wi-Fi, Bluetooth Low Energy (BLE) follows the Bluetooth 4.2/5.0 specifications and offers a low-power alternative for short-range data exchange. BLE operates in the 2.4 GHz band and supports device discovery, pairing, and low-latency communication between devices. Within the TURF system, BLE can serve as a lightweight link for mobile diagnostics or initial configuration, allowing a smartphone or tablet to communicate directly with the robot without requiring external network infrastructure. BLE's energy efficiency is advantageous for maintaining persistent communication without significant power draw, especially during battery operation or field deployment.

Both communication standards incorporate robust security and coexistence mechanisms to ensure reliable performance in interference-prone environments. IEEE 802.11 employs WPA2/WPA3 encryption for data confidentiality and integrity, while BLE uses AES-128 encryption. These standards also include mechanisms for collision avoidance, Wi-Fi through CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) and BLE through adaptive frequency hopping, to minimize packet loss in crowded radio environments. For the TURF robot, which may operate near multiple wireless devices, these features ensure consistent communication without interfering with UWB localization signals operating in higher frequency bands.

Adherence to these standards also ensures regulatory compliance and interoperability with a wide range of commercial devices. Both Wi-Fi and BLE are globally accepted and legally operable. From a design perspective, compliance reduces risk during product certification if the TURF robot was to be commercialized.

In the context of the TURF platform, these standards allow seamless interaction between the robot and user interfaces such as laptops or mobile devices. The combination of IEEE 802.11 and BLE provides both a high-bandwidth configuration link and a low-power monitoring interface, balancing performance with energy efficiency. This dual-protocol approach supports the TURF system's modularity and user accessibility while maintaining full alignment with internationally recognized wireless communication standards.

4.1.3. Serial Peripheral Interface (SPI) Communication Standard

The Serial Peripheral Interface (SPI) standard defines a high-speed synchronous serial communication protocol used for data exchange between microcontrollers and peripheral devices. Developed originally by Motorola, SPI is now an industry-wide de facto standard supported by nearly all modern embedded systems. The protocol provides full-duplex communication using a simple four-wire connection consisting of MOSI (Master Out, Slave In), MISO (Master In, Slave Out), SCK (Serial Clock), and SS/CS (Slave Select or Chip Select). SPI's simplicity, flexibility, and high data rate make it ideal for connecting the ESP32-WROVER-E microcontroller to peripherals such as the DW1000 Ultra-Wideband (UWB) transceiver, motor driver ICs, and various sensors in the TURF robot.

SPI communication operates under a master-slave architecture, where the master device, here the ESP32, generates the clock signal and initiates all data transfers. Slave devices, such as the DW1000 UWB chip, respond synchronously with each clock cycle. This timing-deterministic nature of SPI is essential for TURF's real-time localization and sensor communication, ensuring predictable response times and low latency in data exchange. The standard supports a wide range of clock speeds, up to 80 MHz on the ESP32 WROVER, which is significantly faster than protocols such as I^2C or UART. This speed advantage allows SPI to handle frequent, small packets of high-precision timing data required for the UWB localization system and motor drivers.

One of the defining features of SPI is its mode configuration based on clock polarity (CPOL) and clock phase (CPHA). These two parameters define how data is latched and sampled, allowing compatibility with a wide range of peripherals. The DW1000, for instance, communicates, by default, in SPI Mode 0 (CPOL = 0, CPHA = 0), where data is captured on the rising edge of the clock and propagated on the falling edge. The DW1000 also supports SPI modes 1 through 3 and can be configured as such using external pull-up and pull-down resistors. Understanding and adhering to these timing conventions is critical for maintaining reliable communication and preventing data corruption. Additionally, the Slave Select (SS) signal ensures that multiple SPI peripherals can share the same data lines without interference, an important consideration in multi-device systems such as TURF.

The SPI standard has many variations so manufacturer documentation specifies electrical and logical signal levels to ensure device compatibility and functionality. Logic voltage thresholds, propagation delays, and setup/hold times are defined to maintain data integrity across various operating frequencies and interconnect lengths. In the TURF design, the SPI interface between the ESP32 and DW1000 is protected with small series resistors to prevent signal reflections and to safeguard against pin contention during power-up. Following these common hardware-level practices contributes to system robustness which is critical for accurate UWB signal measurements.

From a system integration perspective, adherence to the SPI standard simplifies firmware development and enhances interoperability among components from different vendors. The ESP-IDF (Espressif IoT Development Framework) natively supports SPI drivers compliant with the standard, allowing efficient use of Direct Memory Access (DMA) for high-speed transfers without overloading the CPU. This facilitates concurrent operation of the UWB transceiver, motor driver, and sensors, all communicating over the same SPI bus under a real-time operating system (FreeRTOS).

In the context of the TURF robot, using the SPI standard ensures deterministic communication, low latency, and signal reliability; all essential for synchronizing sensor feedback with motion control. By conforming, the design achieves electrical compatibility, simplifies debugging, and guarantees long-term maintainability as additional peripherals are added in future system iterations. SPI thus forms the backbone of intra-system communication, linking the robot’s computational, sensing, and localization subsystems into a unified, time-coordinated network.

4.1.4. Electrical Safety and Battery Standards

Battery selection and power distribution must comply with established safety and reliability guidelines, especially because the mower operates outdoors and contains high-current mechanical subsystems. Rechargeable lithium-based batteries are known for having issues when implemented without precaution. Because of this, rechargeable lithium-based chemistries require careful consideration of charging methods, short-circuit protection, and thermal characteristics.

UL 2271 – Batteries for Light Electric Vehicles
This standard provides safety certification requirements for rechargeable lithium packs used in mobile applications such as e-bikes or electric carts. Although the TURF mower prototype is not subject to UL certification, the design follows UL 2271 guidelines by incorporating a $LiFePO_4$ battery equipped with a built-in BMS. Requirements in UL 2271 influenced the selection of a battery with:

- Overcurrent protection
- Overtemperature shutdown
- Cell balancing circuitry
- Safe failure modes under mechanical shock

IEC 62133 – Safety Requirements for Portable Sealed Cells
This is the international benchmark for lithium battery safety. It specifically covers charge/discharge control, cell venting, and failure response. The TURF mower's charging station and docking interface were designed with IEC 62133 charging guidelines, ensuring that the battery is never charged at unsafe voltages or without current regulation.

IEEE 1625 – Battery System Design for Portable Computing Devices
This standard includes guidelines for modularity and safe wiring practices. It influenced cable gauge choices, fuse placement, and the architecture of the 12 V → 5 V / 3.3 V power rails.

By following these standards, the mower's power subsystem minimizes the risk of overheating, short-circuiting, or runaway current conditions.

4.1.5. Mechanical Constraints

Because the mower contains moving wheels and a rotating blade, it must incorporate principles from safety standards governing outdoor machinery. These can be directly applied from existing standards related to autonomous rovers/lawn tools.

ANSI/OPEI B71.1 – Consumer Turf Care Equipment Safety Standard
This is the defining standard for walk-behind and ride-on lawnmowers. Even though TURF is autonomous, key safety concepts still apply:

- Blade must stop immediately when the emergency stop is engaged
- Blade must be guarded by a housing to prevent contact with debris
- Motor drive must disable when the mower is lifted off the ground
- Control electronics must be isolated from the cutting assembly

ISO 13482 – Safety Requirements for Personal Care Robots
This standard provides guidelines for mobile robots operated around humans. Elements such as:

- Collision avoidance
- Maximum allowable robot speed
- Redundant safety stops
- Fault detection and recovery
  influenced the mower's safety logic.

ISO 18497 – Autonomous Agricultural Machinery
This governs autonomous agricultural systems (tractors, harvesters). Relevant guidelines include:

- Ensuring location accuracy
- Detecting boundary violations
- Preventing unintended motion after fault recovery

These standards reinforce the importance of the mower's UWB localization accuracy and obstacle detection system.

4.2.1. Environmental Constraints

Environmental factors play a significant role in the design, performance, and long-term reliability of the TURF robot. Since the system is intended to operate primarily in outdoor environments, it must maintain stability and functionality under variable weather, lighting, and terrain conditions. The TURF robot's localization, motion, and sensing subsystems must therefore be designed with considerations for temperature range, humidity, debris exposure, electromagnetic interference (EMI), and surface irregularities common in grassy or unpaved areas.

Temperature is a key constraint in outdoor robotic operation. Electronic components such as the ESP32-WROVER-E microcontroller, DW1000 UWB transceiver, and AP2112 voltage regulator have defined operating limits, –40°C to +85°C, for these three. Thermal stress caused by prolonged operation in direct sunlight can lead to voltage drift, communication errors, and shortened component lifespan. To mitigate this, the PCB layout and enclosure design must promote adequate heat dissipation, particularly around the voltage regulator and motor driver circuitry, which are expected to generate the most heat. Thermal vias and copper pours can be incorporated beneath power ICs to spread heat evenly and maintain component reliability.

Humidity and moisture exposure also represent serious challenges for outdoor electronics. Even in the absence of direct rain, dew formation, humidity condensation, and grass clippings can introduce short circuits or corrode exposed connectors. The enclosure for a production grade TURF robot must therefore provide some ingress protection, ensuring resistance to dust and light water spray. Conformal coating or gasket sealing can be employed on critical PCBs to provide additional moisture protection. Connectors for power and communication should include rubber seals or locking mechanisms to prevent water ingress, especially in high-humidity regions. Ingress protection will not be necessary for the first prototype.

Electromagnetic interference (EMI) is another important consideration. The TURF robot integrates several high-frequency systems: UWB ranging (3.5–6.5 GHz), Wi-Fi/Bluetooth (2.4 GHz), and PWM-driven DC motors, all of which can produce or be affected by electromagnetic noise. Motor drivers are particularly strong sources of broadband EMI due to fast current switching. To minimize interference, the system includes decoupling capacitors, and strict adherence to reference PCB design. The DW1000 UWB transceiver also requires a controlled impedance RF trace and a well-grounded antenna structure to maintain ranging accuracy. Shielding and proper trace routing help ensure that localization performance remains consistent even when the motors are active.

Mechanical and terrain-related environmental factors are equally significant. The robot operates on grass and uneven ground, where vibration, impact, and slippage can affect sensor readings and wheel encoders. The tracked mobility system mitigates some of these issues by distributing weight evenly and improving traction, but physical vibrations may still affect IMU and UWB readings. To reduce vibration-induced noise, the sensor mounting points should incorporate rubber dampers, and calibration routines in software can compensate for transient position error.

Lastly, lighting and environmental visibility indirectly impact the TURF robot's potential for future upgrades. Although the current system does not include a vision sensor, future versions may integrate cameras or Ultrasonic Ranging, which are sensitive to lighting conditions and airborne debris. Future iterations of TURF will need to include physical shielding and intelligent software to compensate for visibility obstructions.

In summary, environmental constraints influence nearly every subsystem of the TURF robot, from electrical design to mechanical structure. Adherence to proper protection standards, EMI mitigation practices, and environmental sealing ensures that the system remains robust, safe, and reliable in diverse outdoor operating conditions.

4.2.2. Economic Constraints

Economic constraints directly shape the material selection, component choices, and overall design complexity of the TURF robot. As a senior design project, the system must be both cost-effective and technically viable, balancing performance goals against strict financial limitations. The project's primary objective is to demonstrate functional localization and navigation rather than commercial-grade robustness or scalability. Therefore, cost minimization without compromising essential functionality has guided every phase of the design process from hardware selection and PCB layout to subsystem reuse.

The total component cost is constrained by both team funding and academic project guidelines. Within this limit, high-performance components such as the ESP32-WROVER-E microcontroller and DW1000 UWB transceiver were prioritized because they deliver strong computational and sensing performance relative to cost. The ESP32-WROVER-E, for instance, integrates dual-core processing, Wi-Fi, and Bluetooth in a single package, reducing the need for separate modules and simplifying PCB integration. Similarly, the DW1000 UWB chip was selected over its successor, the DW3000, as it offers sufficient ranging precision for prototype validation at a significantly lower price point. These decisions exemplify cost optimization through strategic feature trade-offs.

Another major economic factor is hardware reuse. The design employs a unified PCB for both the Receiver/Kinematics subsystem and the Tag subsystem, even though the computational power of the ESP32 is more than sufficient for the simpler tag node. This shared design minimizes development effort, assembly cost, and manufacturing time by avoiding the need to design, fabricate, and debug multiple boards. Standardizing on one hardware platform also simplifies firmware maintenance and reduces the number of unique components that must be sourced or stocked.

In addition to part selection, manufacturing and assembly costs influence design choices. Custom PCB fabrication costs rise with layer count, board area, and tight manufacturing tolerances. To control costs, the design uses a two-layer PCB with careful routing to maintain signal integrity without resorting to costly impedance-controlled fabrication. All selected components are surface-mount devices (SMDs) compatible with standard reflow soldering, which reduces manual labor during assembly. Common passive components, such as resistors and capacitors, are selected from a limited set across the board to minimize procurement costs and simplify inventory management.

In summary, economic constraints drive the TURF robot's design philosophy toward cost efficiency, modularity, and reusability. By prioritizing affordable, high-performance components, reusing hardware across subsystems, and simplifying manufacturing processes, the project achieves its technical objectives within its financial boundaries. These cost-conscious decisions ensure that the final prototype is not only functional and demonstrative but also representative of a realistic, scalable solution for future iterations or commercial development.

4.2.3. Time Constraints

Time constraints are a fundamental factor influencing the design, development, and testing of the TURF robot. As part of a senior design sequence, the project is limited to two academic semesters, during which the team must complete the full engineering cycle: research, design, prototyping, testing, and documentation. This fixed schedule imposes practical limits on the complexity of hardware and software that can be implemented, requiring careful planning and prioritization to ensure that core system functions are delivered on time.

Because development tasks such as embedded programming, mechanical assembly, and system calibration often proceed in parallel, task interdependence presents a critical scheduling challenge. For instance, the DW1000 UWB transceiver cannot be fully tested until SPI communication with the ESP32-WROVER-E is validated. Similarly, motion control algorithms depend on motor driver testing, which in turn relies on the availability of the mobility platform. As such, early milestones must focus on enabling fundamental communication and power systems to avoid bottlenecks later in the schedule.

To manage these dependencies, the team employs a milestone-based schedule of deliverables. Each milestone corresponds to a functional subsystem test such as power regulation verification, UART communication validation, or ranging accuracy testing. This modular workflow allows progress to continue in other areas while one subsystem is being debugged. Furthermore, early integration testing ensures that major design flaws are identified before the final assembly phase, when time for major revisions is limited.

Software development presents another significant time constraint. Writing and debugging FreeRTOS-based firmware involves configuring multiple concurrent tasks such as sensor polling, motor control, and communication; while ensuring deterministic timing and avoiding resource contention. The choice to use the Arduino programming environment for initial testing, rather than developing directly in ESP-IDF, was made to accelerate firmware prototyping and minimize time spent configuring complex build systems. This trade-off allows the team to meet functionality goals within the semesters while reserving the option for more advanced optimization later.

Finally, time constraints also extend to documentation and presentation requirements. The senior design courses mandate regular progress reports, design reviews, and presentations, each of which must be completed alongside ongoing technical work. These administrative deliverables require careful time allocation to avoid reducing the hours available for testing and integration.

In summary, time constraints dictate the overall design methodology for the TURF robot. By emphasizing modular development, early hardware validation, and use of readily available tools, the team ensures that each subsystem progresses according to schedule.

4.2.4. Reliability, Maintainability, and Testing Constraints

The mower must be maintainable and reliable over long-term outdoor operation.

Reliability constraints include:

- Operation through heat, humidity, vibration, and uneven terrain
- Must withstand minor impact and debris impact
- Must maintain wireless communication despite environmental noise

Due to the outdoor nature of the TURF mower, it is imperative that it maintains consistency and reliability even when faced with different environmental conditions like bumpy terrain or varied weather.

Maintainability constraints include:

- Components must me modular and replaceable

- Motors and battery must be removable for servicing
- PCB must include test points

When we first proposed this project, one of our main ideas was an all-encompassing lawn rover that could take care of mowing, planting, fertilizing, watering, etc. For the purposes of this senior design prototype we are only demonstrating a mower; however, for future iterations of the TURF mower we want to be able to switch functions easily. The motors and battery are the most likely to have wear-and-tear, so it is imperative that they can be removed and replaced easily. The PCB must include designated test points to simplify testing and troubleshooting.

Testing constraints include:

- Outdoor testing under different weather conditions
- UWB accuracy verification
- Localization and safety routines

In order to confidently demonstrate the prototype, we will have to test the mower in several different conditions, such as sunny, cloudy, rainy, or windy and note the discrepancies. Our UWB accuracy and margin-of-error needs to be determined and analyzed during testing so the mower can be calibrated effectively. Localization and safety routines should take up a majority of the testing. This is arguably the most important part of the prototype, and because of this, the mower needs to be tested for safety in a variety of different conditions and variables.

4.2.5. Ethical, User Safety, and Operational Risk Constraints

Autonomous outdoor equipment presents unique ethical and safety challenges. The mower is intended to operate in environments where people, pets, and property may be present, making system safety a non-negotiable requirement. Ethical considerations include preventing uncontrolled motion, minimizing injury risk, and ensuring that the machine shuts down safely under all failure conditions. These principles align with international safety frameworks such as ISO 12100 (risk assessment), ISO 13849-1 (safety-related control systems), and ISO 13482 (safety of personal care robots).

Key constraints derived from these standards include the requirement for a physical emergency stop that directly interrupts motor power, redundant methods of obstacle detection (ultrasonic + mechanical backup), and safe failure modes where loss of communication or microcontroller malfunction leads to immediate motor shutdown. Additionally, ethical considerations extend to data usage: UWB ranging data is used strictly for localization and is not stored for long-term analysis, ensuring that user privacy is respected. The team also evaluated the ethical implications of autonomous blades and thus selected a less hazardous nylon trimmer mechanism for the prototype to minimize injury risk.

4.3. Summary of Constraints

The TURF autonomous lawnmower operates within a broad set of electrical, mechanical, environmental, regulatory, and ethical constraints that collectively shape the system's architecture and design choices. Electrically, the mower must comply with best practices derived from lithium battery safety standards, fault-tolerant motor control principles, and safe buck-converter operation. The constraints imposed by the $LiFePO_4$ battery chemistry, high-current motor drivers, and noise-sensitive RF circuits require careful attention to grounding strategy, power distribution, and thermal management. These electrical considerations ensure reliable operation while minimizing the risk of short circuits, overcurrent events, or electromagnetic interference that could disrupt UWB or Wi-Fi communication.

Mechanical constraints include the need for a sturdy yet lightweight chassis, appropriate ground clearance, and durable mounting for motors, sensors, and electronics. Outdoor use introduces additional challenges such as vibration, debris impacts, and uneven terrain, all of which influence material selection, structural layout, and enclosure design. Environmental constraints further emphasize the need for partial ingress protection, heat dissipation, and weather resistance, ensuring that the mower remains operational despite exposure to humidity, grass clippings, temperature fluctuations, and sunlight.

Regulatory and legal constraints—particularly those related to radio emissions, battery safety, and lawn equipment standards—guide the system's wireless communication choices, blade design, and safety subsystems. Ethical considerations overlap with safety requirements by dictating that the mower must operate without endangering people, pets, or property. This leads to constraints such as mandatory emergency stops, sensor redundancy, conservative blade design, and safe-failure behavior when faults occur. Software constraints, including timing requirements, memory limits, and real-time responsiveness, further shape the control algorithms and firmware architecture.

Together, these constraints establish a rigorous framework that informs every subsystem of the TURF mower's design. By understanding and integrating these limitations early in the engineering process, the team ensures that the final prototype will be not only functional and efficient, but also safe, compliant, and capable of operating reliably in the real outdoor environments for which it is intended.

5. Application of ChatGPT and Other Similar Platforms

5.1. Overview

The integration of AI-assisted platforms, such as ChatGPT, into engineering projects has grown increasingly common in academic and professional settings. These platforms offer a combination of natural language understanding, contextual reasoning, and technical knowledge retrieval, which can accelerate development and reduce cognitive load on students. In the context of Senior Design, ChatGPT serves as a supplemental resource that can provide explanations of algorithms, software design practices, technical trade-offs, debugging strategies, and documentation guidance. By leveraging these capabilities, team members can access near-instant technical insights, clarify complex concepts, and generate structured written content for reports and presentations. However, the use of AI platforms is not without limitations. While they can enhance productivity and learning, improper reliance may introduce inaccuracies, bias, or over-simplified explanations, which can negatively impact technical understanding if not carefully verified scale.stanford.edu.

5.2. Advantages of AI Platforms in Senior Design

5.2.1. Accelerated Knowledge Retrieval

One of the most significant benefits of platforms like ChatGPT is the rapid retrieval of information. In complex projects involving embedded systems, control theory, and software architecture, students often spend considerable time searching textbooks, research papers, or online forums for explanations of relevant concepts. ChatGPT provides immediate contextualized responses, synthesizing information across multiple domains. For example, in our Automated Lawnmower project, the team queried ChatGPT for guidance on triangulation algorithms, UWB localization principles, and boustrophedon path planning. This accelerated the initial research phase, allowing the team to focus on implementation and testing rather than spending hours on literature review.

5.2.2. Support for Technical Writing

AI platforms can also assist in technical writing and report structuring. Writing clear and professional documentation is often challenging for students who are simultaneously managing coding and hardware development. By providing suggestions for paragraph organization, section headings, and explanation clarity, ChatGPT helped the team produce well-structured content that aligns with SD1 report requirements. Additionally, the platform offers grammatical corrections and formatting guidance, which ensures that reports meet academic standards without sacrificing technical depth.

5.2.3. Conceptual Understanding

Beyond procedural guidance, ChatGPT promotes conceptual understanding by breaking down complex topics into digestible explanations. For instance, when designing the mower's path planning system, the team used AI to clarify the trade-offs between different coverage strategies, such as boustrophedon versus spiral or random paths. This enabled informed decision-making and fostered a deeper understanding of algorithmic efficiency and system design constraints. By presenting multiple perspectives and highlighting potential pitfalls, the AI platform reinforced critical thinking and facilitated discussions within the team.

5.3 Limitations and Potential Pitfalls

Despite its advantages, AI platforms have notable limitations when applied to engineering projects.

5.3.1. Accuracy and Verification

AI-generated content may contain inaccuracies or oversimplifications, particularly in technical domains. While ChatGPT can provide explanations of algorithms or system architectures, its outputs are not guaranteed to be correct. For example, early queries on UWB localization produced simplified mathematical formulas that required careful verification against textbooks and academic sources. Relying solely on AI outputs without cross-checking can propagate errors into the project, which may impact both design decisions and the credibility of documentation.

5.3.2. Lack of Context-Specific Insight

AI platforms lack access to the physical context of a project. While they can provide general guidance, they cannot sense real-world conditions such as sensor noise, environmental interference, or hardware limitations. For example, when implementing the mower's obstacle detection system, ChatGPT could suggest standard interrupt-driven routines, but it could not predict performance nuances caused by uneven terrain or lighting conditions affecting optical sensors. Thus, while AI can guide design choices, practical experimentation and context-aware adjustments remain essential.

5.3.3. Risk of Over-Reliance

Another limitation is the potential for over-reliance on AI outputs. Students may be tempted to accept answers without critical evaluation, which undermines learning. To mitigate this, the team used AI as a **supplementary tool**, verifying each suggestion with textbooks, academic papers, and peer review. This practice ensured that AI assistance enhanced learning rather than replacing experimentation or critical analysis.

5.4. Examples of AI-Assisted Learning in Senior Design

5.4.1. Triangulation Algorithm Guidance

The team asked ChatGPT to explain triangulation techniques for UWB-based localization. The platform provided step-by-step derivations of the equations used to compute (x, y) coordinates from three anchor distances. While the initial output contained simplifications, it served as a starting point for coding, followed by manual verification to ensure accuracy. This interaction illustrates how AI can accelerate understanding while reinforcing the need for critical evaluation.

5.4.2. Path Planning Strategy Comparison

Another example involved evaluating coverage strategies. ChatGPT provided pros and cons for boustrophedon, spiral, and random coverage methods. By presenting comparative tables and highlighting efficiency trade-offs, the platform facilitated informed decision-making and justified the selection of the boustrophedon method for rectangular mowing areas.

5.4.3. Report Drafting and Technical Writing

During report preparation, the team used AI to draft sections on software architecture and subsystem interaction. ChatGPT suggested paragraph structures, explained technical concepts in readable language, and proposed logical sequencing of sections. These drafts served as a foundation for further elaboration, allowing the team to focus on technical accuracy and report compliance with SD1 formatting requirements.

5.4.4. Debugging Conceptual Guidance

AI was also used to troubleshoot conceptual issues in motion control and safety modules. While it could not debug code directly, ChatGPT suggested common pitfalls in control logic, such as handling lift detection interrupts or ensuring priority of safety routines over navigation commands. These suggestions prompted team members to implement robust safety checks in the code, illustrating how AI supports design thinking rather than replacing hands-on problem solving.

5.5. Integrating AI Responsibly

To maximize benefits and minimize risks, the team established guidelines for responsible AI usage:

1. **Cross-Verification**: Every AI suggestion was verified against academic resources or empirical testing.

2. **Documentation of Prompts and Responses**: All queries and responses were recorded in **Appendix B**, ensuring transparency and proper citation.

3. **Supplementary Use**: AI was treated as an assistant rather than a decision-maker, supporting learning rather than replacing experimentation or critical analysis.

4. **Citations**: All content directly derived from AI outputs was cited appropriately to avoid plagiarism.

This disciplined approach ensured that AI usage enhanced learning, supported design decisions, and complied with academic integrity standards.

5.6. Summary

AI-assisted platforms such as ChatGPT provide significant advantages in accelerating research, enhancing technical writing, and clarifying complex engineering concepts. They promote efficiency and foster conceptual understanding but require careful verification and critical thinking to mitigate inaccuracies, context limitations, and over-reliance. In the context of the Automated Lawnmower project, AI support facilitated algorithm selection, system design trade-offs, safety planning, and report drafting. Proper documentation of prompts and responses, combined with cross-verification, ensures responsible use that enhances both learning and project quality. The prompts, outcomes, and resulting insights are included in **Appendix B**, providing a transparent record of AI-assisted contributions to the Senior Design experience.

6. Hardware Design

6.1. Design From Senior Design 1

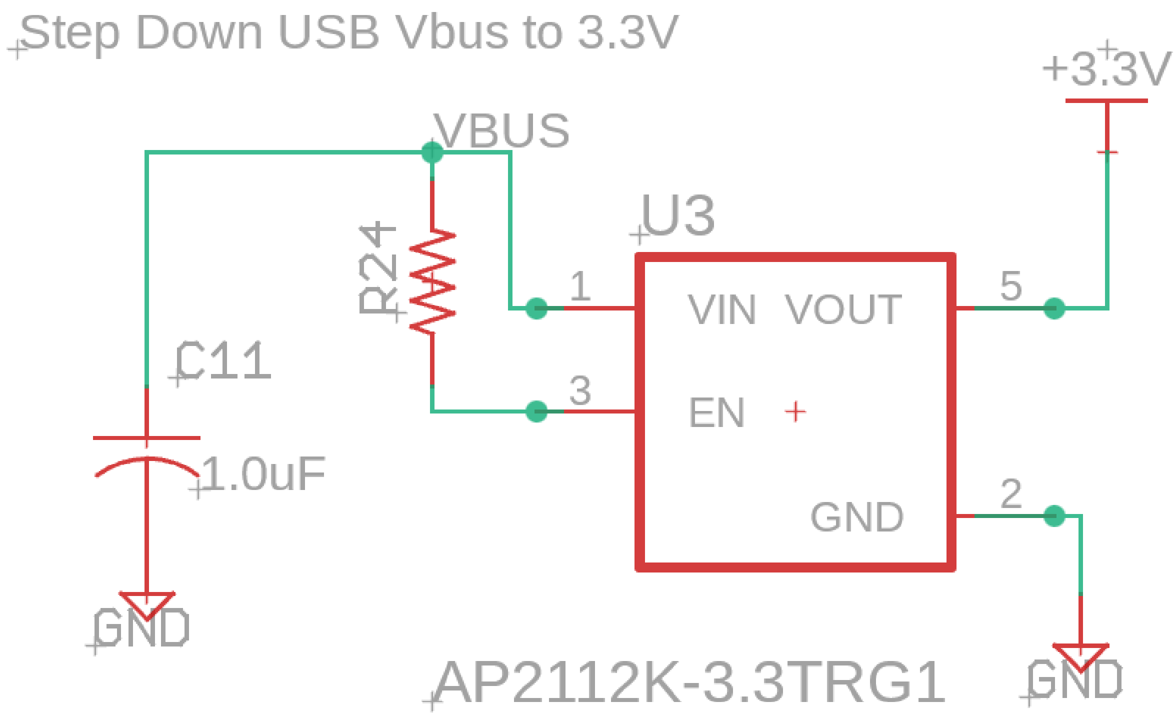


Figure 9: Vbus to 3.3V Schematic

Figure 9: Vbus to 3.3V Schematic shows the AP2112 low-dropout regulator connections between the USB 5 V supply (VBUS) and the system's regulated 3.3 V rail, which powers the ESP32 and associated peripherals. The AP2112 is a compact and efficient linear regulator that requires minimal external components; typically just input and output decoupling capacitors for stable operation, as outlined in Chapter 3. A filter capacitor is placed close to the input pin to reduce voltage ripple and ensure reliable startup behavior when the USB supply is connected. A pull-up resistor is connected to the regulator's enable (EN) pin, which keeps the regulator permanently enabled whenever the 5 V USB bus is powered. This configuration ensures that the 3.3 V rail is automatically active whenever the system receives power from USB, eliminating the need for a separate power-on control signal. Since the AP2112 features a low quiescent current and built-in internal protection circuitry, there is no practical advantage in adding logic control to the enable pin for this application. This simple, always-on configuration reduces circuit complexity and ensures consistent power delivery to the digital logic section of the TURF system.

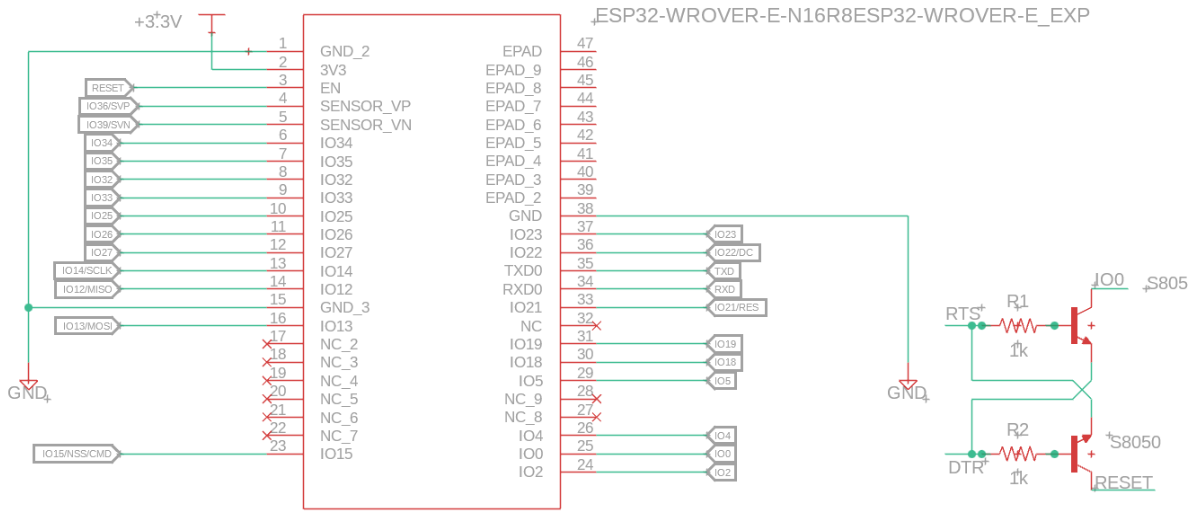


Figure 10: ESP32-WROVER-E Schematic

Figure 10: ESP32-WROVER-E Schematic shows the ESP32-WROVER-E microcontroller with labeled pin assignments and its associated auto-programming interface connected to the USB-to-serial converter. The circuit on the right implements an automatic bootloader and reset control using two S8050 NPN transistors and a pair of 1 kΩ base resistors. These components translate the USB control signals, RTS (Request to Send) and DTR (Data Terminal Ready), from the USB-to-UART bridge into the active-low pulses required by the ESP32's GPIO0 (BOOT) and EN (RESET) pins. During the firmware flashing process, the USB interface automatically toggles these control lines in a predefined sequence: the RTS line briefly pulls GPIO0 low while the DTR line pulses the EN pin, causing the ESP32 to reset into its UART bootloader mode. This sequence allows firmware uploads to occur seamlessly through standard tools such as the Arduino IDE or ESP-IDF without requiring any manual button presses. The transistors serve a dual purpose; inverting and isolating the logic levels between the USB interface and the microcontroller to ensure clean signal transitions, prevent voltage contention, and protect the ESP32's input pins from potential overcurrent or timing conflicts during power-up and programming. This design provides a robust and fully automated programming interface, improving reliability and ease of use during both development and deployment.

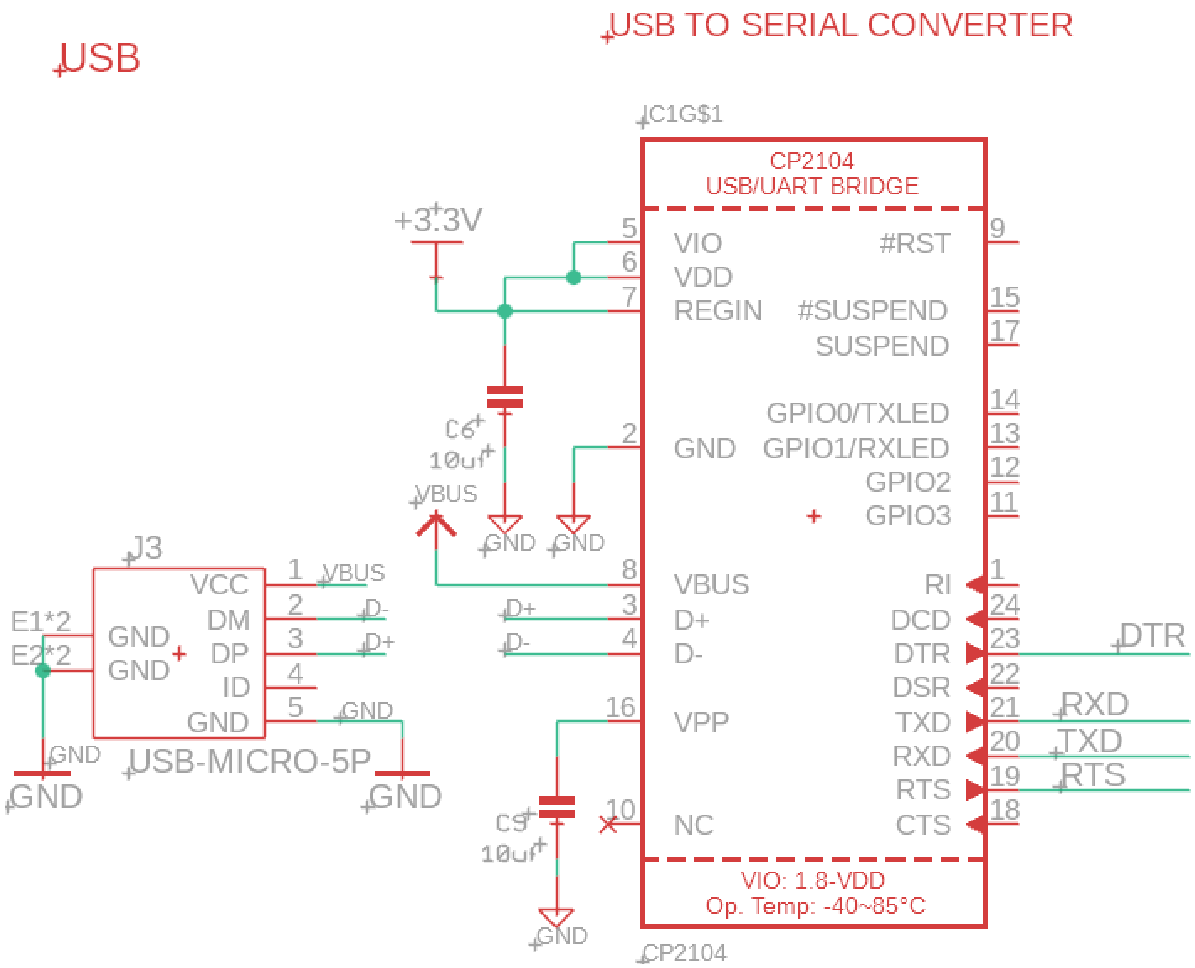


Figure 11: USB to Serial Converter CP2104

Figure 11: USB to Serial Converter CP2104 shows the CP2104 USB-to-UART bridge circuit on the right, which provides the communication interface between the host computer and the ESP32 microcontroller. The CP2104 handles all USB protocol processing internally, converting USB signals into standard UART transmit (TX) and receive (RX) lines for serial communication. The device requires minimal external components, consisting primarily of a few decoupling capacitors for power supply filtering and stability. To the left of the figure is a Micro-USB connector, which serves as the physical interface between the TURF system and a host computer via a standard USB cable. This connector supplies both the 5 V power (VBUS) and the data lines (D+ and D–) to the CP2104. The bridge shows automatically as a virtual COM port on most operating systems, allowing seamless firmware uploads, debugging, and serial monitoring without additional drivers or interface hardware. This simple and compact design provides reliable USB connectivity while minimizing PCB space and component count.

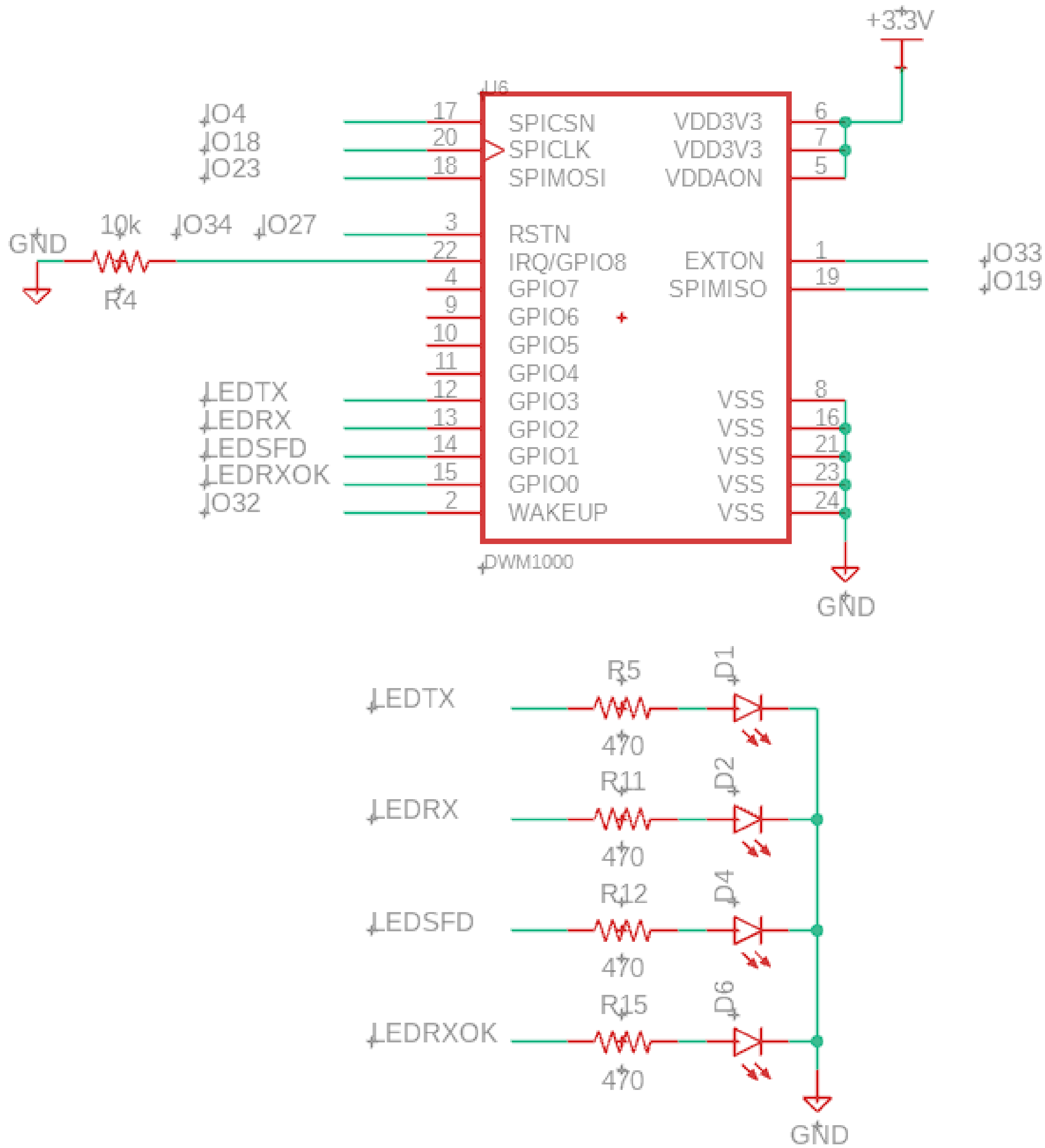


Figure 12: DW1000 Schematic and Support Circuitry

Figure 12: DW1000 Schematic and Support Circuitry shows the DW1000 Ultra-Wideband (UWB) transceiver with its associated support circuitry and signal connections to the ESP32 microcontroller. The previous design included small series resistors placed on the I/O lines between the ESP32 and the DW1000 to prevent excessive current flow and protect against pin contention during system boot. This

updated schematic makes use of a vendor supplied module that includes protection circuitry built in. The primary communication interface between the microcontroller and the UWB IC is implemented using a 4-wire SPI bus consisting of MOSI, MISO, SCK, and CS lines, which enable high-speed data transfer for configuration and ranging operations. To ensure reliable operation in the previous version, two decoupling capacitors, a bulk capacitor and a smaller high-frequency bypass capacitor, were connected close to the power pins of the DW1000 to stabilize the 3.3 V supply and minimize voltage ripple. The updated module does not require this. A set of diagnostic indicator LEDs are included on key status outputs such as transmit, receive, and synchronization signals. These LEDs provide immediate visual feedback during testing and calibration, allowing the team to verify communication activity and UWB signal events in real time. Together, these support components ensure stable power delivery, electrical protection, and observable operation of the UWB subsystem within the TURF robot's localization system.

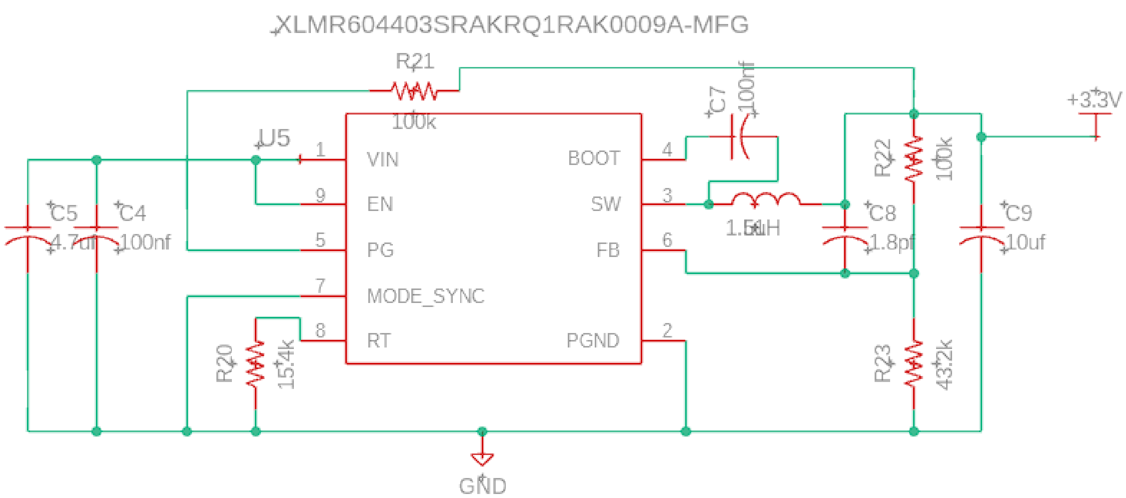


Figure 13 3.3V Regulator From Battery

Figure 13 3.3V Regulator From Battery shows a 3.3 volt regulator circuit from Texas Instruments' WEBENCH. It produces a regulated 3.3V output up to 2A with an input from 6V to 15V. This design was chosen for the large input range since a battery had not been selected at that time. This simplifies sourcing for batteries. Additionally, the IC chosen includes built-in compensation to minimize sensitivity to PCB layout and trace shape. The Regulator circuit was not customized in anyway and follows the recommended schematic directly from webench. This design avoids TPS and BQ series regulators and makes use of the LM series of ICs as advised by Dr. Weeks.

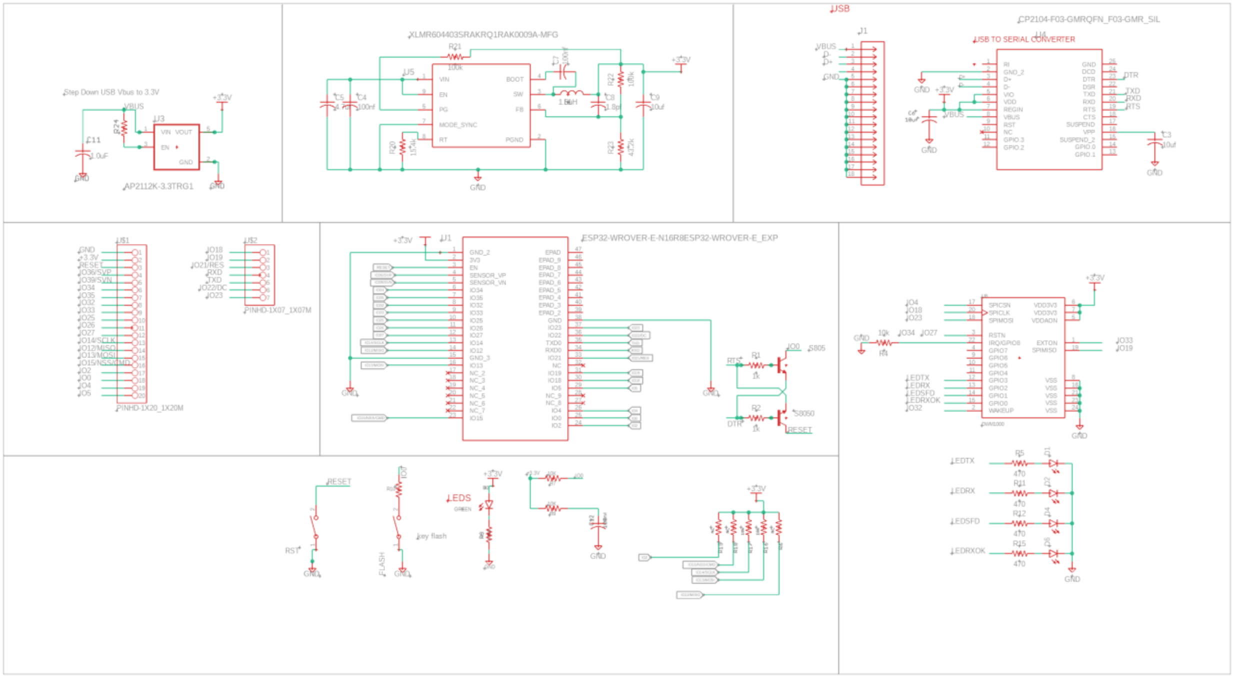


Figure 14: Current Receiver and Kinematics System Schematics

Figure 14: Current Receiver and Kinematics System Schematics shows the complete circuit design currently intended for use in both the Receiver and Kinematics subsystem and the Tag subsystem of the TURF robot. The circuit integrates the ESP32-WROVER-E microcontroller, power regulation, USB-to-serial interface, and UWB transceiver within a unified design. Although the computational capabilities of the ESP32 are greater than what is strictly required for the Tag subsystem, reusing the same hardware architecture across both modules greatly simplifies development, reduces design validation effort, and ensures firmware compatibility. Standardizing on a single PCB design also minimizes manufacturing complexity and supports easier maintenance and future updates.

In the lower-left portion of the schematic, the manual Reset and Flash buttons for the ESP32 are included, allowing the team to manually place the microcontroller into programming or reboot modes if required. Associated pull-up resistors are connected to key UART and control lines to maintain stable logic levels during serial communication and to prevent floating inputs during power-up. This combined design provides a consistent and reliable platform for both localization (UWB Tag) and motion control (Receiver and Kinematics), ensuring streamlined integration across all subsystems of the TURF platform.

6.2. Hardware Changes Made in Senior Design 2

Two key changes were made to the hardware design before ordering PCBs. The CP2104 USB/UART bridge was replaced with the CP2102. While the CP104 is newer, has a lower cost, and is more performant, the team was advised by faculty to use the older CP2102 due to its reliability being known.

The team was also advised to use a USB-A header instead of a USB micro-B header.

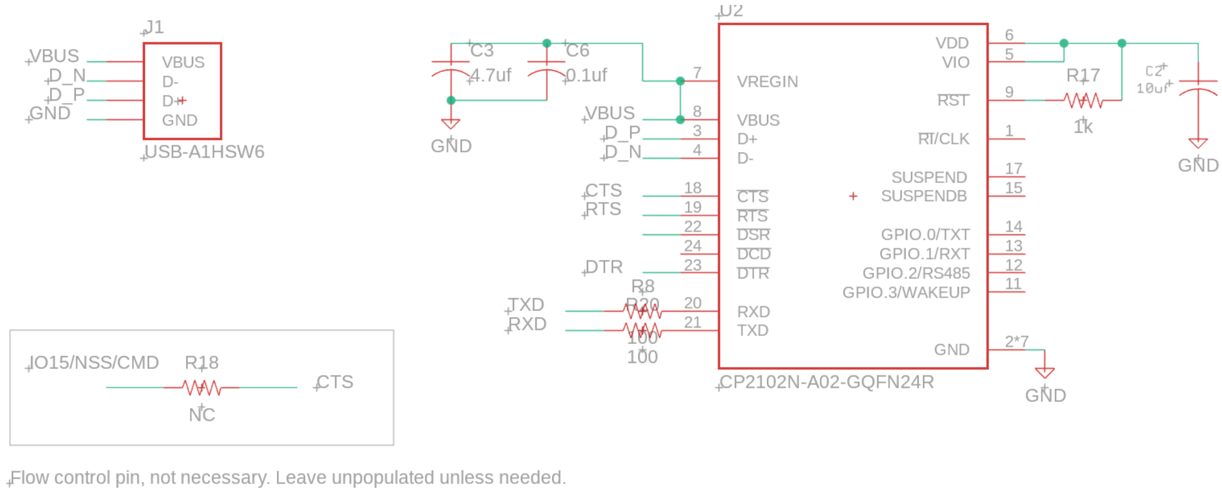


Figure 15: Updated USB/UART Bridge Circuit

7. Software Design – Automated Lawnmower Project

7.1. Overview

The TURF software system is a modular embedded platform running on an ESP32-WROVER-E microcontroller, coordinating localization, autonomous coverage, motor control, and operational safety for the robotic mower. Its primary objective is to navigate a user-defined rectangular mowing region using position data derived from Ultra-Wideband (UWB) ranging. The robot determines its own position locally by ranging between its onboard UWB tag and several fixed anchors placed around the field.

A dedicated companion application provides the necessary configuration and supervisory functions. Before operation, the user enters the physical coordinates of each anchor and the coordinates of the rectangle to be mowed; these parameters are transmitted directly to the robot over a wireless link. During operation, the app allows real-time monitoring of battery life and total runtime and provides an emergency stop command that immediately halts motion. By combining onboard computation with lightweight external configuration, TURF maintains robustness and autonomy while offering a simple and intuitive user interface.

The system is intentionally modular to support future enhancements such as additional anchors, environmental sensing, or more advanced control. This flexibility represents a strategic trade-off in the design: by prioritizing modularity, initial development may take longer, but maintainability, scalability, and integration of new features are significantly simplified.

7.2. Software Architecture

The TURF software architecture consists of five core subsystems: localization, coverage path generation, motion control, Wi-Fi and REST API communication, and safety management. These subsystems operate cooperatively on the ESP32 to compute the robot's position, determine the next waypoint, drive the motor controller, and serve the companion app.

Localization Module

The localization module maintains the robot's position using two independent methods that are continuously cross-checked and fused. Dead reckoning estimates position incrementally by integrating motor movement and heading over time, providing a low-latency but drift-prone estimate. Trilateration computes an algebraic circle-intersection solution using distances measured from three fixed anchors, one placed at each corner of the mowing area, to derive an independent (x, y) position estimate. Each main loop iteration, the firmware compares the two estimates and raises a position warning flag if their disagreement exceeds a 0.5-meter threshold. The final position is produced by a weighted fusion of the two methods, with trilateration weighted at 70% and dead reckoning at 30% under normal conditions. When the disagreement exceeds the threshold, the dead reckoning state is corrected toward the triangulated result to prevent accumulated drift from compounding. Anchor coordinates are supplied by the companion app via the /api/field-config endpoint and stored in a FieldConfig struct.

Coverage Path Generation

The robot uses a boustrophedon (back-and-forth) mowing pattern across the configured rectangular field. After the field dimensions are received from the app, the firmware generates sequential horizontal stripes 0.4 meters apart, alternating direction on each pass. Each stripe endpoint is passed to the motion control subsystem as a waypoint. Progress metrics including mowed area, remaining area, and overall completion percentage are updated after each stripe and reported to the app through the status API. When the final stripe is completed, the mower automatically stops the blade and returns to the origin dock position.

Motion Control

The motion subsystem drives the differential drivetrain by computing the heading error between the robot's current orientation and the bearing toward the next waypoint. When the heading error exceeds 10 degrees, the robot executes an in-place turn using differential motor commands, applying opposing PWM signals to the left and right motors via the DRV8874 motor driver, before resuming forward motion. Position is continuously updated using simplified dead reckoning during travel. The moveToPosition function runs a closed loop that yields to the HTTP server on each iteration, allowing the system to remain responsive to emergency stop commands even during active navigation.

Wi-Fi and REST API Communication Module

All communication between the companion app and the ESP32 is handled over Wi-Fi through an HTTP server running on port 80. The firmware exposes three REST endpoints: /api/status returns a JSON object containing battery level, mowing progress, mowed and remaining area, total distance, runtime, current position, and any active warnings; /api/command accepts POST requests to issue pause, resume, and emergency stop commands; and /api/field-config accepts the field dimensions and anchor coordinates needed to configure the mowing area. CORS is enabled to allow connections from the React Native app. The server's handleClient() call is interleaved within the motion control loop to ensure commands are processed without blocking navigation.

Safety Management

The safety subsystem enforces three protective conditions on every loop iteration. If an emergency stop command is received via the API, both drive motors and the blade motor are immediately cut and the mowing flag is cleared, halting all motion regardless of current state. If the battery level falls below 20%, the firmware automatically stops mowing, disengages the blade, and navigates back to the dock at the origin coordinates. Dock detection combines a hardware sensor reading with a position check, confirming that the robot is physically present at the dock before transitioning to the charging state and disabling all motors.

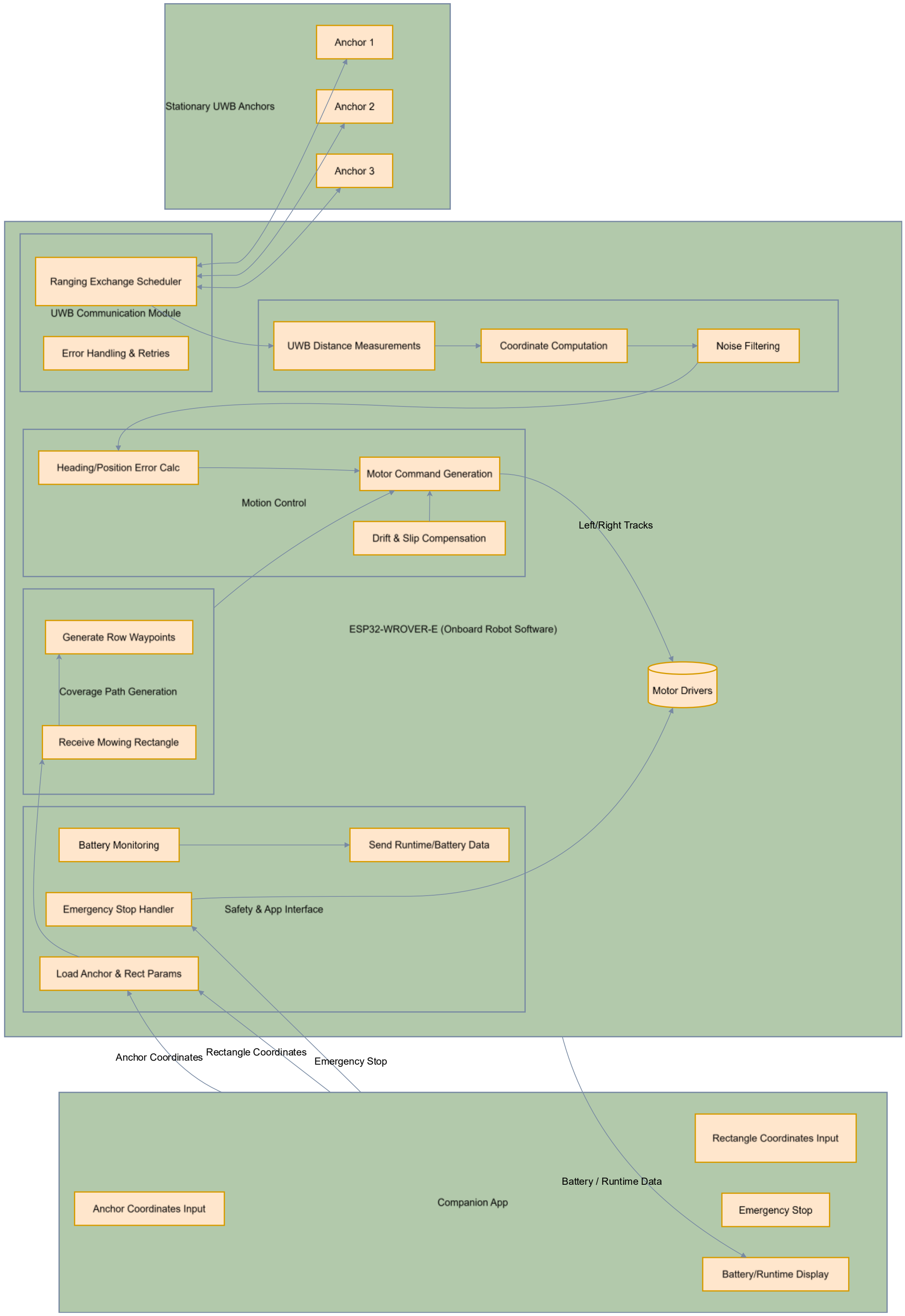


Figure 16 Software Architecture

7.3. Data Flow

TURF's data flow operates in a continuous cycle that links UWB ranging, localization, coverage-path logic, motion control, and safety monitoring. The cycle begins with the UWB communication module, which performs periodic ranging exchanges between the robot-mounted tag and the stationary anchors. These round-trip timestamps are converted into individual distance measurements and forwarded to the localization module. Using the known anchor coordinates received from the companion app, the localization module computes the robot's current (x, y) position and applies filtering to reduce noise and stabilize updates.

The updated position is then passed to the coverage path module, which determines the next target waypoint within the mowing rectangle defined by the user. The module tracks row completion, switches direction at each boundary, and advances to the next row when appropriate. This waypoint is forwarded to the motion control subsystem, which computes the heading error and distance error needed to reach the target. The controller outputs left-track and right-track motor commands and continuously corrects for drift, uneven terrain, and UWB fluctuations.

In parallel, the safety and interface subsystem handles external commands and system state reporting. The companion app transmits anchor coordinates, mowing-area coordinates, and emergency stop requests; these are immediately processed by the firmware. An emergency stop command overrides all active motion control outputs and forces the tracks to halt. Battery voltage, runtime, and status information flow in the opposite direction, from the mower back to the app, providing real-time monitoring during operation.

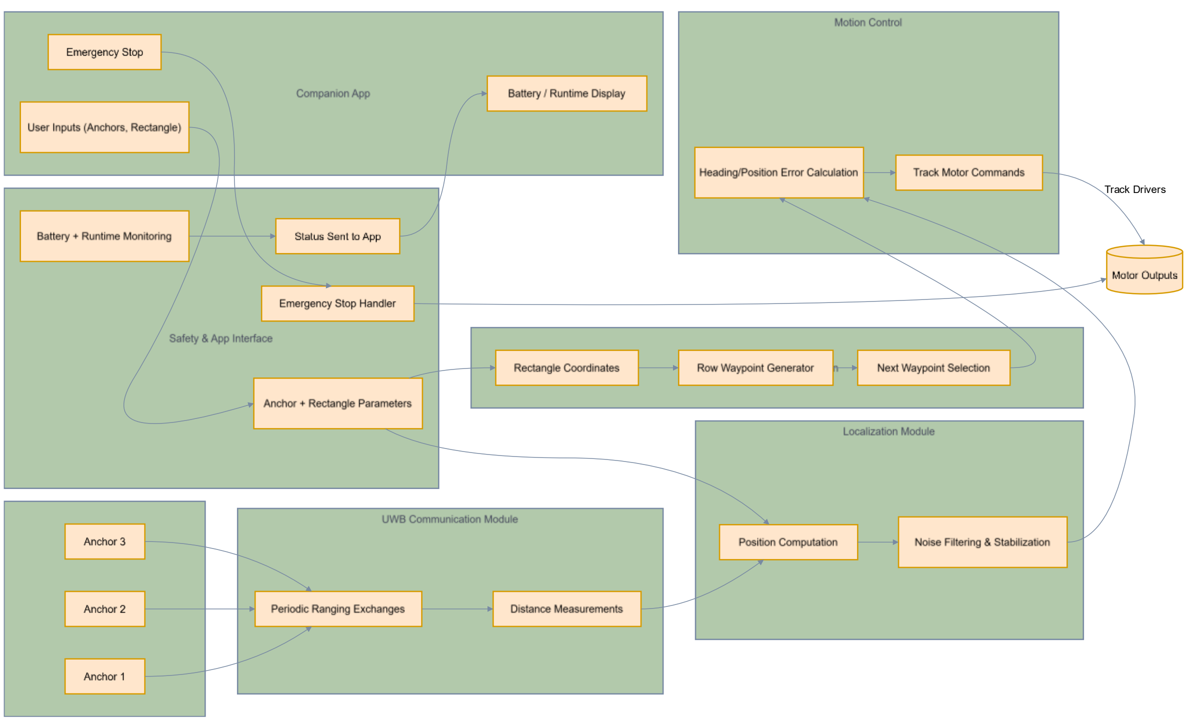


Figure 17: Data Flow

7.4. Localization Algorithm

Accurate localization is essential for enabling the TURF robot to follow straight mowing rows and transition cleanly between waypoints. The localization subsystem uses UWB-based trilateration, where the ESP32 receives distance measurements from each stationary anchor and computes its own (x, y) position relative to their known coordinates. For each anchor, the UWB ranging exchange yields a time-of-flight estimate, which the software converts into a scalar distance. With at least three anchors, the system solves for the one point on the plane that best satisfies all circle constraints defined by each anchor's position and measured radius.

Because real UWB measurements contain noise, the algorithm does not rely on exact geometric circle intersections. Instead, it uses a least-squares estimation method to compute the position that minimizes the error across all anchors. Additional filtering is applied to reject extreme outliers, smooth rapid fluctuations, and maintain stability during movement. If a measurement is inconsistent, such as a sudden large jump caused by multipath or partial signal blockage, it is discounted to prevent corrupting the position estimate.

The system's localization update frequency represents a key design compromise. Faster updates improve responsiveness and reduce drift between waypoints but increase processor load and UWB radio activity. Slower updates conserve energy but may lead to delayed corrections during row tracking. TURF selects an update interval that aligns with the motion control loop, providing reliable, real-time position information without excessive power draw.

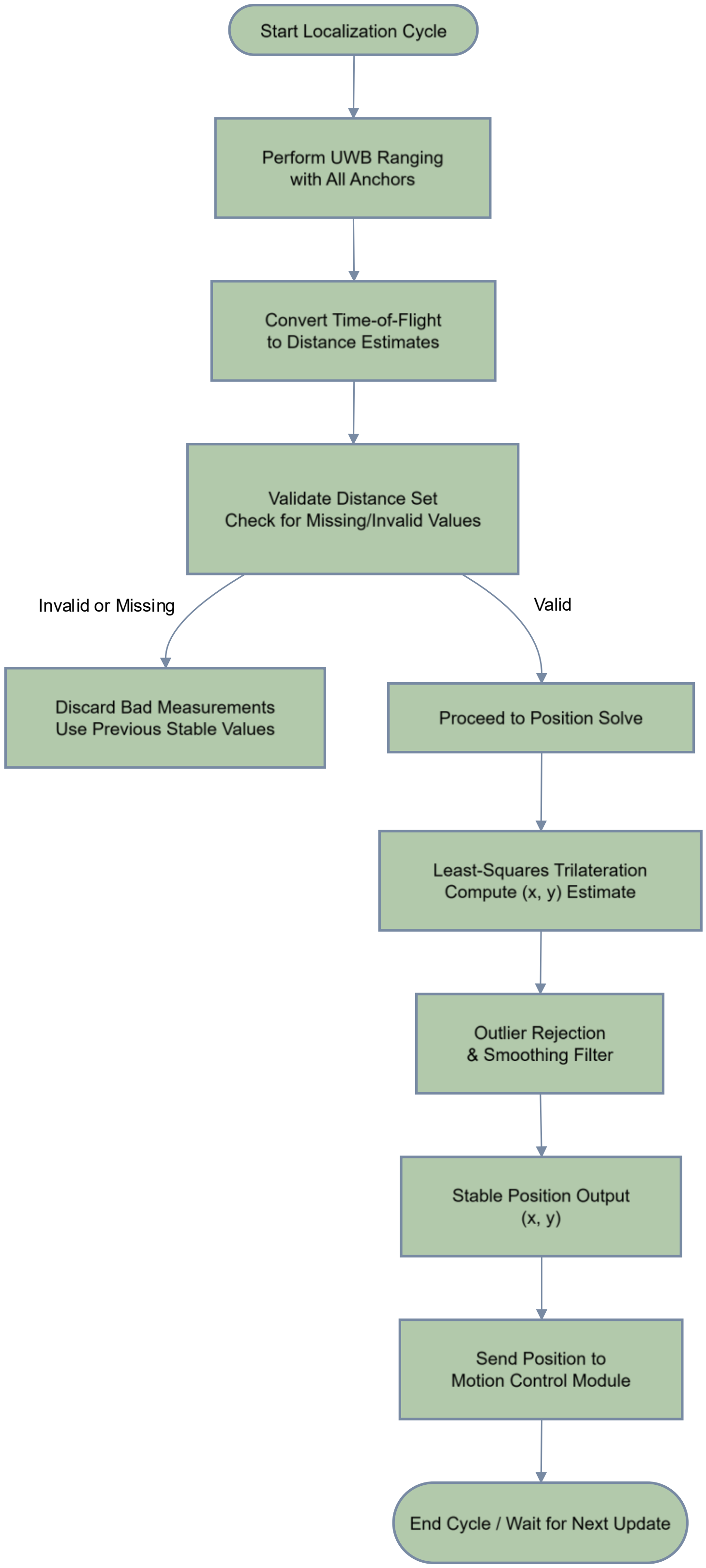


Figure 18: Localization Algorithm

7.5. Anchor Node Behavior

The UWB anchor nodes operate as low-maintenance responders that support the robot's trilateration process. During normal mowing operation, each anchor remains in an **active ranging-response state**, continuously listening for ranging messages from the robot's UWB tag and replying immediately through the DW1000 hardware protocol. This ensures the robot receives timely and reliable distance measurements for localization.

To reduce power consumption when the robot is not active, the anchors support a **low-power standby mode**. In this state, the anchor disables continuous UWB reception and wakes at periodic intervals to listen briefly for a **wake-up signal** originating from the robot. If a valid wake-up request is detected, indicating that a mowing session is starting, the anchor transitions into its full active mode and resumes its continuous ranging-response behavior.

Anchors do not compute their own position, store anchor coordinates, or process application-level data. All spatial interpretation occurs exclusively on the robot. This keeps the anchor firmware simple: its responsibilities are limited to

(1) sleeping efficiently when the system is idle
(2) becoming fully responsive when awakened
(3) replying deterministically to all incoming ranging messages during operation.

The resulting two-state design; standby and active; balances energy efficiency with the responsiveness needed for accurate real-time localization. Figure illustrates this behavior as a state diagram, showing the transitions between low-power standby, periodic wake checks, and active ranging operation.

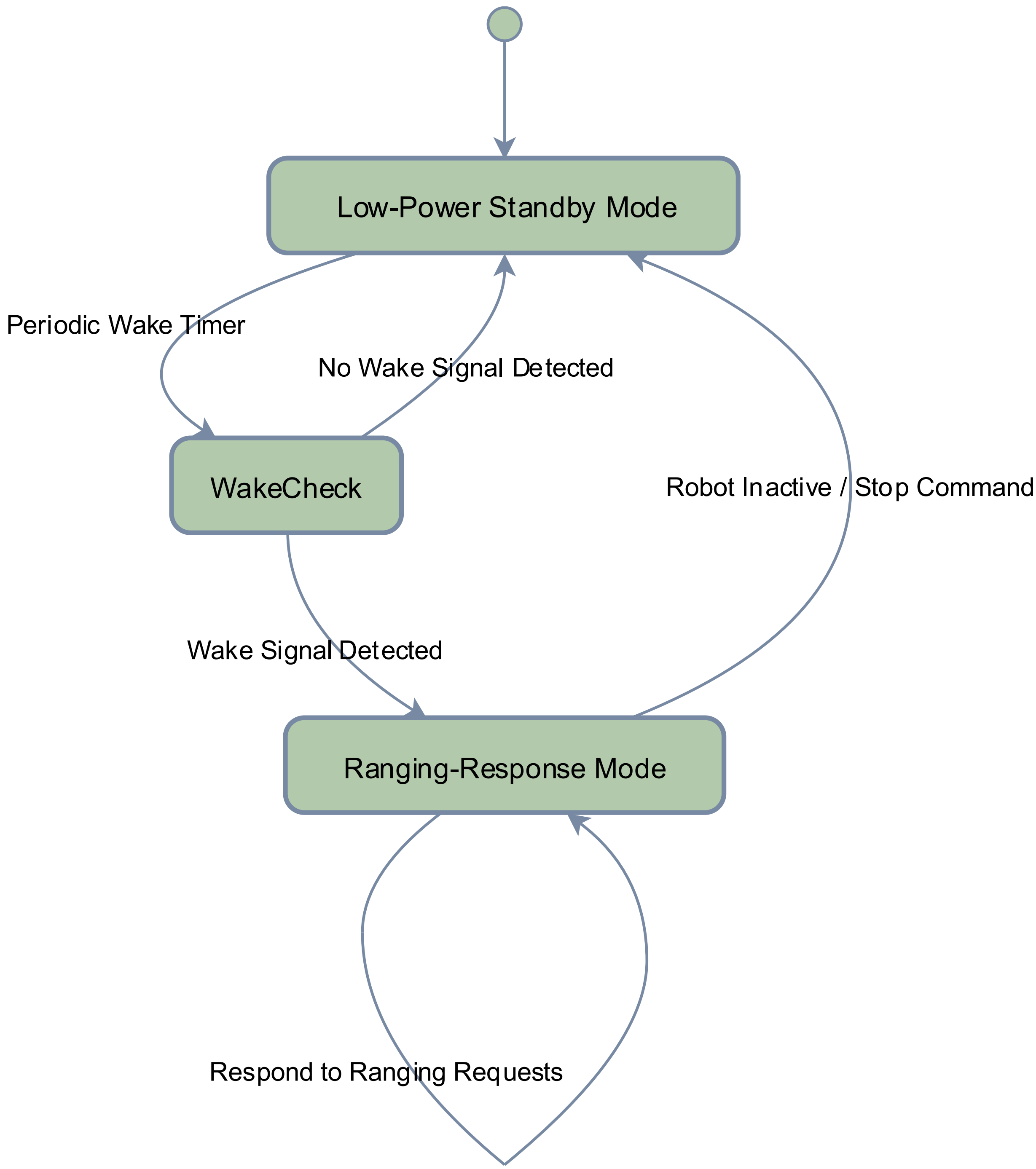


Figure 19: Anchor State Diagram

7.6. Mower Control Functions

The mower operates through a structured sequence of control modes that govern configuration, energy management, localization, safety, and autonomous mowing behavior. Each mode is designed to support a specific stage of operation while ensuring deterministic, predictable behavior suitable for an embedded robotic system.

In **setup mode**, the ESP32 initializes its Wi-Fi subsystem and creates a temporary hotspot that the companion application can join. Through this interface, the user uploads all configuration parameters required for operation. These include the absolute coordinates of each UWB anchor placed around the mowing field and the corner coordinates of the rectangular mowing region the robot must cover. The robot validates these inputs, stores them in non-volatile memory, and provides confirmation back to the app. Once configuration is complete and verified, the mower transitions into its idle state.

In **sleep mode**, the mower minimizes its energy consumption by disabling high-power subsystems such as the UWB radio and drivetrain electronics. The microcontroller uses a timed wake routine to periodically become active long enough to check for incoming start commands from the companion app. This approach balances responsiveness with energy efficiency, ensuring that the mower remains ready to operate without requiring constant power draw. Upon receiving a valid start request, the mower exits sleep mode, powers up the UWB subsystem, reinitializes communication with each anchor, and confirms that all anchors are responsive and within expected operating conditions before proceeding.

The **localization mode** is responsible for determining the mower's real-time position within the mowing field. Using periodic UWB range measurements exchanged with the anchors, the mower computes its (x, y) location through trilateration and applies filtering techniques to stabilize the output. This continuous position stream is fed directly to the motion controller, which uses it to orient the robot toward the starting corner of the user-defined rectangle. Once the robot reaches the start point, it transitions into **active mowing mode**.

During **active mowing mode**, the robot follows a structured row-based traversal pattern across the rectangular field. The coverage algorithm generates evenly spaced parallel rows that correspond to the cutting width of the mower. The motion controller drives the robot along each row while monitoring its real-time position to correct drifting, uneven terrain effects, or UWB noise. At the end of each row, the robot performs a controlled turning maneuver and advances to the next row, alternating direction to minimize unnecessary travel. This process continues until all rows have been completed.

A dedicated **safety and override subsystem** operates continuously and independently of the main control loop. Any emergency stop command issued from the companion app immediately disables motor outputs, overriding all current activities. Boundary enforcement supplements safety by preventing the mower from leaving the user-defined rectangular region; if the localization output indicates that the robot has crossed or is approaching the boundary, the system halts movement until the condition is resolved. Additional hardware safety mechanisms such as tilt, lift, or collision detection may also be integrated. These sensors provide instantaneous interrupts that trigger an immediate stop, ensuring user safety and preventing damage to the robot in abnormal situations.

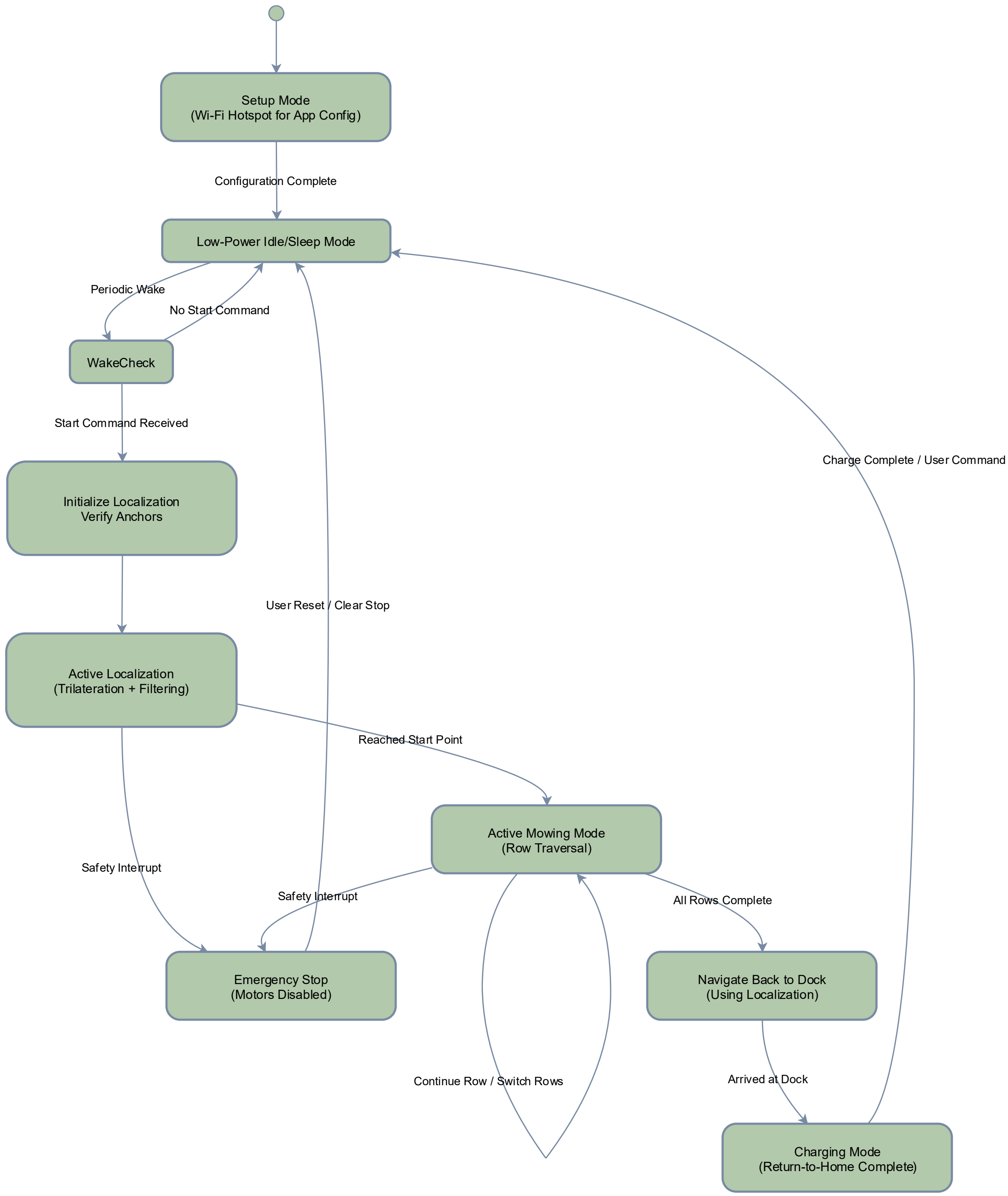


Figure 20: Mower Control Functions

7.7. Path Planning and Following

The TURF mower uses a structured, deterministic path-planning strategy tailored for rectangular mowing regions. Rather than employing a general-purpose planner or computationally expensive search algorithms, the system uses a parameterized coverage pattern optimized for embedded hardware and predictable lawn-mowing workflows. This ensures efficient coverage, minimal computational overhead, and high repeatability.

Path Generation

After receiving the corner coordinates of the mowing rectangle from the companion application, the robot generates a grid-aligned coverage plan that divides the rectangle into a series of evenly spaced, parallel rows. The spacing between rows is derived from the mower's cutting width, ensuring that each pass covers the intended strip of ground without overlap or missed gaps. The planner identifies which corner of the rectangle lies closest to the robot's current position and selects it as the starting point to minimize unnecessary traversal.

The coverage algorithm uses an alternating ("zig-zag") pattern where each successive row is traversed in the opposite direction of the previous one. This boustrophedon-style strategy reduces the number of turns and idle travel distance, improving energy efficiency and reducing total runtime. The planner stores these rows as ordered waypoints, each defined by a start and end coordinate. These coordinates are fed sequentially into the motion controller throughout mowing.

Waypoint Tracking

Once the path has been generated, the mower transitions into waypoint-following mode. The motion control subsystem receives a target waypoint and computes the heading and position errors relative to the mower's current UWB-localized pose. The controller adjusts left and right track speeds to minimize these errors, aligning the robot with the desired row and keeping it centered along the planned path.

Waypoint transitions occur when the robot reaches the end of a row, determined by comparing its real-time position to the target endpoint with a defined tolerance. Upon reaching a row endpoint, the controller executes a coordinated turning maneuver, rotates the mower into alignment with the next row, and advances to the next waypoint in the sequence. This ensures smooth and predictable traversal across the entire rectangle.

Error Compensation During Following

Path following is continuously corrected using feedback from the localization module. Because UWB measurements may contain short-duration noise or drift, the controller uses filtered position updates to adjust heading and track speeds as needed. The system compensates for:

- **Track slippage** on uneven or soft terrain
- **Heading deviations** caused by small disturbances

- **Localization jitter**, which can slightly skew the perceived path
- **Accumulated drift** between long rows

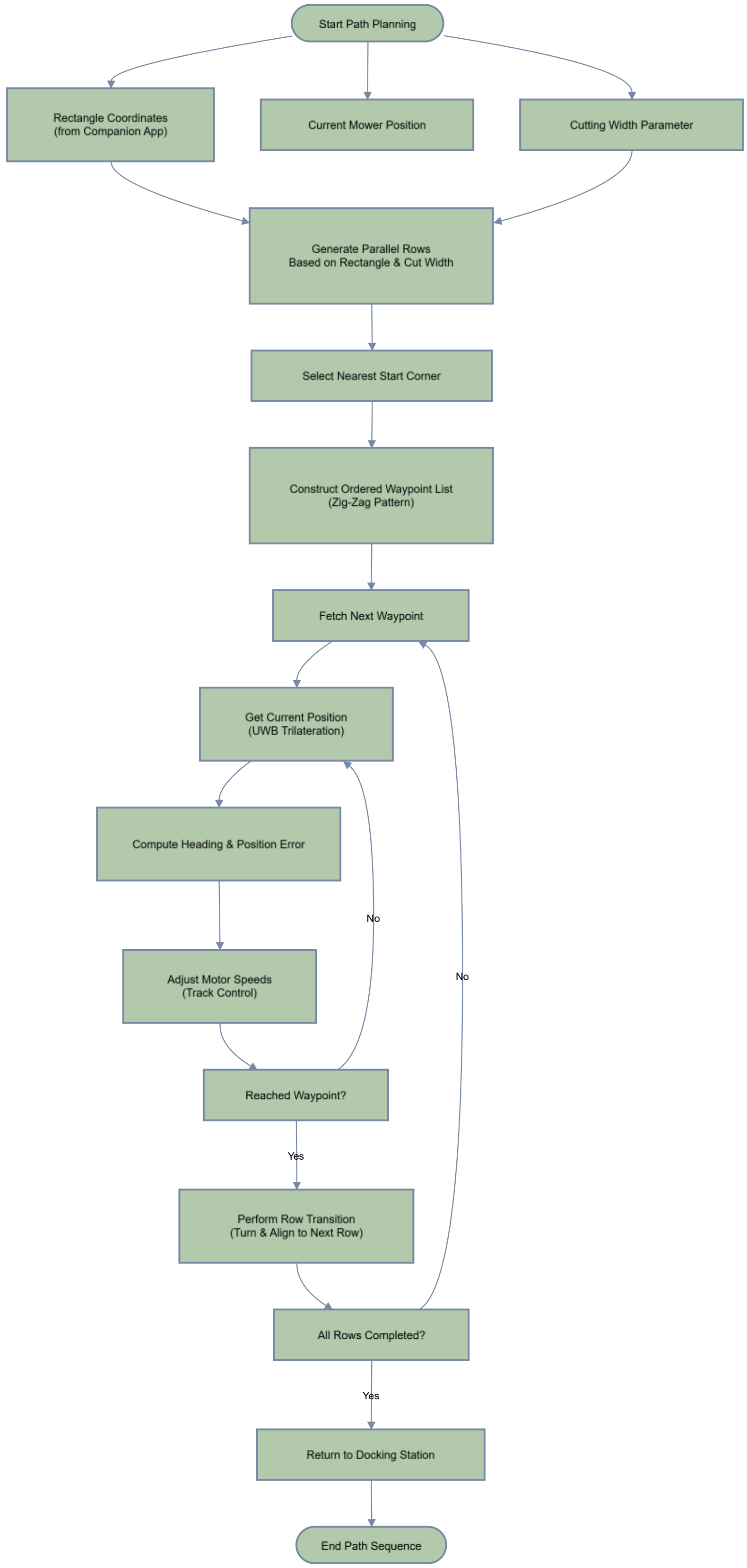
These corrections allow the mower to maintain consistent alignment with each mowing row even under imperfect conditions.

Boundary Protection

The planned path is always constrained within the user-defined rectangle. If the localization subsystem detects that the mower is approaching or crossing the rectangle boundary during path following, the motion controller immediately halts and waits for further commands. This ensures safe operation and prevents the mower from exiting the designated area due to error or drift.

Completion and Transition to Return-to-Home

Once all rows have been successfully traversed, the path planner indicates that the coverage task is complete. The mower then transitions to its return-to-home routine, using waypoint navigation similar to row following to guide the robot back to its docking station for charging.


Start Path Planning
Rectangle Coordinates
(from Companion App)
Current Mower Position
Cutting Width Parameter
Generate Parallel Rows
Based on Rectangle & Cut Width
Select Nearest Start Corner
Construct Ordered Waypoint List
(Zig-Zag Pattern)
Fetch Next Waypoint
Get Current Position
(UWB Trilateration)
Compute Heading & Position Error
No
Adjust Motor Speeds
(Track Control)
No
Reached Waypoint?
Yes
Perform Row Transition
(Turn & Align to Next Row)
All Rows Completed?
Yes
Return to Docking Station
End Path Sequence

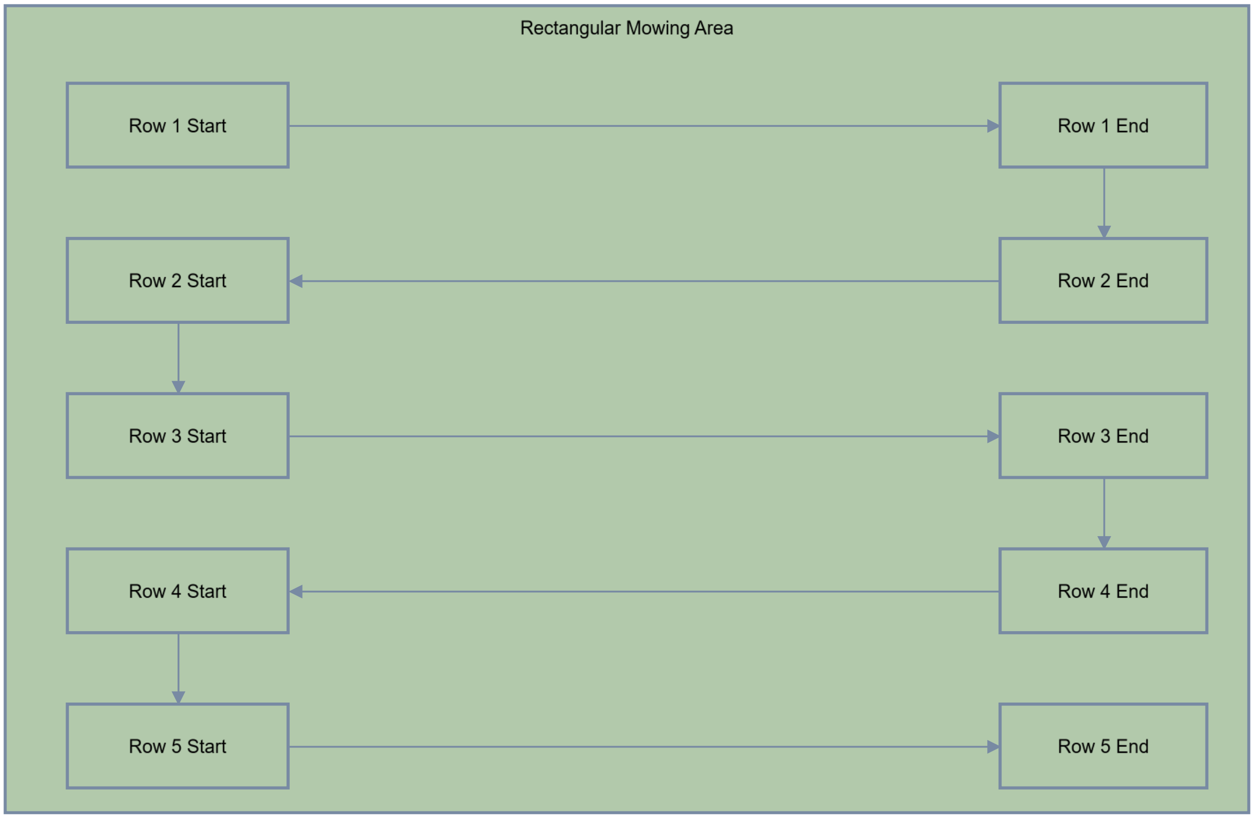


Figure 21: Path Planning

7.8. Safety and Interrupt Handling

Safety is reinforced through interrupt-driven routines and multi-layered sensor integration. Lift detection halts the mower immediately if removed from the ground. Collision detection engages upon bumper contact, halting or reversing the mower. Boundary sensors prevent accidental exit from the mowing area, while anchor loss triggers a return-to-home routine. Additional example scenarios illustrate safety considerations: if a pet enters the mowing area, optical or ultrasonic sensors detect it, triggering a stop and alert to the mobile application. If heavy wind pushes the mower off course, position corrections from the localization module ensure recovery without crossing boundaries. This multi-layered approach balances safety with autonomous operation efficiency.

7.9. User Interface

The mobile application provides full control and monitoring. Users define mowing areas, schedule tasks, pair anchors, and monitor operation. During active mowing, real-time feedback includes position tracking, progress, battery level, and alerts. Emergency stop functionality allows users to override autonomous operation immediately. Figure 7.7 shows the use case diagram illustrating user interactions with the mower and mobile application.

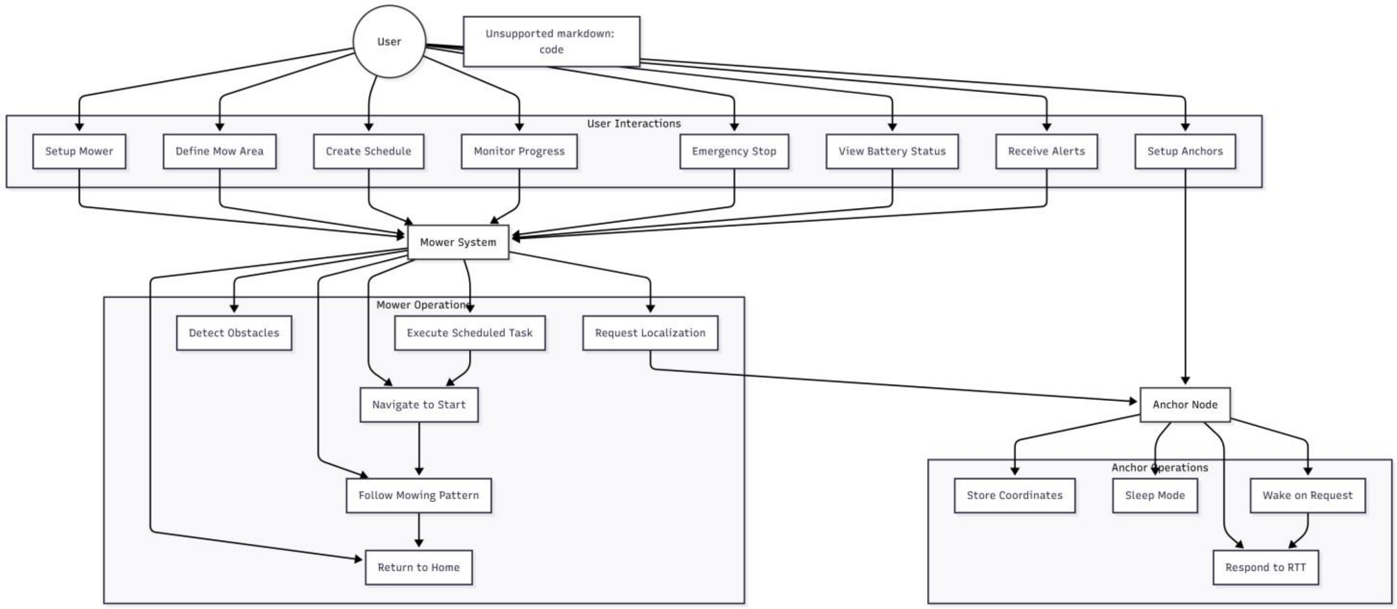


Figure 22: User Interface

7.10. Key Data Structures

The software uses structured data representations for anchors, mower state, and mowing area. Anchors include coordinates, ID, and status; the mower stores position, heading, battery level, and operational state; the mowing area defines rectangular boundaries and cutting width. These structures enable efficient computation and reliable system operation. Figure 7.8 shows a data structure diagram illustrating the relationships.

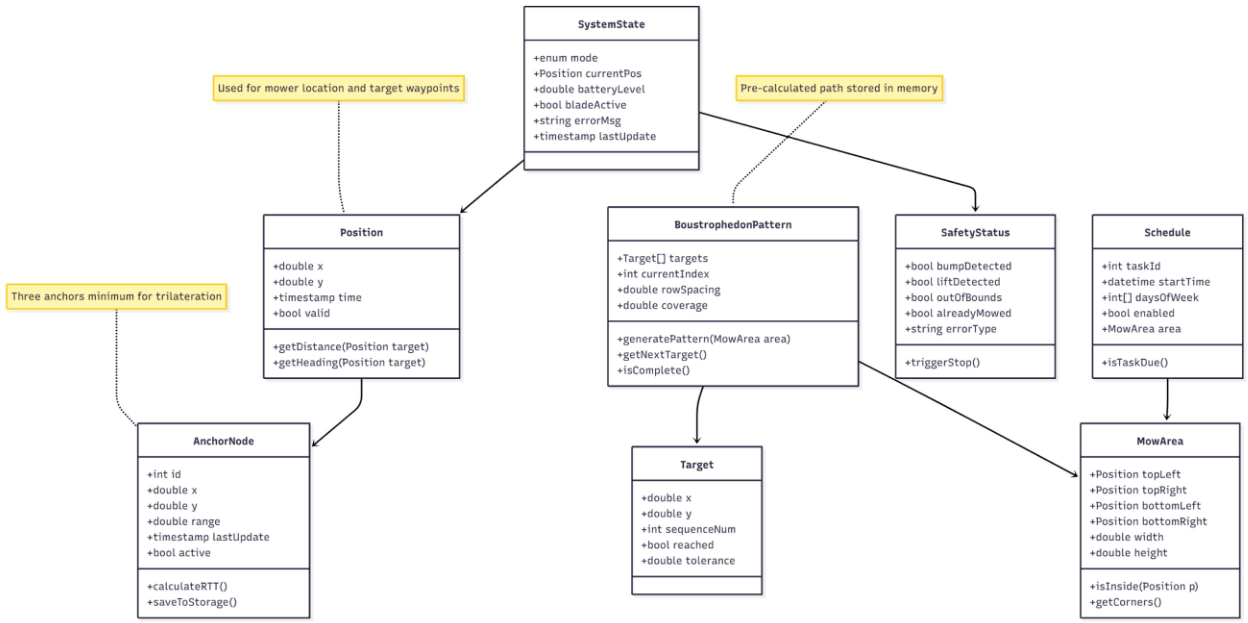


Figure 23: Key Data Structures

7.11. Data Communication

Communication occurs across multiple layers. UWB provides short-range ranging between anchors and mower. Wi-Fi links the mower to the mobile application for setup, telemetry, and control. Internal sensor and motor communications use I²C or SPI. Figure 7.9 shows the data transfer diagram highlighting UWB, Wi-Fi, and internal bus communications.

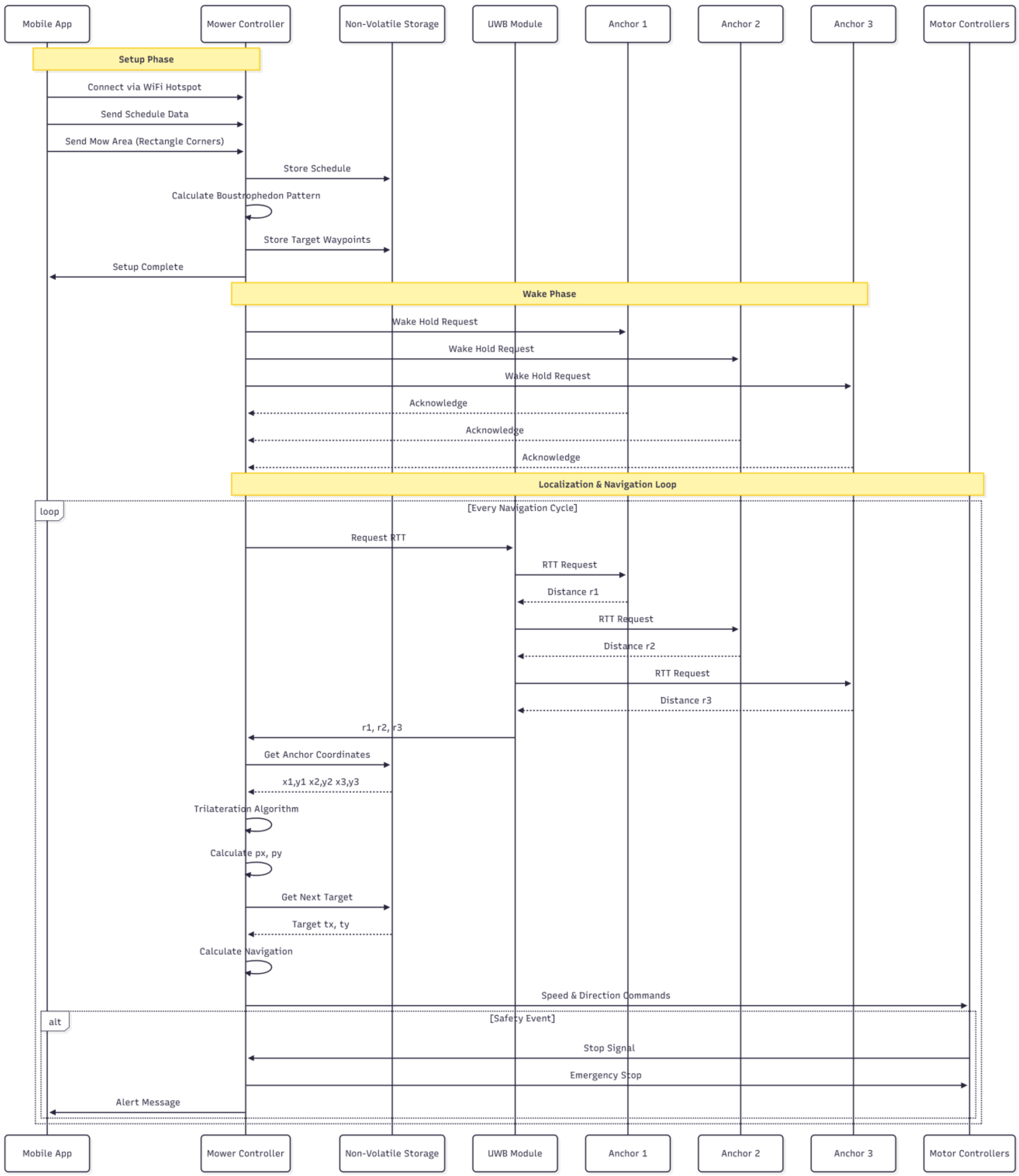


Figure 24: Data Communication

7.12. Power Management

Both mower and anchors implement energy-saving strategies. The mower sleeps until scheduled tasks, waking periodically to check updates. Anchors remain in low-power mode until receiving wake-hold signals. This balance between energy efficiency and responsiveness ensures operational readiness while minimizing power consumption. Figure 7.10 shows the power management state diagram.

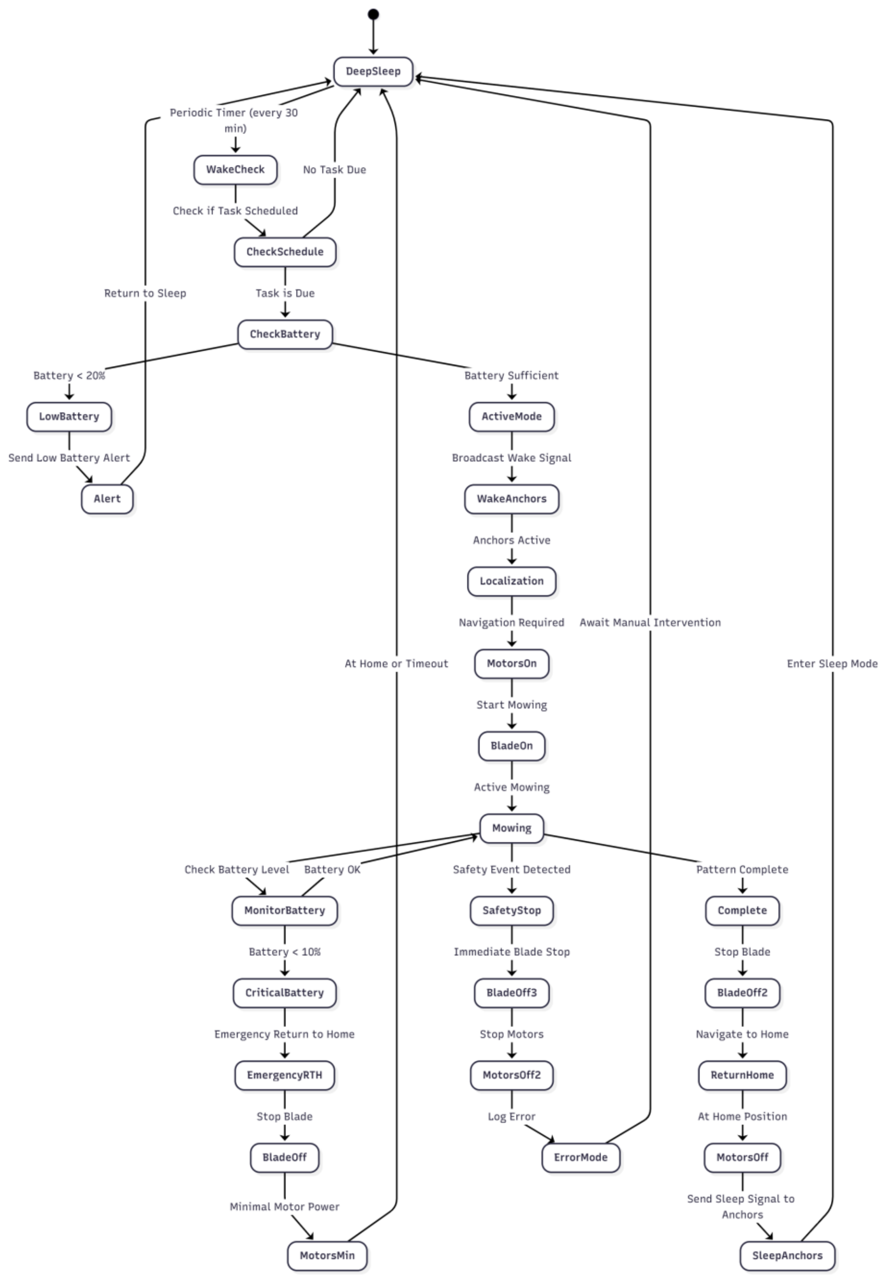


Figure 25: Power Management

7.13. Summary

The software design integrates modular subsystems for autonomous operation, precise localization, efficient path planning, real-time safety, and user-friendly interface management. Technical trade-offs—such as localization update frequency, path planning method, and anchor sleep intervals—were carefully considered to balance efficiency, accuracy, energy usage, and safety. Multi-layered safety and interrupt handling ensures reliability under varied operational scenarios. The design is maintainable, scalable, and ready for future expansion. All source code and algorithm implementations are included in **Appendix A**, following SD1 report guidelines.

8. System Fabrication and Prototype Construction

8.1. PCB

PCB design is done using Autodesk Fusion. Standard Eagle libraries are used, when possible, for passive components. Vendor provided libraries are used in all other cases. SMD ICs were chosen to minimize potential sensitivity to PCB layout. Chosen voltage regulator ICs have internal compensation; Microcontroller (MCU) and Ultrawide Band (UWB) IC are on pre-populated SMD modules that are verified to function.

Keep out zones were defined as recommended by datasheets for RF modules. This ensures that ground planes do not interfere with chip antennae. Current main PCB design routes all MCU input/output (IO) and key UWB module pins to headers. The next revision of the mainboard will replace headers for ribbon cable connectors where appropriate.

Components layout was chosen to maximize available space between packages. This will allow for more effective circuit corrections and testing if necessary, after PCBs have been manufactured.

All resistors, capacitors, and inductors are in 1206 Imperial Sized packages. Copper traces were done at 20 mil width. When necessary, exceptions were made for traces to ICs with 10 mil pad thickness.

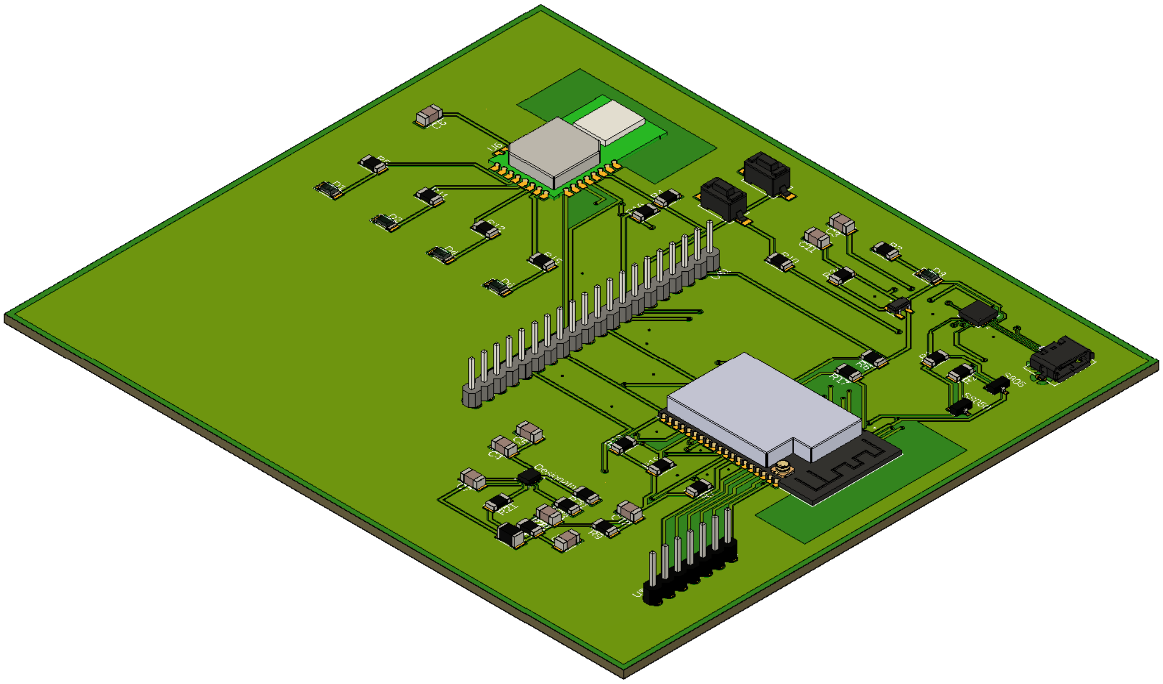


Figure 26 3D PCB Render. ESP32 Wrover at bottom center. DW1000 Module at back right. Micro-USB Port at bottom right. Reset and Flash Buttons at center right.

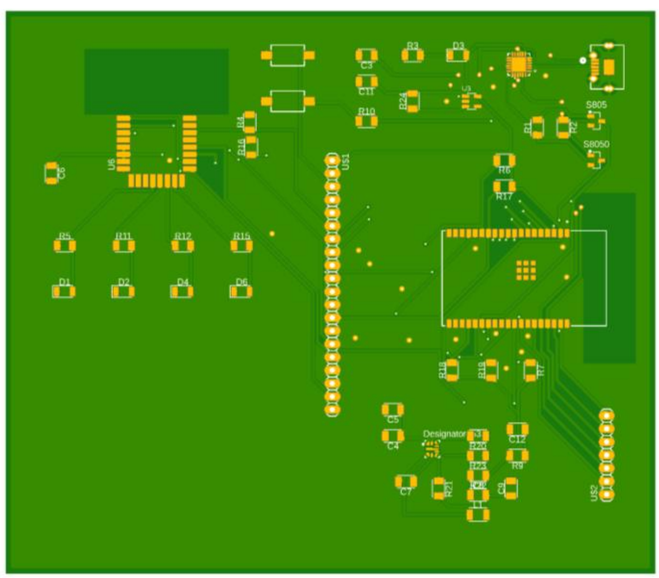


Figure 27 PCB Top

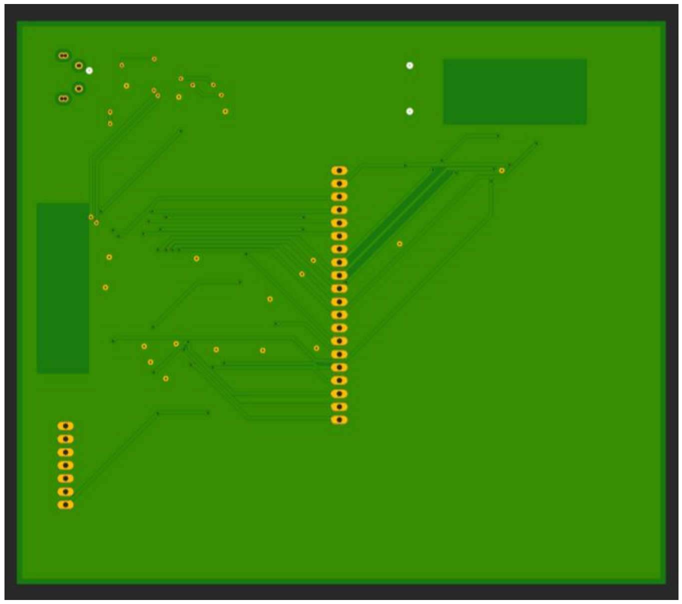


Figure 28 PCB Bottom

8.2. Chassis and Drive Motors

A pre-designed and fabricated chassis was obtained from a vendor on Amazon.com.

The chassis maintains the tracked design from TURF prototype illustrations and came paired with two DC motors with dual hall sensors for rotational velocity monitoring.

Figure 29 Vendor Image of Chassis

The chassis satisfies space requirements for holding all essential components. If more space is necessary, additional aluminum panels can easily be attached to the chassis top.

8.3. Sensor Mounting and Fabrication

Mounting the sensors properly plays a vital role in ensuring reliable obstacle detection and localization performance. Although mechanical fabrication begins in SD2, in SD1 we have our designs for the proper placement and angles of the sensors. Ultrasonic sensors will be positioned approximately 20 cm above ground level and angled horizontally to maximize detection range while avoiding reflections from grass. Research indicated that this height offers the best balance between accuracy and obstacle visibility. Light protective glass may also shield the sensors from debris without restricting their capabilities.

The UWB tag will be mounted on the upper electronics deck of the chassis to ensure consistent line-of-sight communication with outdoor anchor nodes. Anchors will be elevated on small stands to reduce interference and improve ranging accuracy. This modular sensor layout ensures the system remains flexible for additional sensing hardware introduced in SD2.

8.4. Power System Construction

The power system for TURF is built around a 12-volt $LiFePO_4$ battery that supplies all major subsystems including the drive motors, blade motor, sensors, and control electronics. During SD1, we finalized the layout and wiring strategy which will be implemented in SD2. The battery will be mounted centrally in the chassis to ensure balanced weight distribution, reduce tipping risk, and maintain traction during operation, while smaller components will be placed in close proximity to the battery in order to minimize signal loss and to keep our circuitry intact.

8.5. Drive Motor and Blade Assembly

The drive motor and blade assembly form the mechanical core of the mower’s functionality. SD1 efforts focused on defining the mounting strategy and ensuring structural stability for these components. The differential drive motors will be mounted on reinforced brackets that maintain alignment under vibration and uneven outdoor terrain. The rubber casing on our chassis' wheels will absorb most of the vibration from movement, ensuring that our electronics don’t get moved around during operation.

8.6. Docking and Charging Station Construction

The docking station allows the mower to recharge autonomously, which is essential for long-term operation. Research in SD1 explored several alignment and charging strategies, leading to a design that uses magnetic self-centering contacts. Magnets embedded in both the mower and the dock help guide the mower into place and maintain consistent electrical contact even with slight misalignment. This method balances reliability, cost, and ease of construction, making it well suited for outdoor environments.

The dock frame will be built from weather-resistant materials and include angled guide rails to improve alignment as the mower approaches. A $LiFePO_4$-compatible CC/CV charging controller will be integrated into the dock, along with reverse-polarity protection and isolating circuitry to prevent accidental shorting. These design choices result in a robust and safe docking system that the mower can reliably engage with during SD2 testing.

9. System Testing and Evaluation

9.1. Hardware Testing

9.1.1. ESP32 UWB (Ultra-Wideband) Development Board

Four Development Boards were obtained from MakerFabs.com, each including one MCU identical to TURF schematics and one UWB module of equivalent specifications and operation.

To test the boards for functionality, they were flashed with software to act either as an UWB anchor or an UWB tag. When powered and paired, the development boards reported, over a serial connection, distances between anchor and tags that varied as the boards were moved closer together or further apart.

Development boards were additionally tested when used to test motor drivers as below.

9.1.2. DRV8833 Motor Driver Module and DC motor

A team member already had within their possession a DRV8833 Driver Module. Motors were obtained with robot chassis. The procedure for testing the module and obtained DC motors is as follows.

The driver module and a previously tested development board were placed on a breadboard. Connections were made between the two as necessary, and the motors were connected to the drivers using the breadboard. A 6.4 volt battery was connected to the breadboard to supply power to the motor drivers, and a Voltage Step-Down Module was used to supply a stable 3.3 volts to the development board. The development board was flashed with software to drive the motors in opposite directions. Alternating the direction of each motor every 3 seconds. The setup could be observed rotating clockwise for 3 seconds, then rotating counterclockwise for 3 seconds and repeating.

9.1.4. Voltage Regulator Testing

Our step-down voltage regulator design is from Webench, so it had to be tested and verified for electrical output. After assembling, a 12 V DC input was connected. The regulator was tested for output stability, thermal performance, and efficiency: It produced a clean 3.3V and 5V line, ensuring an ideal power source for the various components on TURF. The regulator exhibited no signs of heating up or thermal instability during the test duration. The efficiency reported in the Webench designer tool also closely matched the measured value.

9.1.5 $LiFePO_4$ Battery Testing

A 12 V 100Ah battery was purchased on Amazon to be the main source of power for this project. It was tested for open-circuit voltage, voltage drop under load, recharge behavior, and thermal stability under load: The measured open-circuit voltage for 100% charge was around 13 V, as expected, and slowly dropped as the battery lost its charge. Under a simulated motor load, the voltage remained stable, highlighting the $LiFePO_4$ battery's stability. Recharge testing was successful, albeit the test only charged the battery from around 90% to 100%. The battery remained within acceptable thermal values for the duration of testing. These results all met our runtime and safety constraints for the mower.

9.1.6 Sensor Hardware Testing

Ultrasonic Sensors were tested for detection accuracy, refresh rate, and noise susceptibility. Using the 5 V rail, the sensor consistently detected objects between 20 cm and 150 cm, matching the operating specifications. Variability increased slightly under brighter conditions, simulating intense sunlight, which will need to be addressed and filtered in SD2.

9.2. Updated Hardware Evaluation from Senior Design 2

Once the ESP32 UWB mainboards were fabricated, testing was done to evaluate localization accuracy using trilateration.

It was discovered that the manufacturer recommended calibration procedure did not produce accurate results during trilateration. Therefore, data was collected to determine the errors in measurement produced by each anchor device. An anchor was placed at a known distance from the tag, and eleven distance measurements were recorded. This was done at 0.5-meter intervals over a 4-meter test distance. This procedure was done for all three anchors, producing the summarized data in the following three tables.

Table 13 Anchor A Measured Distances

Displacement	Average Measurement	Average Error
0.5	0.132727273	-0.367272727
1	0.759090909	-0.240909091
1.5	1.308181818	-0.191818182
2	1.940909091	-0.059090909
2.5	2.332727273	-0.167272727
3	2.793636364	-0.206363636
3.5	3.295454545	-0.204545455

4	3.83	-0.17

Table 14 Anchor B Measured Distances

Displacement	Average Measurement	Average Error
0.5	0.095454545	-0.404545455
1	0.691818182	-0.308181818
1.5	1.221818182	-0.278181818
2	1.842727273	-0.157272727
2.5	2.257272727	-0.242727273
3	2.787272727	-0.212727273
3.5	3.258181818	-0.241818182
4	3.754545455	-0.245454545

Table 15 Anchor C Measured Distances

Displacement	Average Measurement	Average Error
0.5	0.074545455	-0.425454545
1	0.645454545	-0.354545455
1.5	1.226363636	-0.273636364
2	1.842727273	-0.157272727
2.5	2.255454545	-0.244545455
3	2.812727273	-0.187272727
3.5	3.279090909	-0.220909091
4	3.753636364	-0.246363636

Using this data, Correction Functions were created by fitting a curve to the median of the recorded data.

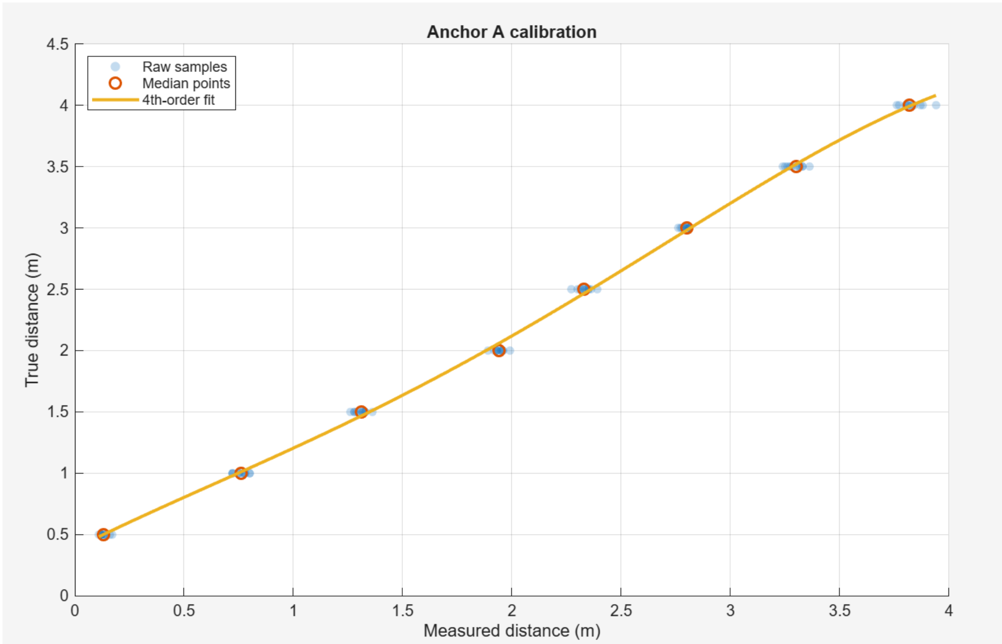


Figure 30 Anchor A Calibration Curve

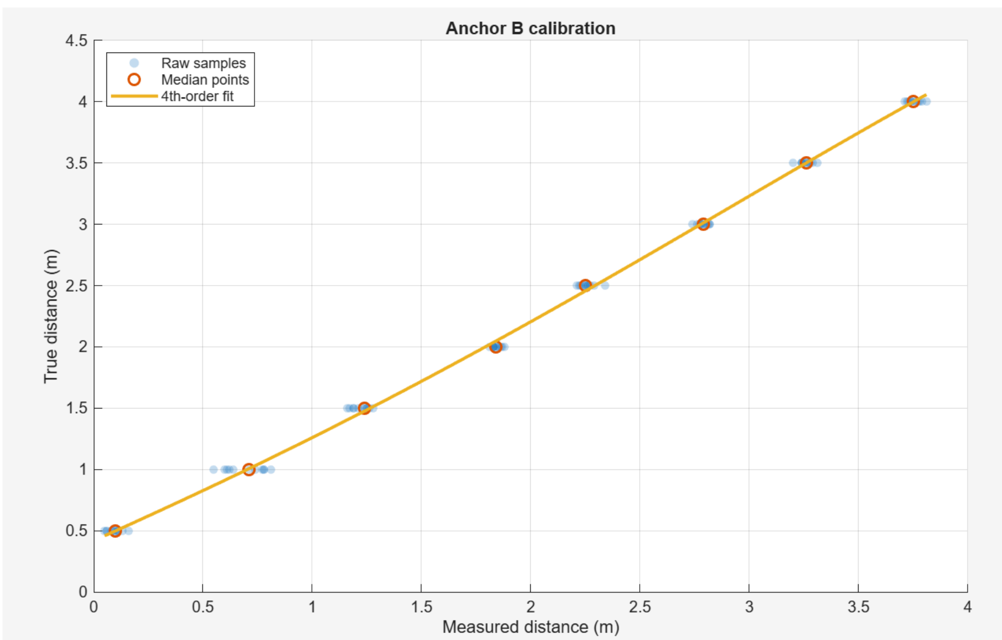


Figure 31 Anchor B Calibration Curve

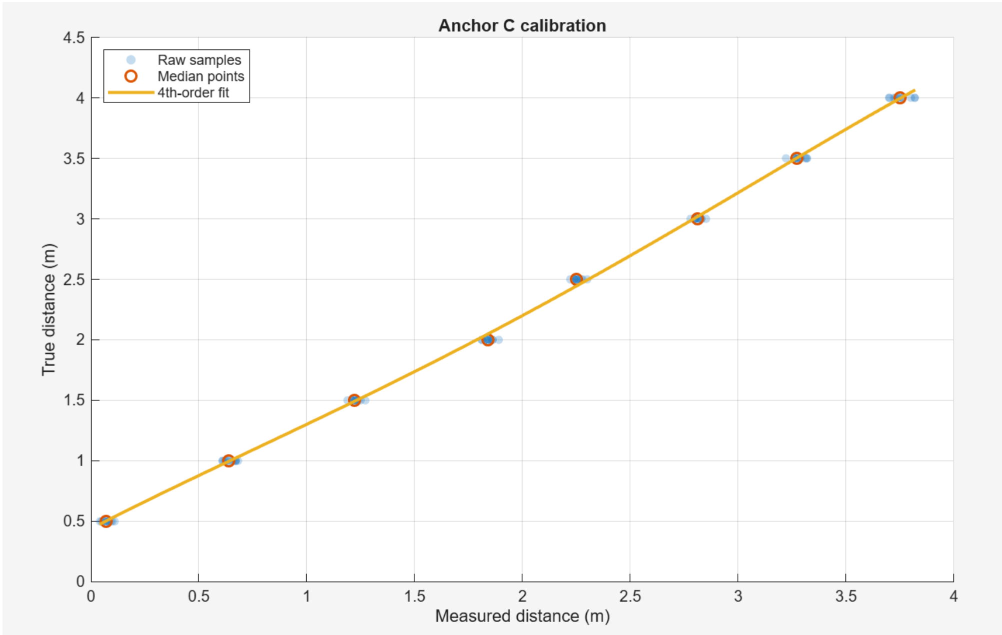


Figure 32 Anchor C Calibration Curve

Using these Calibration Curves Localization Testing was performed. The robot was placed at known positions, and several randomly selected UWB measurements were taken. Using the mean of the collected data, a Root Mean Square Error of 0.1850 meters was produced. Using the median of the collected data, a Root Mean Square Error of 0.1873 meters was produced. The collected data is visualized in Figure 33 Visualization of Localization Accuracy.

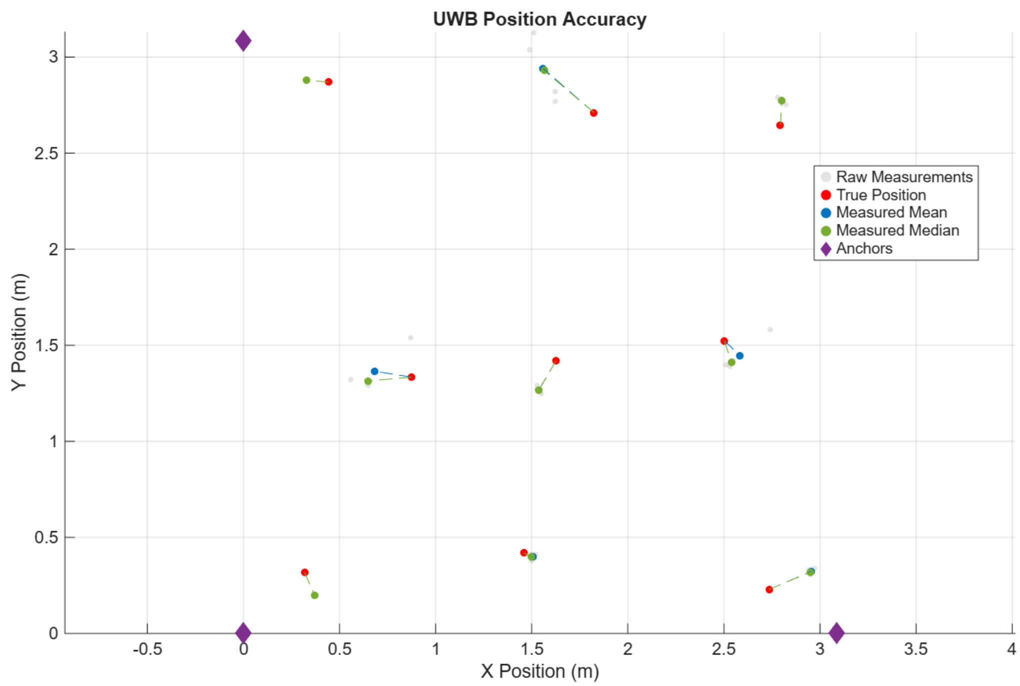


Figure 33 Visualization of Localization Accuracy

9.3. Software Testing

Software testing during Senior Design I focused on validating the fundamental control logic, communication protocols, navigation framework, and safety features that will govern the TURF mower's autonomous operation in Senior Design II. Because full system integration is scheduled for SD2, software testing in this phase centered on unit tests, module-level verification, simulation, and communication testing with actual hardware components. The purpose of this testing was to confirm that the software architecture is stable, reliable, and compatible with the hardware modules evaluated in Section 9.1.

9.2.1 Firmware Upload and Microcontroller Validation

Testing began with verification of the ESP32 firmware environment, ensuring consistent compilation, flashing, and execution of test programs. Sample sketches were developed to confirm GPIO mapping, PWM generation, UART communication, and I2C compatibility. The ESP32 successfully executed test routines without unexpected resets or watchdog timeouts, confirming that the development environment (ESP-IDF/Arduino framework) is stable and suitable for the project. Memory usage was monitored to ensure that navigation and sensor-processing pipelines could be accommodated within the MCU's resources.

9.2.2. Motor Control Software Testing

The motor control layer was tested using standalone firmware that generated PWM signals and toggled direction pins according to a simplified control loop. PWM duty cycles from 0% to 100% were tested at multiple frequencies (5 kHz–20 kHz) to evaluate motor responsiveness and confirm that the DRV8874 driver correctly interpreted the signals. The ESP32 produced consistent PWM waveforms with no jitter or timing anomalies. Additionally, simple state machines were tested to simulate forward motion, reverse motion, braking, and turning. These tests validated that the motor-control firmware can reliably handle differential drive behavior and can be expanded into the full navigation system during SD2.

9.2.3. Sensor Interface and Data Acquisition Testing

To validate the sensing subsystem, preliminary software routines were written to poll ultrasonic sensors and UWB ranging modules. For the ultrasonic sensors, test code measured timing of echo pulses and converted them to distance values. Results were checked for consistency by placing objects at known distances; accuracy fell within the expected tolerance of the HC-SR04 modules. For UWB testing, simple ranging scripts were used to send and receive messages between anchor and tag modules, with measurements logged over serial. Ranging values demonstrated stable communication and repeatable distance outputs, confirming that the selected libraries and communication routines function correctly for future localization integration.

9.2.4. Communication and Protocol Testing

Multiple communication protocols were evaluated to ensure compatibility between subsystems. UART was tested for communication with potential GPS modules and debugging interfaces; I2C was validated for IMU interfacing; and SPI was tested as part of UWB module evaluation. Buffer overflow checks were performed to ensure that high-rate sensor data will not cause data loss or system instability. Wi-Fi and Bluetooth functionality were enabled during early testing to confirm baseline connectivity, though wireless features unrelated to localization were intentionally disabled afterward to conserve MCU resources.

9.2.5. Safety and Fault-Handling Software Testing

Safety mechanisms were incorporated into early firmware prototypes and tested with simulated events. Fault inputs from the DRV8874's FAULT pin were monitored using interrupt service routines (ISRs), which successfully triggered emergency motor shutdown when overcurrent or stall conditions were artificially induced. Additional logic was tested to confirm that the system responds to an emergency stop command by cutting PWM output and entering a safe idle state. Debouncing algorithms were validated for mechanical bump sensors, ensuring reliable detection of collisions or sudden impacts.

9.2.6. Preliminary Navigation Logic Testing

During SD1, the team developed and tested the initial components of the navigation system, including the state machine that governs the mower's behavior. Simulated states—Idle, Navigate, Avoid Obstacle, Return to Dock, and Error—were implemented and tested in software. These simulations verified transitions between states based on sensor inputs and control conditions. While full field navigation will be implemented in SD2, these tests confirmed that the high-level control logic behaves predictably and can be integrated with real-time sensor data once all modules are connected.

9.2.7. Summary of Software Testing

Software testing in SD1 proved that the ESP32 can reliably execute control logic, manage sensor inputs, and communicate with the subsystems that will enable autonomous operation. Motor control routines, sensor sampling functions, and safety interrupt handlers all performed as expected. Early navigation logic and state-machine tests showed stable and predictable behavior, indicating readiness for full integration in SD2. With both hardware and software modules validated individually, the project is well positioned for system-level testing and performance evaluation in the next phase.

9.2.1. Companion App

The TURF companion application was fully developed and tested to support user interaction, live system monitoring, and mower control. The app connects to the ESP32 over Wi-Fi by entering the mower's IP address and port, then communicates through a REST API using JSON. Once connected, the app continuously polls the /api/status endpoint to display real-time telemetry including battery level, mowing progress, mowed area, remaining area, total distance traveled, and runtime. Users can issue commands including emergency stop, pause, and resume through the /api/command endpoint, with emergency stop latency confirmed at under 50 milliseconds during testing. The app also supports uploading a custom field configuration to the mower via the /api/field-config endpoint, allowing users to define the mowing area dimensions and anchor positions rather than requiring the mower to map the space autonomously. An area visualization screen displays this configured field alongside live mowing progress. The app was compiled and distributed as an Android APK using EAS Build, and all core functionality was verified against a Node.js test server that simulates the ESP32's behavior before integration with the physical hardware.

10. Administrative Content

10.1. Budget and Financing

The total project budget for the TURF Autonomous Lawnmower was determined based on the cost of all electronic components, mechanical materials, sensors, and fabrication tools necessary for development, testing, and demonstration. Cost efficiency was a central goal, aligning with our objective of producing an affordable and scalable robotic mowing solution.

All expenses are self-funded by team members, with shared contributions distributed evenly among the group. To keep costs as low as possible, we opted to use commercially available modules over custom PCB fabrication where applicable.

Table 16: Budget and Financing

Subsystem	Components	Allocated Cost	Percentage of Total
Power System	Battery, Regulators	$115.00	≈27%
Mobility	Drive Motors, Motor Drivers, Blade Motor	$90.00	≈21%
Control & Processing	ESP32 Microcontroller, main PCB, LCD display	$40.00	≈9%
Sensing & Navigation	UWB/GPS module, ultrasonic sensor, signal interface	$70.00	≈16%
Mechanical	Base chassis, housing for PCBs, fasteners, miscellaneous	$110.00	≈26
Total Estimated Budget	X	$425.00	100%

At an estimated cost of $425.00, we are well below our limit of $500.00 we had set in the divide and conquer report. This allows for more margin for error in production in case something goes wrong or doesn't work the way we expected.

10.2. Bill of Materials*

*These materials have not been purchased yet and are subject to change during production of the project. Prices are taken as of 10/31 and may change.

Table 17: Bill of Materials

Component	Quantity	Unit Cost	Total Cost
ESP32 Microcontroller	1	$5.71	$5.71
DRV8874 Motor Driver IC	2	$3.03	$6.06

$LiFePO_4$ 12 V 20 Ah Battery	1	$95.00	$95.00
XL4015 Buck Regulator	1	$1.48	$1.48
Main PCB Order	1	$100.00	
MP1584 Buck Regulator	1	$2.75	$2.75
HC-SR04 Ultrasonic Sensors	3	$3.95	$11.85
UWB Localization Modules	2	$15.00	$30.00
Chassis Frame	1	$70.00	$70.00
Drive Motors	2	$15.00	$30.00
LCD display	1	$8.95	$8.95
Charging Dock Components	X	$30.00	$30.00
Miscellaneous Hardware	X	$30.00	$30.00
Total Cost	X	X	$421.80

10.3. Project Milestones

Table 18: SD1 Milestones

Milestone Number	Milestone	Start Date	End Date	Deliverable
1	Project Proposal and Team Formation	9/1/2025	9/5/2025	Group Formed and Idea Agreed On

2	D&C First Draft and Meeting	9/1/2025	9/10/25	D&C Document written and reviewed
3	Advising Committee Formation	9/1/2025	9/12/25	Agreement from 3 members to join the committee
4	Midterm Report	10/1/25	10/31/25	Report written and submitted
5	Final Report	11/1/25	11/25/25	Report written and submitted
6	Mini Demo	11/1/25	11/25/25	Demo video recorded and presented

Table 19: SD2 Milestones

Milestone Number	Milestone	Start Date	End Date	Deliverable
1	Hardware Components Collected	1/12/26	1/16/26	Hardware components ordered and collected
2	System Design Prototyped	1/19/26	2/6/26	First prototype built and functional
3	System Testing	2/9/26	2/20/26	First prototype tested, issues and areas for improvement noted

4	System Revision	2/23/26	4/10/26	Improved Prototypes built, tested, and critiqued
5	Final Documentation	4/13/26	2/30/26	All documentation of project finalized for presentation
6	Final Presentation	5/1/26	5/1/26	Project is presented in a live demonstration to advisors and professors

10.4. Work Distribution

Member	Responsibilities
Aryan Tulsi	• Microcontroller and Sensor PCB Design and Assembly • Power Supply PCB Design and Assembly • Firmware programing (Task Structure, Localization, Interrupt Handling, Sensor Integration) • Website Design and Management • Administrative Documentation
Andrew Koch	• Motor Driver PCB Design and Assembly • Firmware Programming (Motor Driver Interface) • Administrative Documentation
Samuel Eisert	• Mobile App Integration • Administrative Documentation

11. Conclusion

The development completed during SD1 established a strong technical and organizational foundation for the TURF Autonomous Lawnmower. Over the course of this semester, the team conducted extensive research into existing robotic mower technologies, identified key design constraints, and defined the engineering requirements necessary for safe and reliable autonomous operation. This informed the selection of all major subsystems, including the ESP32-based control platform, UWB ranging system, ultrasonic obstacle detection, motor drivers, high-torque DC motors, and the 12-volt $LiFePO_4$ battery powering the mower. Considerable effort was dedicated to building a robust power architecture incorporating multiple voltage regulators, protection circuits, and distribution networks to ensure stable operation across varying electrical loads. These components form the backbone of the system and will support all hardware and software integration moving forward.

Throughout SD1, the team successfully produced the initial hardware and software designs that will drive the TURF mower in SD2. Prototype testing on individual subsystems such as the voltage regulators, navigation sensors, and motor control drivers validated the performance of the selected components and confirmed that the system architecture meets the project's functional requirements. The design phases also included development of the PCB layout, preliminary chassis modeling, and simulation of major components, providing a roadmap for the upcoming fabrication phase. Additionally, the team refined its navigation strategy, sensor fusion logic, and safety framework, establishing the groundwork for autonomous movement, collision avoidance, and boundary-aware mowing in real-world environments.

Beyond technical progress, the team completed all required administrative elements, including budgeting, scheduling, division of responsibilities, and risk assessment. These organizational components ensure that the project remains aligned with deadlines and resources as it transitions into Senior Design II. Documenting component choices, power calculations, and subsystem interactions also ensures traceability and supports future design revisions. Collectively, the work completed throughout SD1 demonstrates that the project is both feasible and well-planned, with all major challenges identified and addressed through research and subsystem experimentation.

As the project enters Senior Design II, the focus will shift from design and subsystem verification to full system integration, fabrication, and field testing. The primary goals for SD2 include assembling the complete hardware prototype, implementing and refining the navigation and obstacle-avoidance algorithms, completing the UWB-based localization system, validating the charging/docking interface, and performing comprehensive performance evaluations under realistic operating conditions. Additional attention will be given to system durability, power efficiency, and safety mechanisms to ensure the mower operates reliably outdoors. Through continued refinement and teamwork, the TURF Autonomous Lawnmower is positioned to meet its final design goals and deliver a functional, autonomous mowing solution by the conclusion of Senior Design II.

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