TURF

Turf Upkeep & Robotic Fieldcare

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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.

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)

- Use ultrasonic rangefinder to stop before obstacles

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.

2.4. 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.

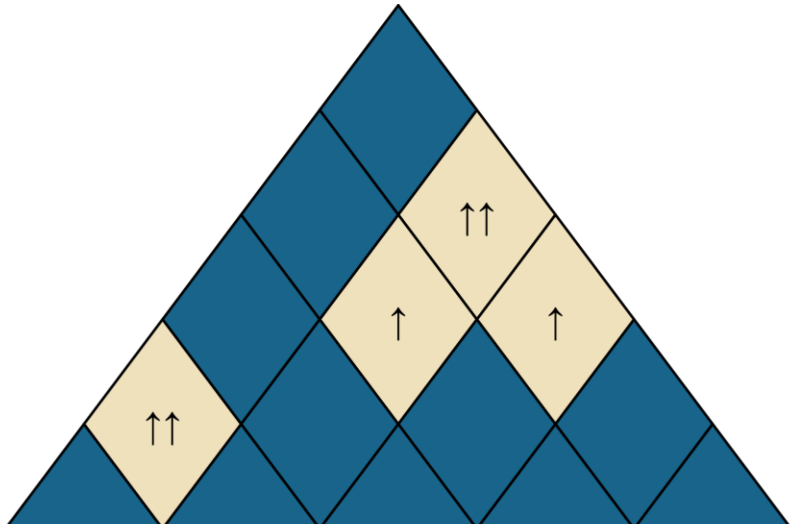
2.5. Engineering-Marketing Tradeoff Matrix

Table 2: 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 3: 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

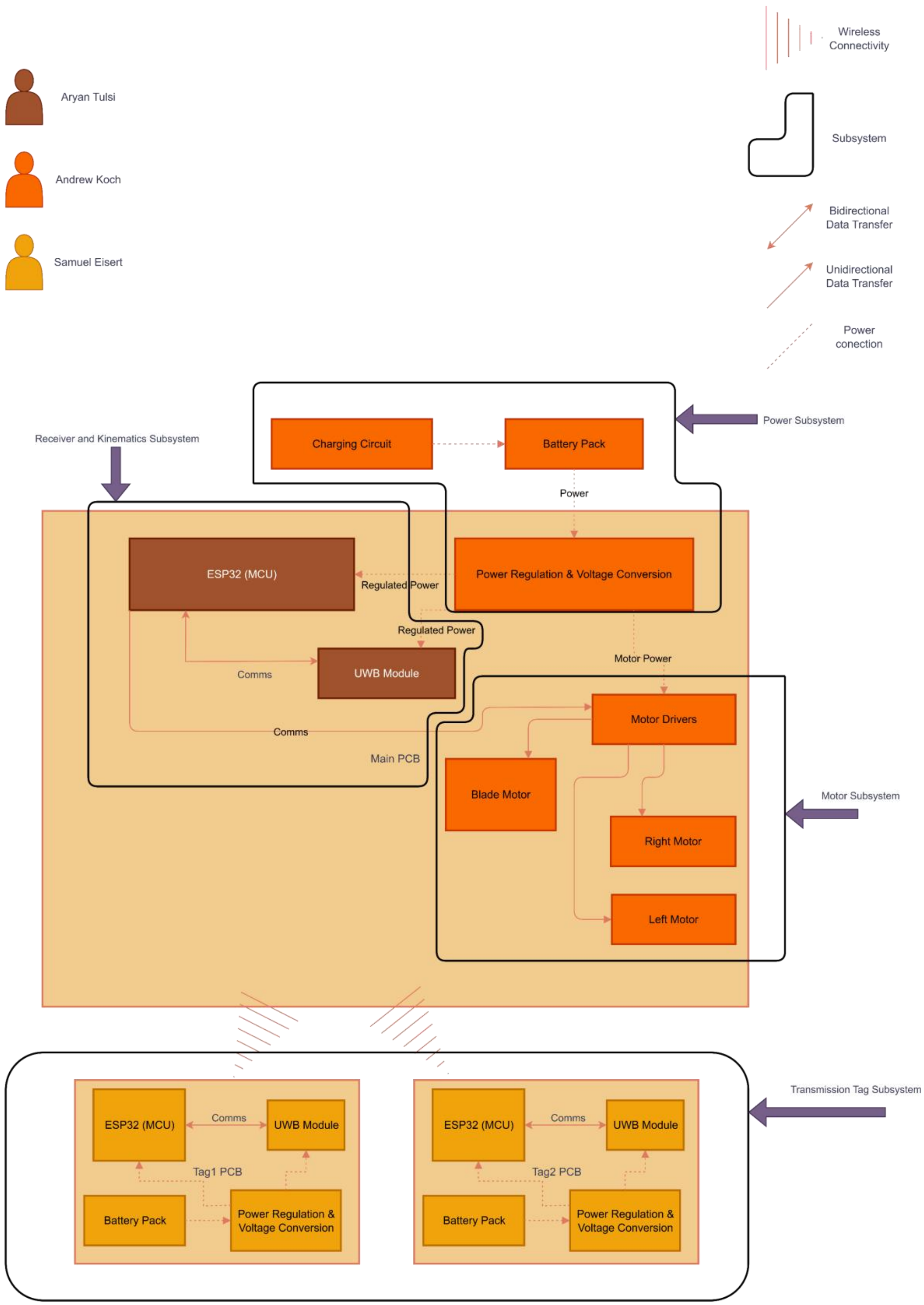


Figure 1: Hardware Diagram

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

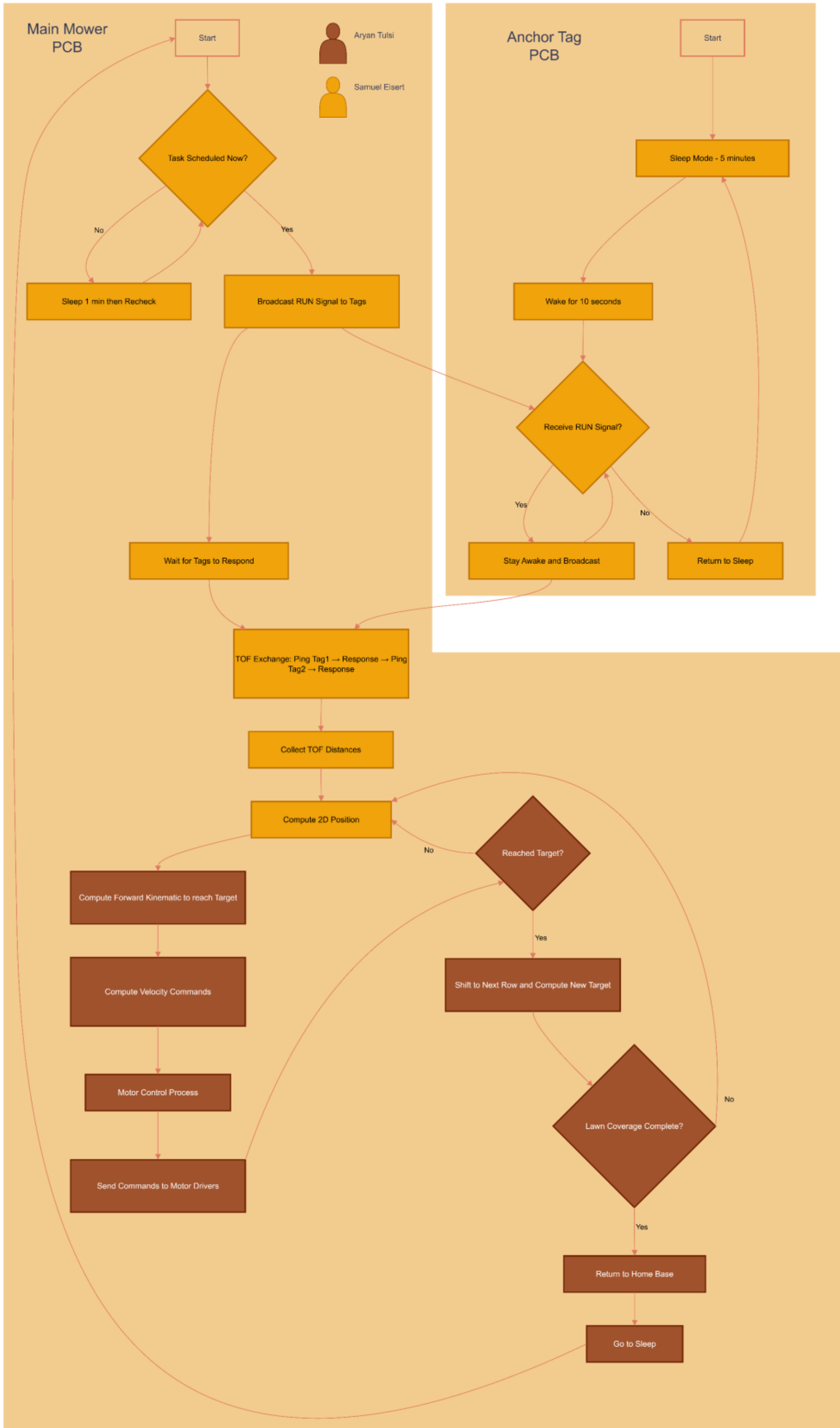


Figure 2: Software Diagram

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]

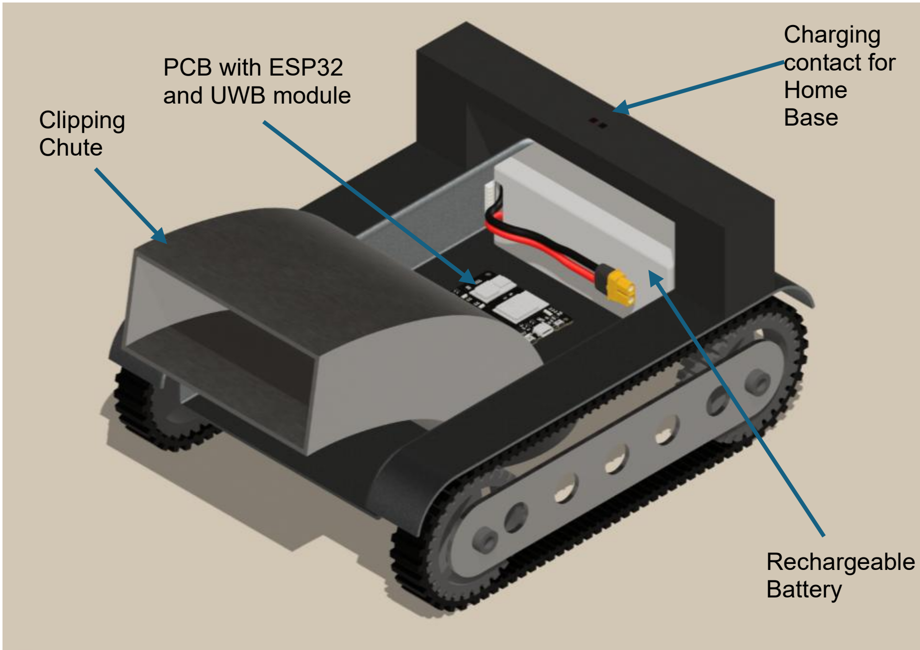


Figure 3: Top-Front-Left View

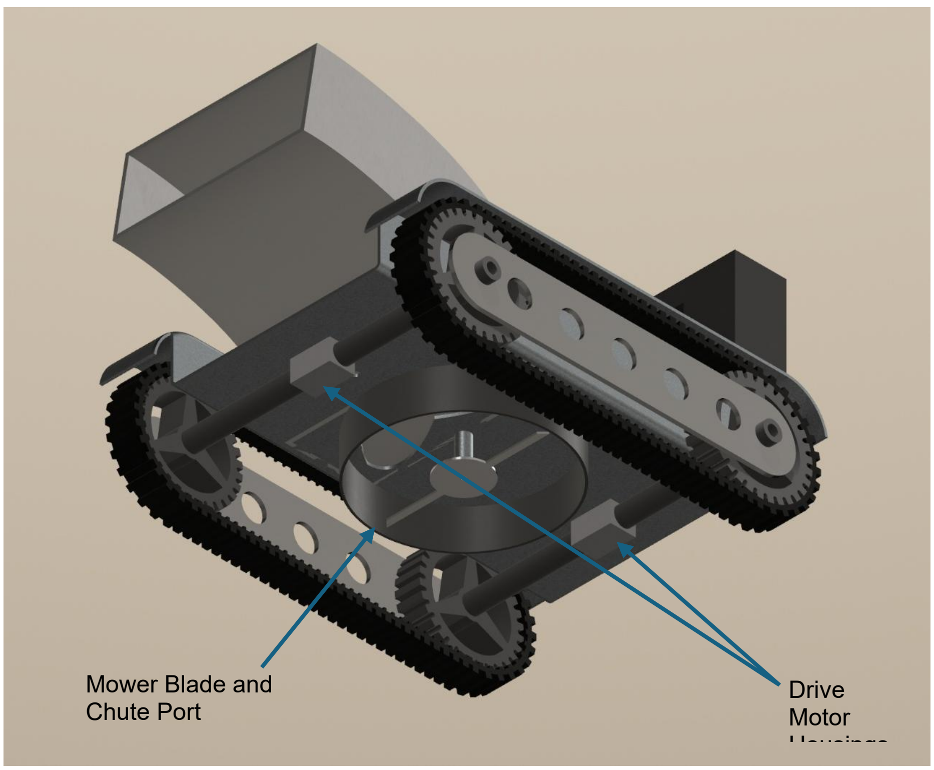


Figure 4: Bottom-Front-Left View

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

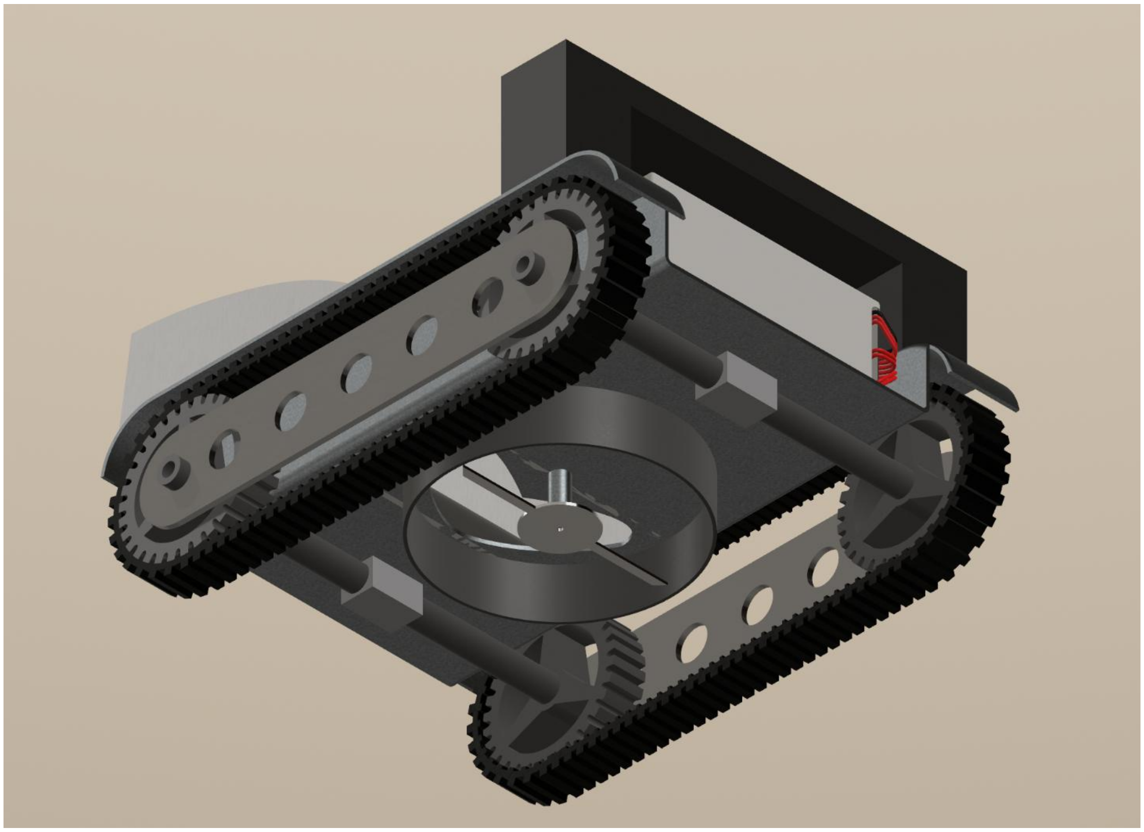


Figure 5: Bottom-Rear-Left View

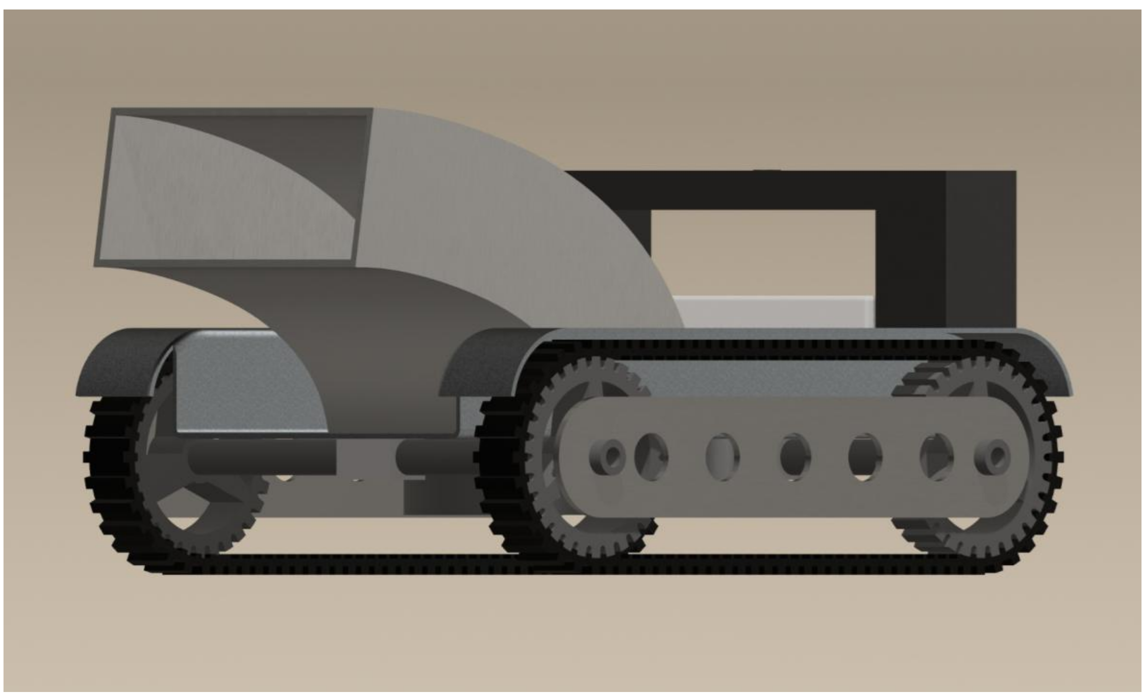


Figure 6: Front-Left View

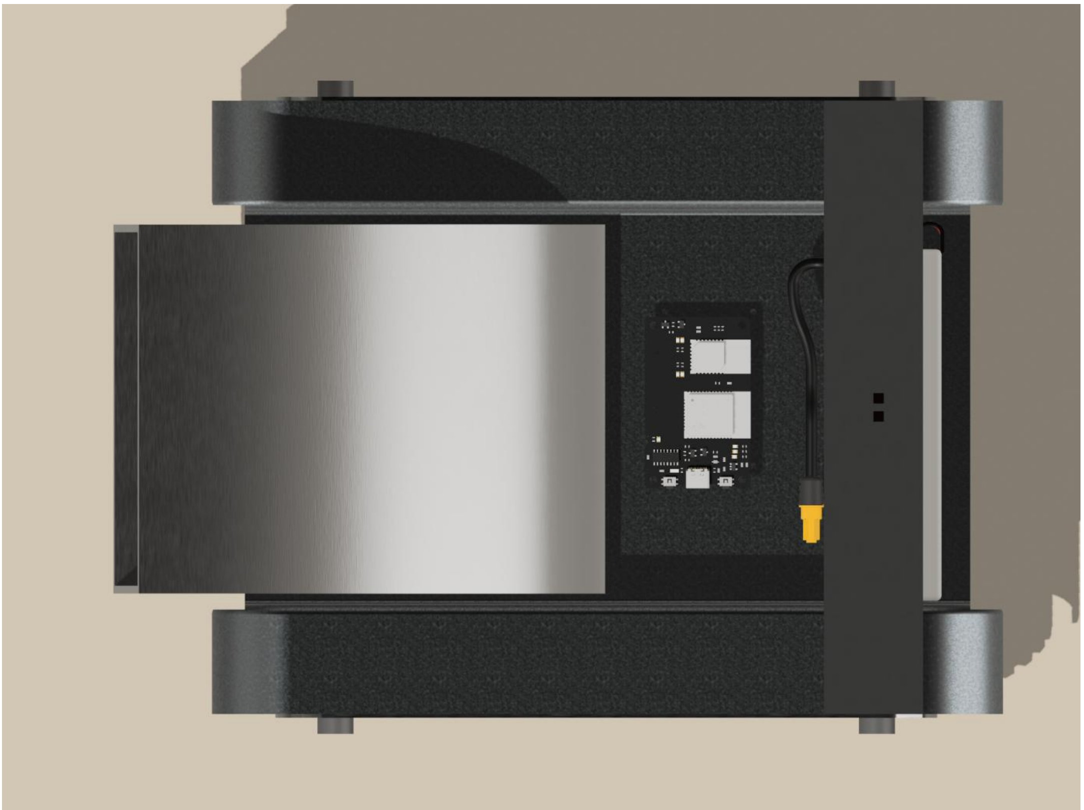


Figure 7: Top View

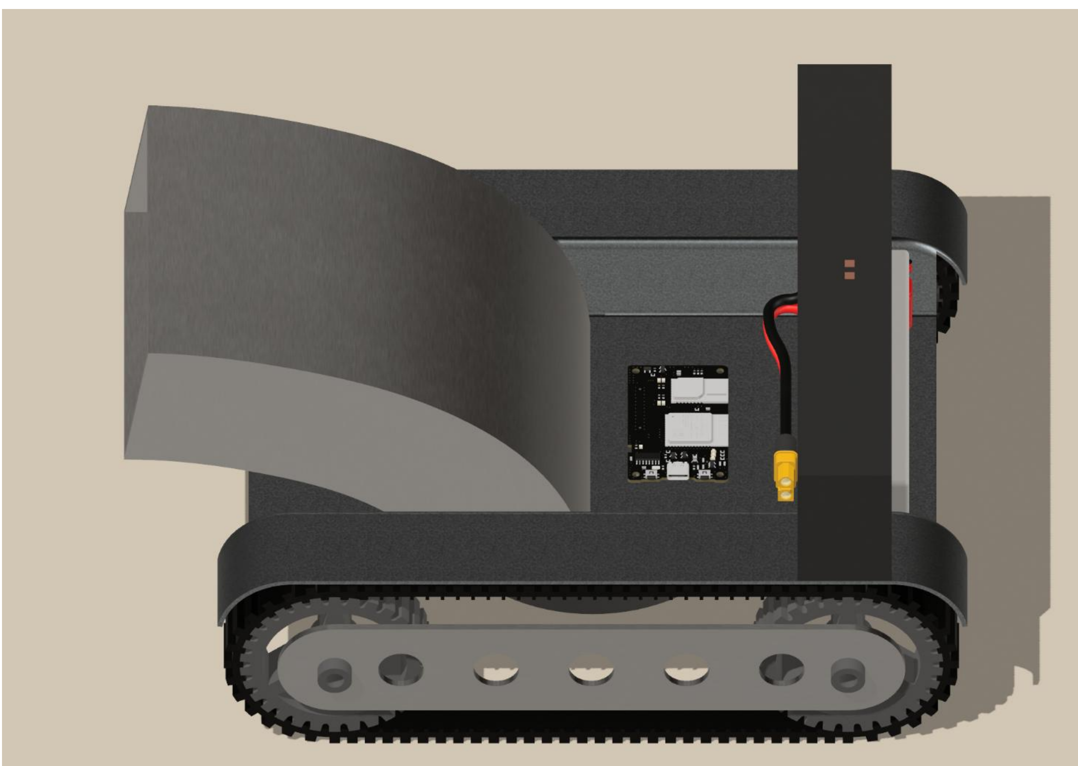


Figure 8: Top-Left View

3. Research and Investigation

3.1.1. 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 4: 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 5: 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

3.2.1. 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 6: 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 7: 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

3.3.1. 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 8: 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

3.4.1. 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 9: 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

3.5.1. Miscellaneous Support Circuitry

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

3.5.1.1. 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.

3.5.1.2. 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.

3.5.1.3 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.

3.5.1.4 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.

3.5.1.5. 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 10: 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 11: 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.

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.

4.2.1. 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.

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

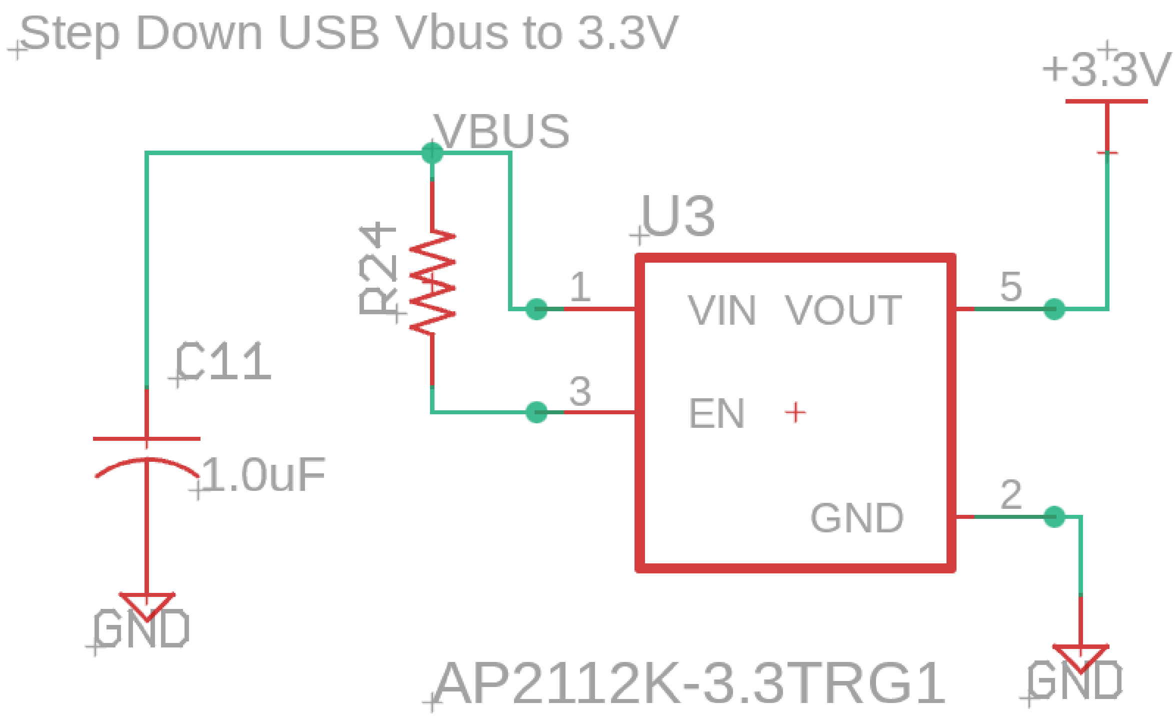


Figure 9: Vbus to 3.3V Schematic

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.

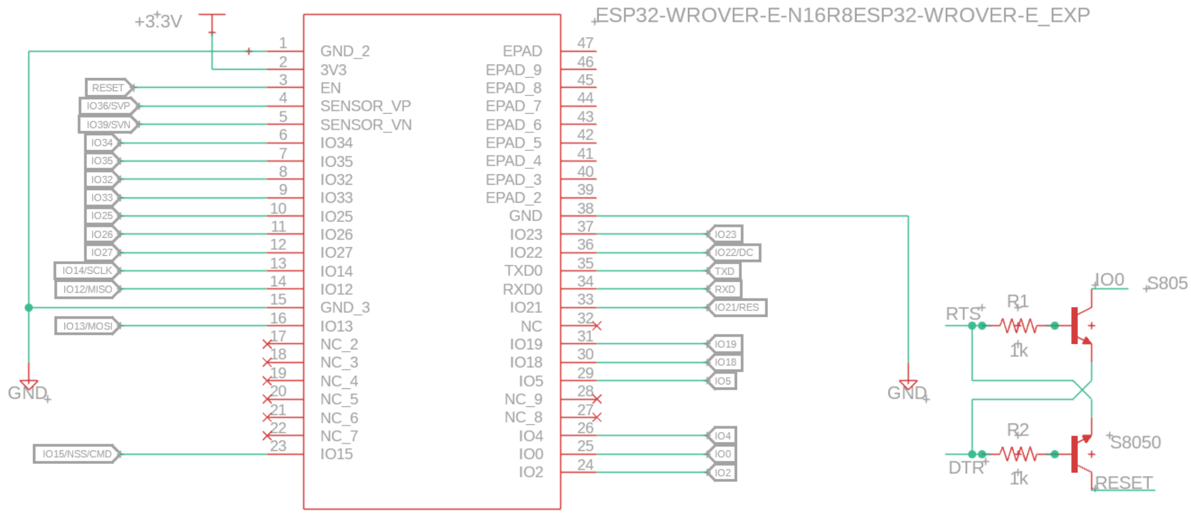


Figure 10: ESP32-WROVER-E Schematic

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.

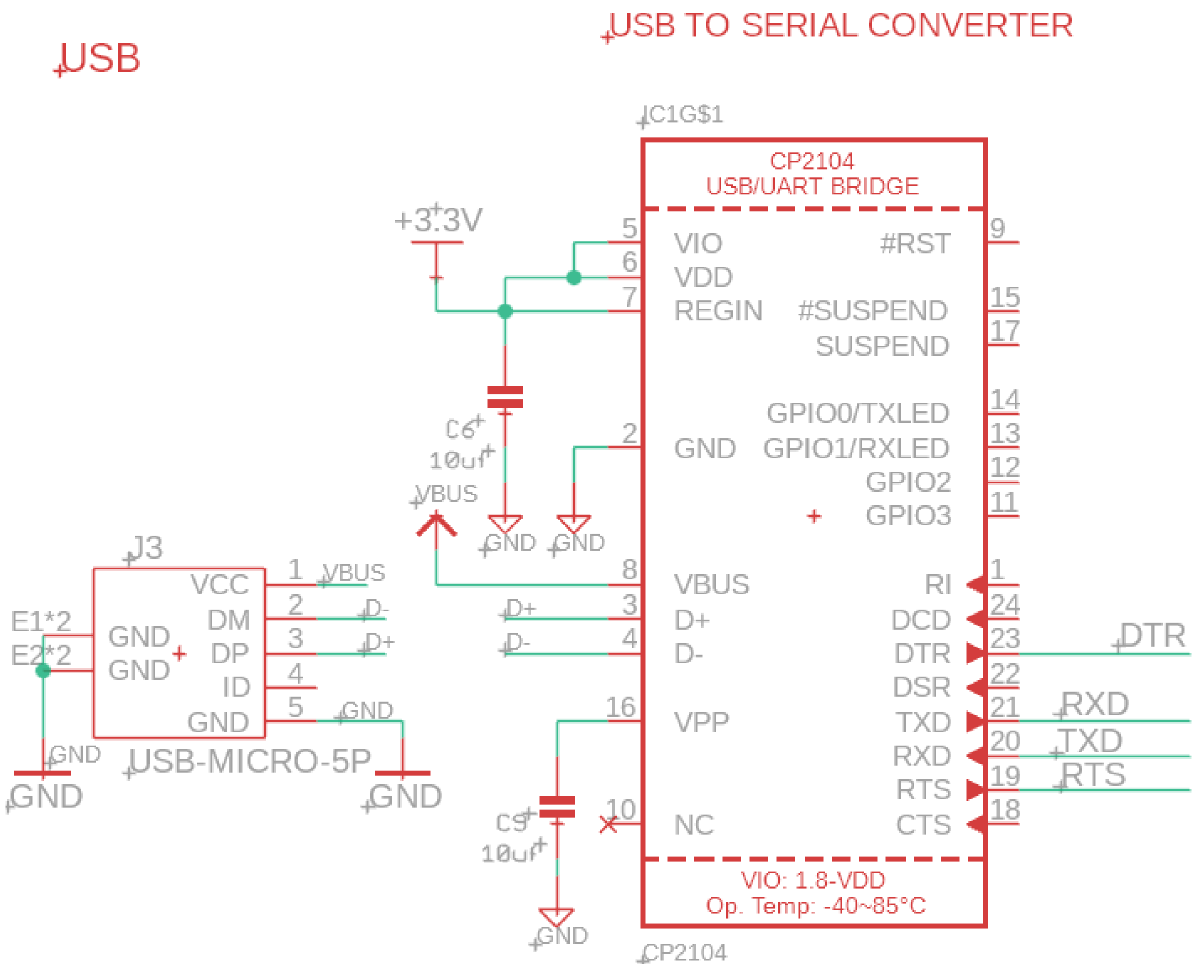


Figure 11: USB to Serial Converter CP2104

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.

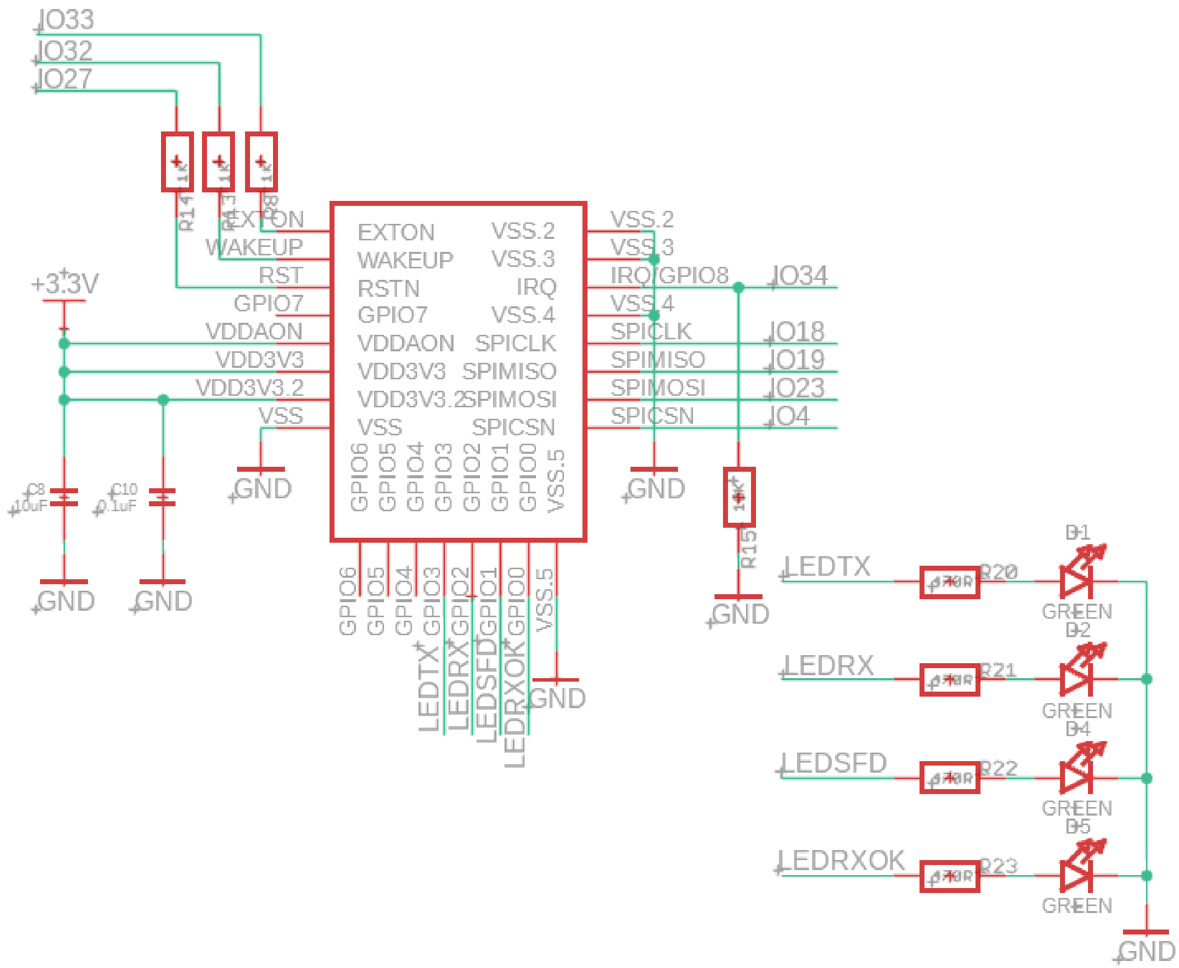


Figure 12: DW1000 Schematic and Support Circuitry

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 design includes 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, when the two devices may not be fully synchronized in their power-up states. 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, two decoupling capacitors, a bulk capacitor and a smaller high-frequency bypass capacitor, are connected close to the power pins of the DW1000 to stabilize the 3.3 V supply and minimize voltage ripple. In addition, 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.

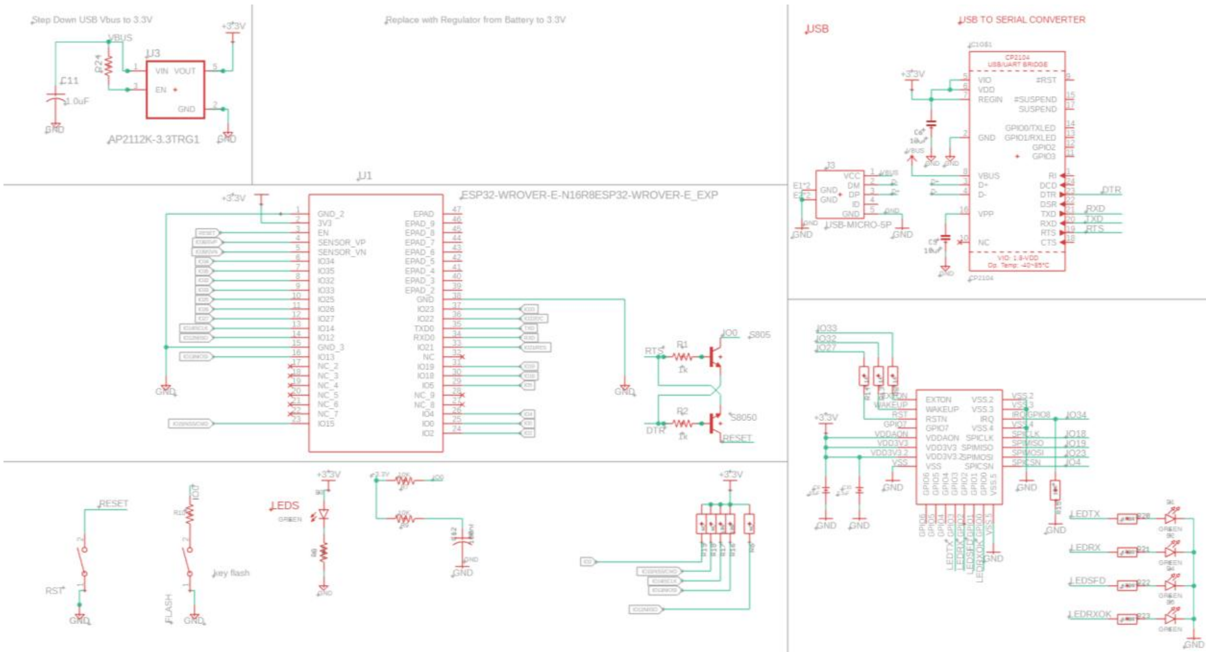


Figure 13: Current Receiver and Kinematics System Schematics

Figure 13: 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.

7. Software Design – Automated Lawnmower Project

7.1. Overview

The software system for the Automated Lawnmower Project integrates multiple autonomous functionalities, including localization, path planning, motion control, communication, safety, and user interface management, into a modular embedded architecture. Its primary objective is to allow the mower to operate autonomously within a user-defined area, executing a precise mowing pattern without human intervention, while simultaneously maintaining energy efficiency and operational safety. Triangulation-based localization using Ultra-Wideband (UWB) signals from three stationary anchor nodes enables the mower to determine its real-time position accurately, which is critical for avoiding missed spots, redundant coverage, or collisions with obstacles. A complementary mobile application provides users with the ability to define mowing areas, schedule tasks, monitor progress, and trigger emergency stop functions. The modular design also allows for future enhancements, such as integrating additional sensors, alternative path planning methods, or advanced AI-based obstacle detection, without requiring significant changes to the existing system. 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 software architecture consists of six primary subsystems: localization, path planning, motion control, anchor communication, safety and interrupt handling, and user interface. The **localization module** computes the mower's real-time position based on distance measurements from the anchors and applies a triangulation algorithm to derive (x, y) coordinates. This module also incorporates filtering and validation mechanisms to compensate for signal noise, multipath effects, or temporary anchor failure. The **path planning module** generates a boustrophedon path, which is an efficient back-and-forth coverage pattern that guarantees complete coverage of the defined area. Alternative path planning approaches, such as spiral or random coverage, were considered; spiral patterns reduce turns but are less efficient for rectangular areas, while random coverage ensures flexibility in irregularly shaped areas but increases overall mowing time. The chosen boustrophedon method represents a trade-off: it maximizes coverage efficiency in rectangular areas but requires precise localization and obstacle handling.

The **motion control module** receives positional data and waypoints, translating them into motor commands while compensating for factors such as wheel slippage, terrain variability, and heading deviations. The **anchor communication module** manages UWB interactions, including periodic ranging, wake/sleep cycles, and error recovery. The **safety module** monitors sensor inputs and interrupts normal operation if unsafe conditions are detected, enforcing lift detection, collision response, and boundary violation prevention. Finally, the **user interface module** enables the mobile application to configure the mower, monitor its status, and receive alerts. Figure 7.1 depicts the subsystem architecture, showing both functional modules and data flows, highlighting how software components interact to enable autonomous operation.

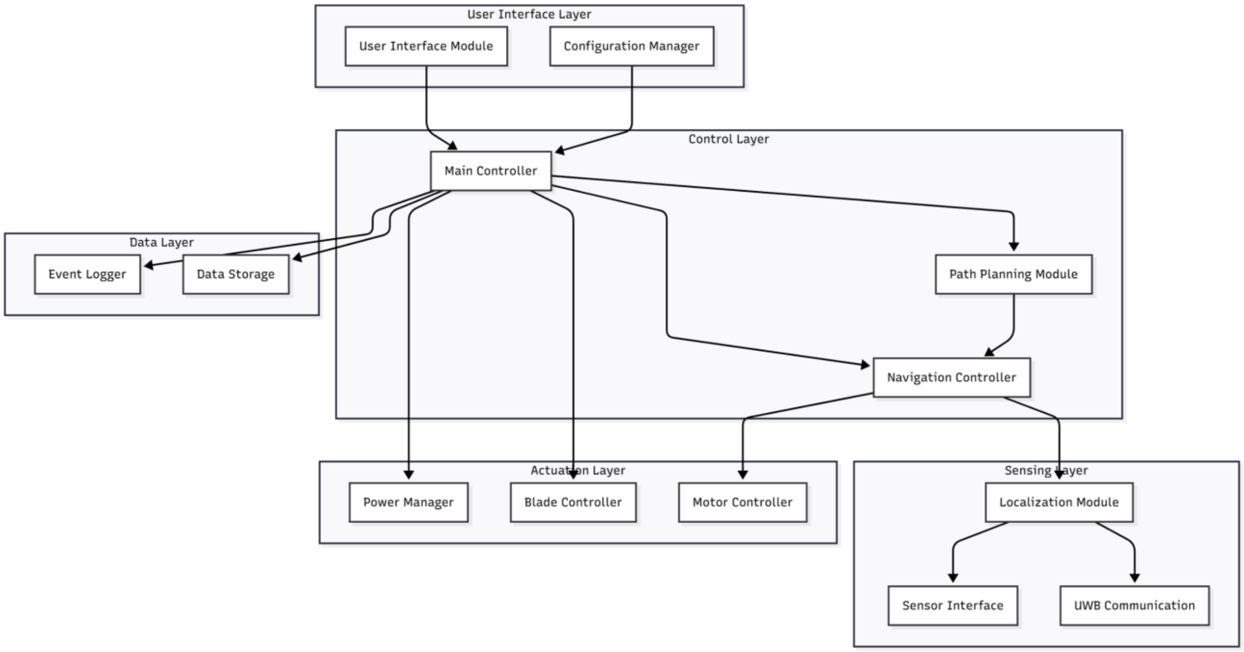


Figure 14: Software Architecture

7.3. Data Flow

Data flows cyclically among modules to maintain accurate, real-time operation. Anchors broadcast timing pulses, which the mower uses to calculate distances via UWB round-trip time. These measurements are sent to the **localization module**, which computes the mower's position while compensating for measurement noise and occasional signal loss. The **path planning module** then determines the next waypoint along the boustrophedon path, taking into account both completed rows and obstacle avoidance adjustments. The **motion control module** calculates precise motor commands to navigate toward the waypoint, dynamically correcting for deviations caused by terrain, wheel slippage, or external disturbances such as wind or uneven ground.

The **safety module** continuously monitors sensor inputs. For example, if a sudden obstacle appears mid-path, the bumper sensor triggers an interrupt to halt the mower immediately, overriding the planned path. Similarly, if the mower is lifted off the ground, the lift sensor triggers an emergency stop to prevent injury or hardware damage. Data on position, battery level, and operational status are simultaneously transmitted to the mobile application, providing real-time monitoring and alerts. Figure 7.2 illustrates this data flow, emphasizing how information moves between anchors, localization, path planning, motion control, safety, and the mobile application.

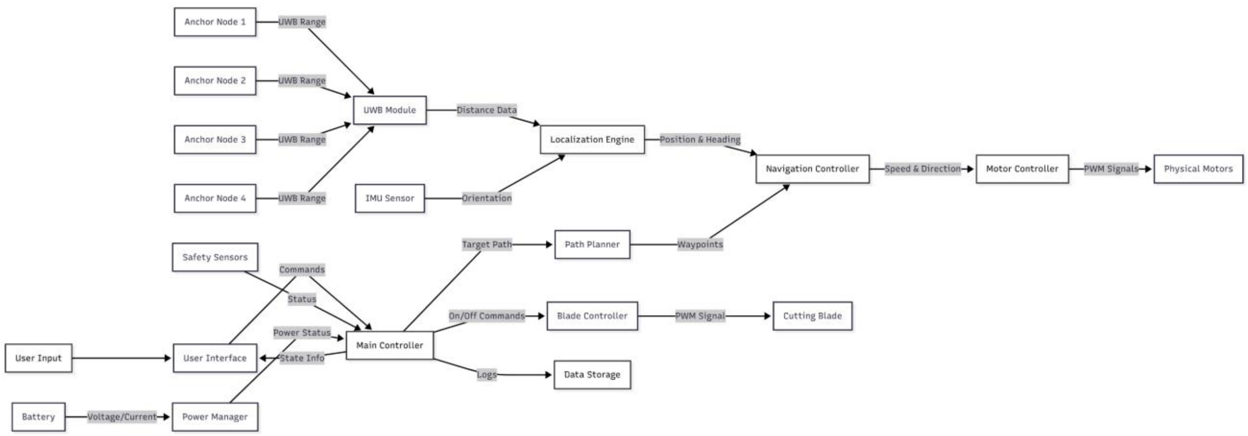


Figure 15: Data Flow

7.4. Localization Algorithm

Localization is central to accurate autonomous operation. The algorithm relies on triangulation using distances from three anchors to compute the mower's (x, y) coordinates. Each anchor defines a circle with a radius equal to the measured distance, and the intersection of these circles determines the mower's position. The algorithm incorporates error handling strategies, such as ignoring measurements that result in mathematically invalid intersections and performing weighted averaging to mitigate the effect of outliers. This ensures reliability even in challenging conditions, such as when signals are partially blocked by obstacles or reflective surfaces create multipath errors.

Localization frequency represents another design trade-off: high-frequency updates provide more precise navigation but increase computational load and power consumption, whereas low-frequency updates reduce resource usage but risk trajectory deviation. The chosen update interval balances accuracy, real-time control, and energy efficiency. Figure 7.3 presents a flowchart of the localization process, from distance measurement to position output.

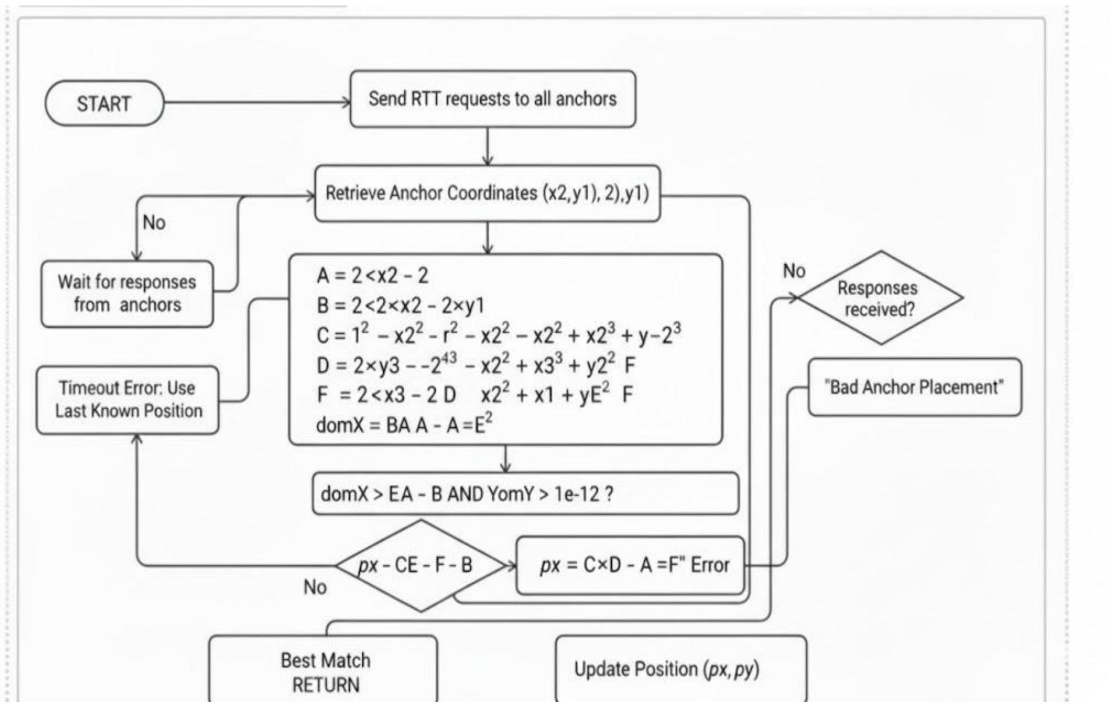


Figure 16: Localization Algorithm

7.5. Anchor Node Behavior

Anchor nodes operate in setup, sleep, and broadcast states. Setup mode allows initial configuration via the mobile application and physical button triggers. Sleep mode conserves energy, waking periodically to detect wake-hold signals from the mower. Broadcast mode is active during mowing operations to respond to ranging requests. Anchors store configuration in non-volatile memory, preserving operational readiness even after power loss.

State transitions between these modes incorporate trade-offs between energy efficiency and responsiveness. For instance, a short sleep interval increases responsiveness but consumes more energy, while longer intervals save power but risk delays in localization updates. Figure 7.4 shows the anchor state diagram.

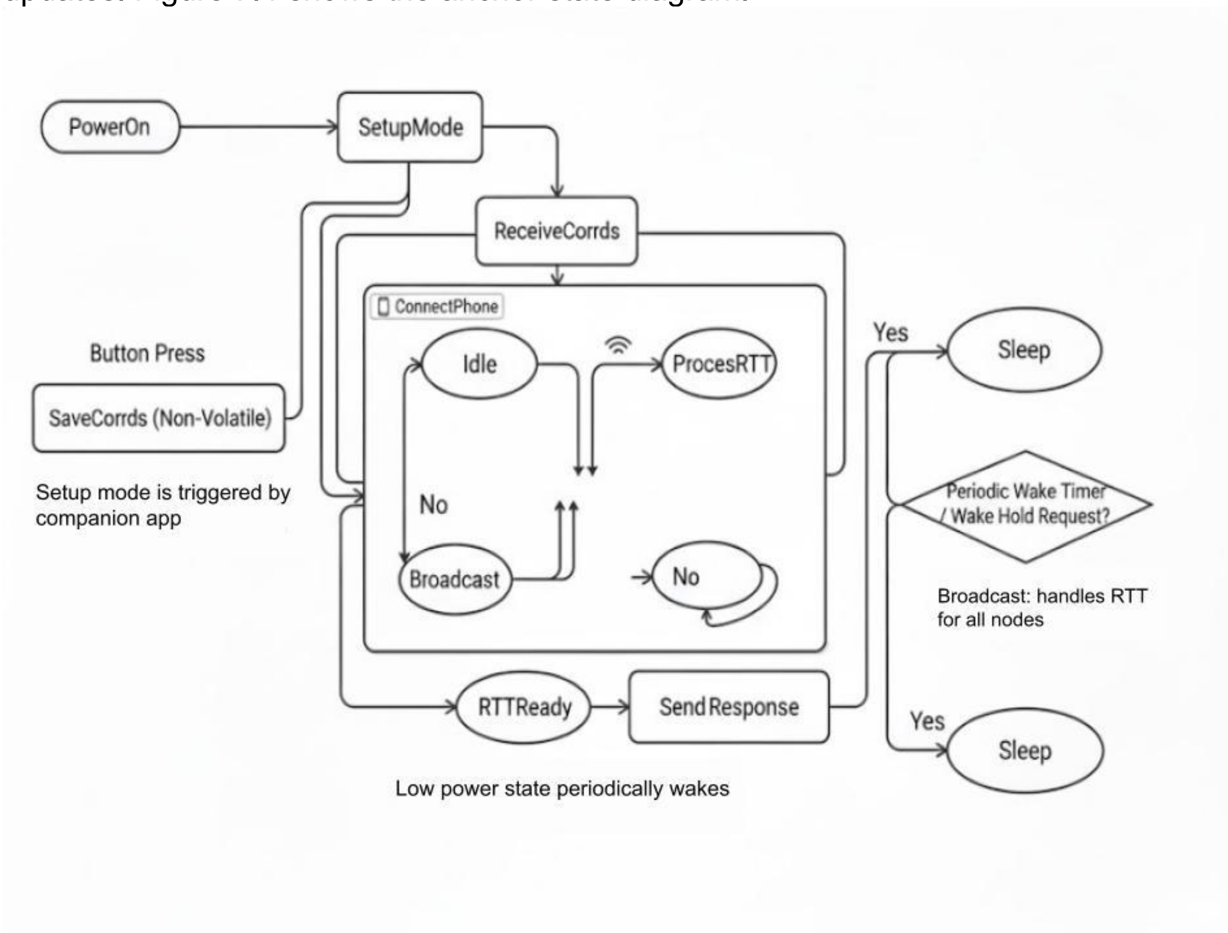


Figure 17: Anchor Node Behavior

7.6. Mower Control Functions

The mower integrates setup, sleep, localization, and running functions. Setup creates a Wi-Fi hotspot for configuration, allowing scheduling, area definition, and anchor pairing. Sleep conserves power while periodically checking for scheduled tasks. The localization function provides real-time positioning for accurate path following. During running, the mower broadcasts wake-hold signals, navigates to the starting location, and follows the boustrophedon path.

Safety interrupts override standard operation during hazardous conditions. For example, if a child steps into the mowing area mid-operation, the bumper or optical sensor triggers an immediate stop. Lift detection prevents injury or mower damage if the unit is picked up. Boundary monitoring ensures the mower does not exit its designated area, even in GPS-denied environments. Figure 7.5 shows the mower control flow, including transitions between setup, sleep, active mowing, safety interrupts, and return-to-home functions.

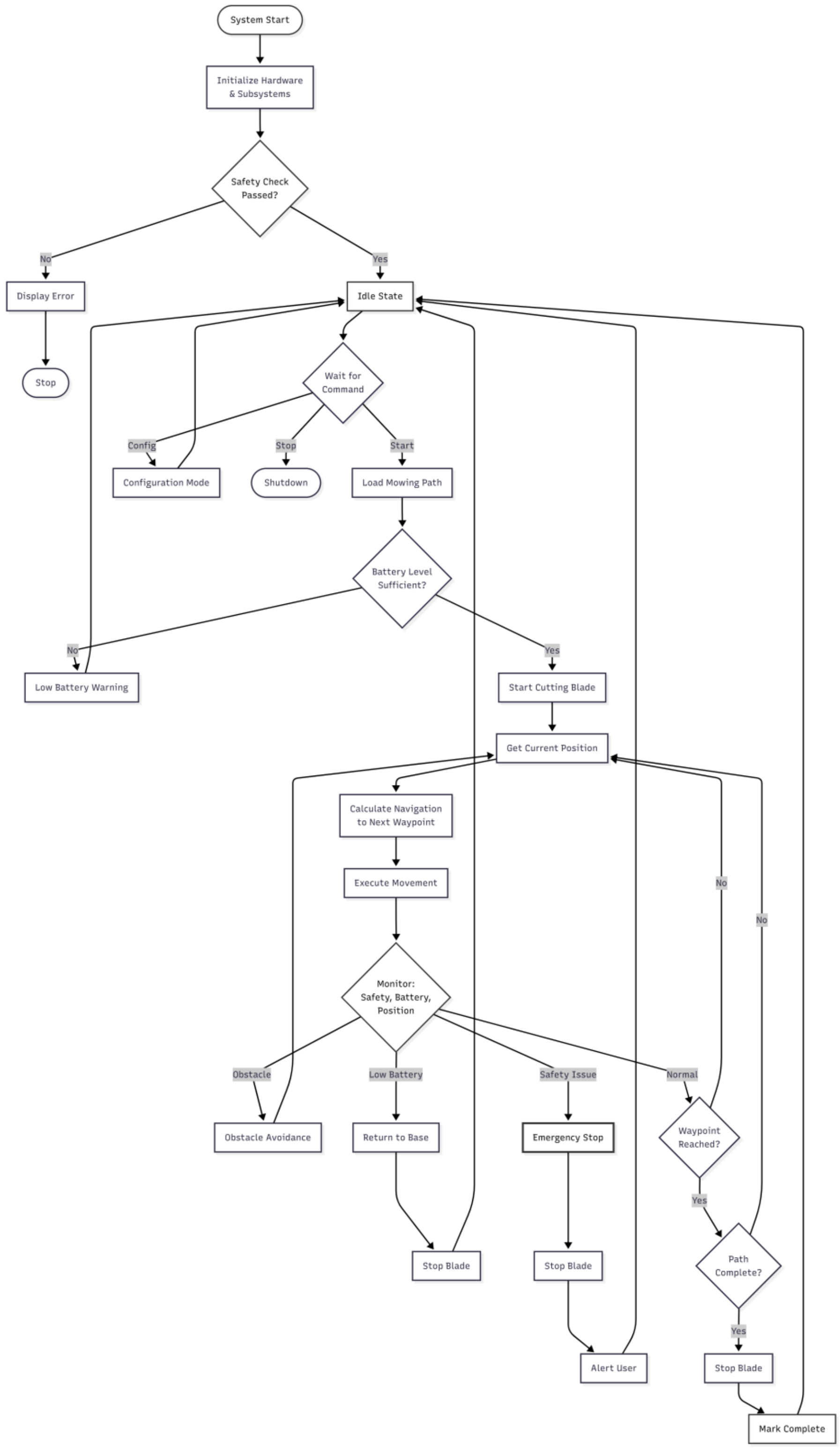


Figure 18: Mower Control Functions

7.7. Path Planning

Path planning ensures efficient area coverage using a boustrophedon method. The system divides the mowing area into parallel rows based on cutting width and generates sequential waypoints at row ends. Alternative path planning methods were considered, including spiral and random coverage. Spiral paths minimize turning but are less efficient for rectangular areas, whereas random paths provide flexibility for irregular shapes but increase total runtime. Boustrophedon was chosen for its predictability, efficiency, and ease of implementation given precise localization.

Waypoint following incorporates dynamic adjustments: if an obstacle temporarily blocks a row, the mower can recalculate a short detour and resume the original path, ensuring coverage continuity. Figure 7.6 shows the path planning and waypoint-following flowchart.

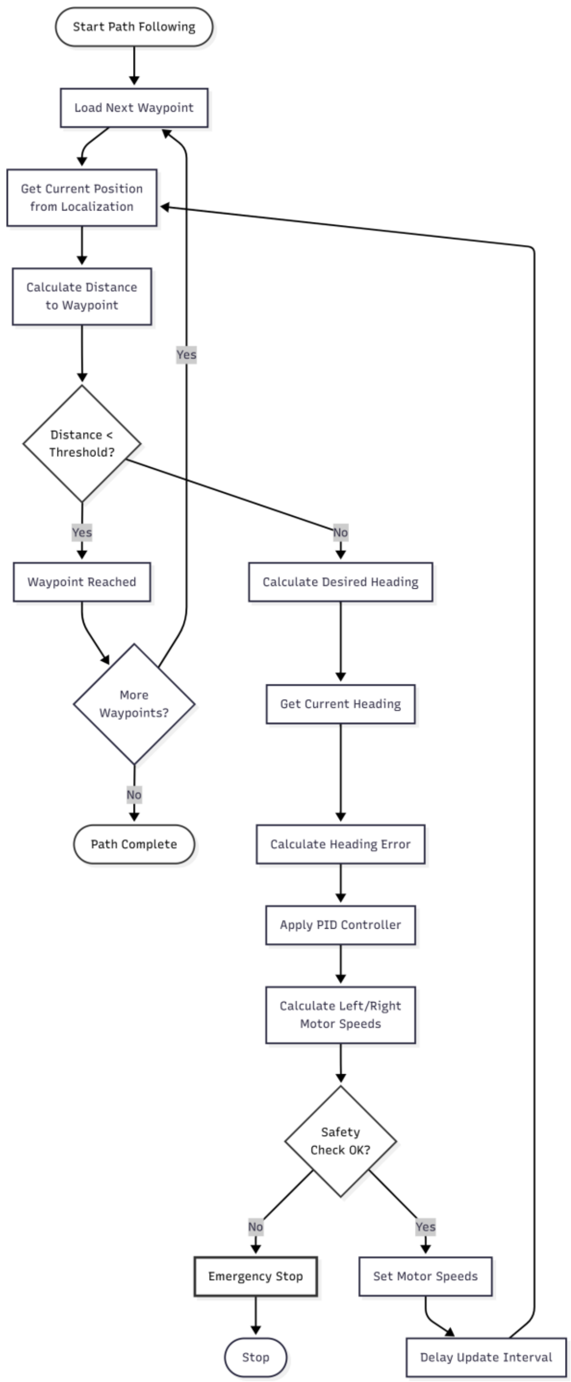


Figure 19: Path Planning

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.

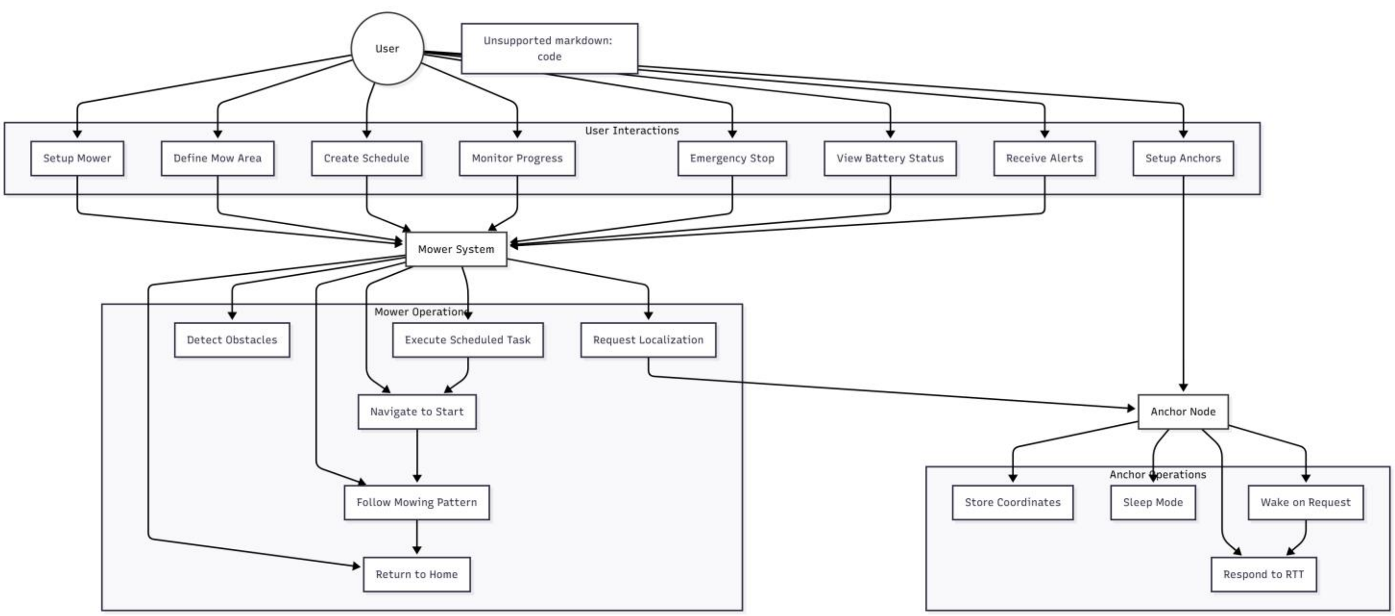


Figure 20: User Interface

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.

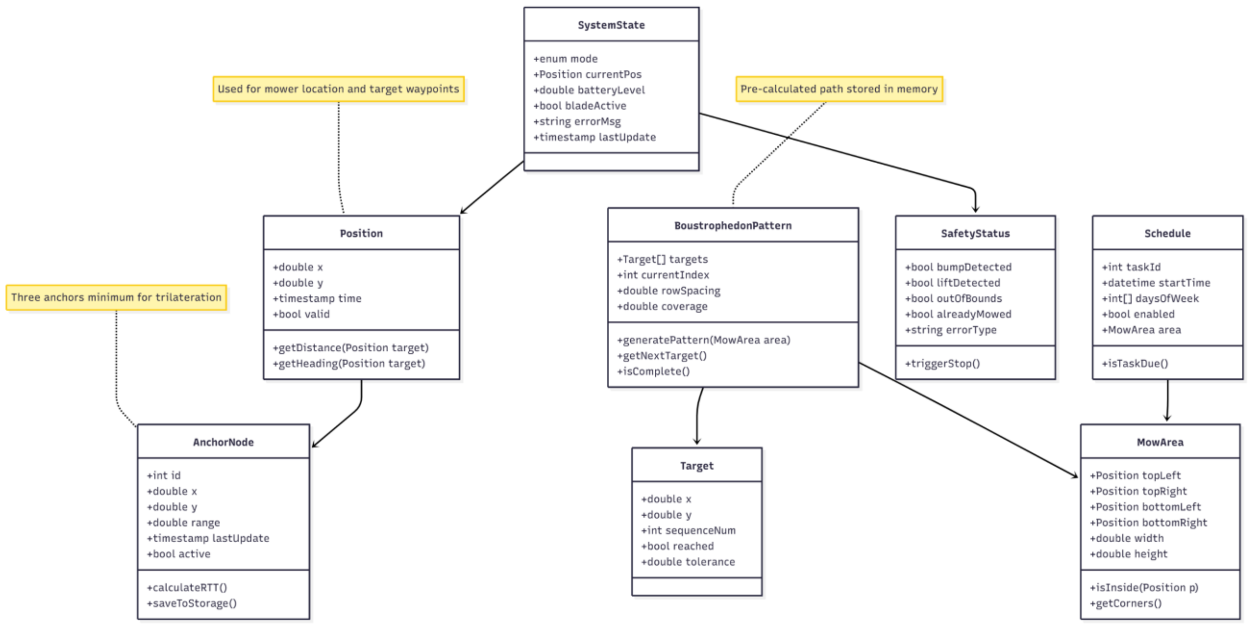


Figure 21: Key Data Structures

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.

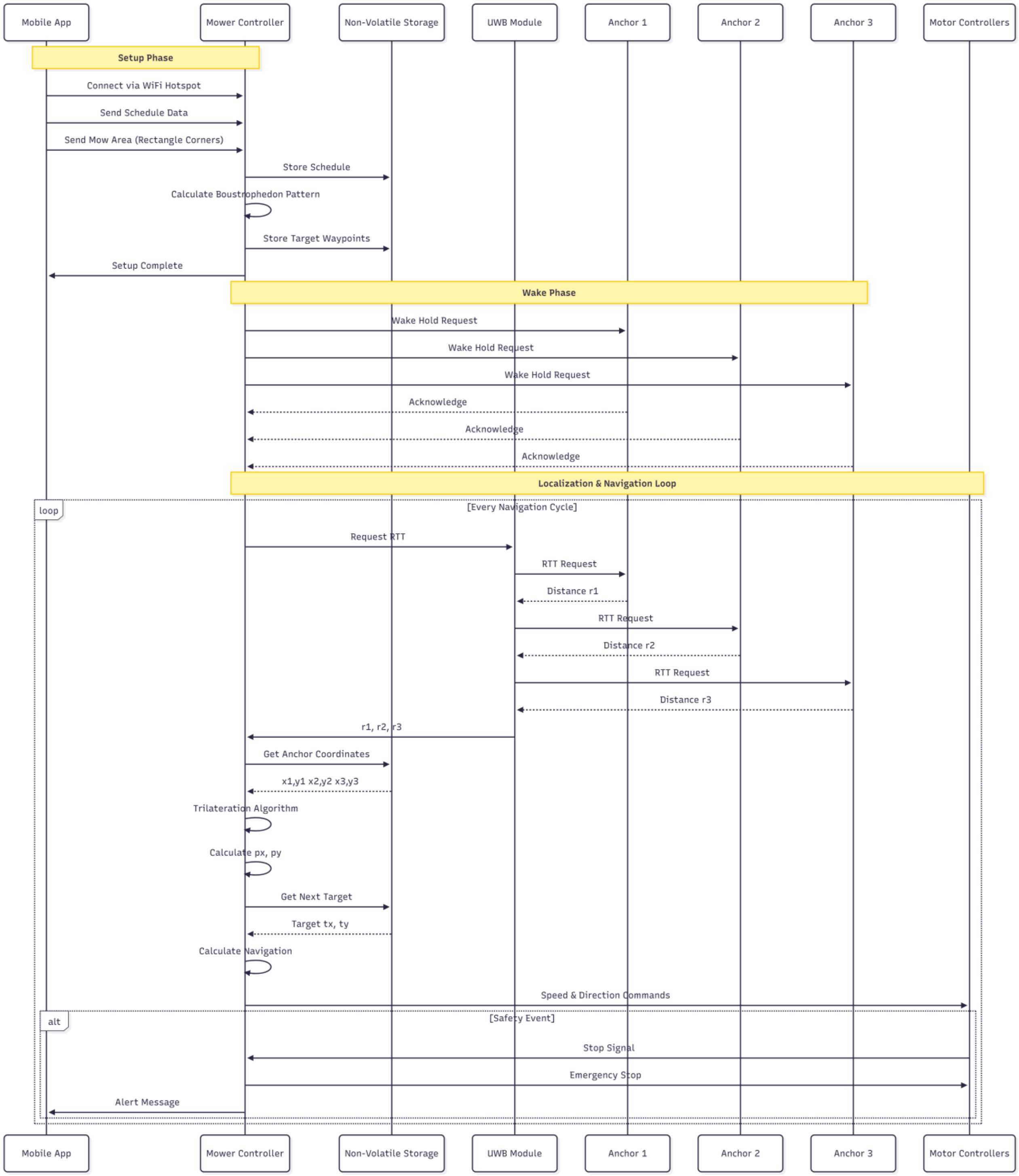


Figure 22: Data Communication

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.

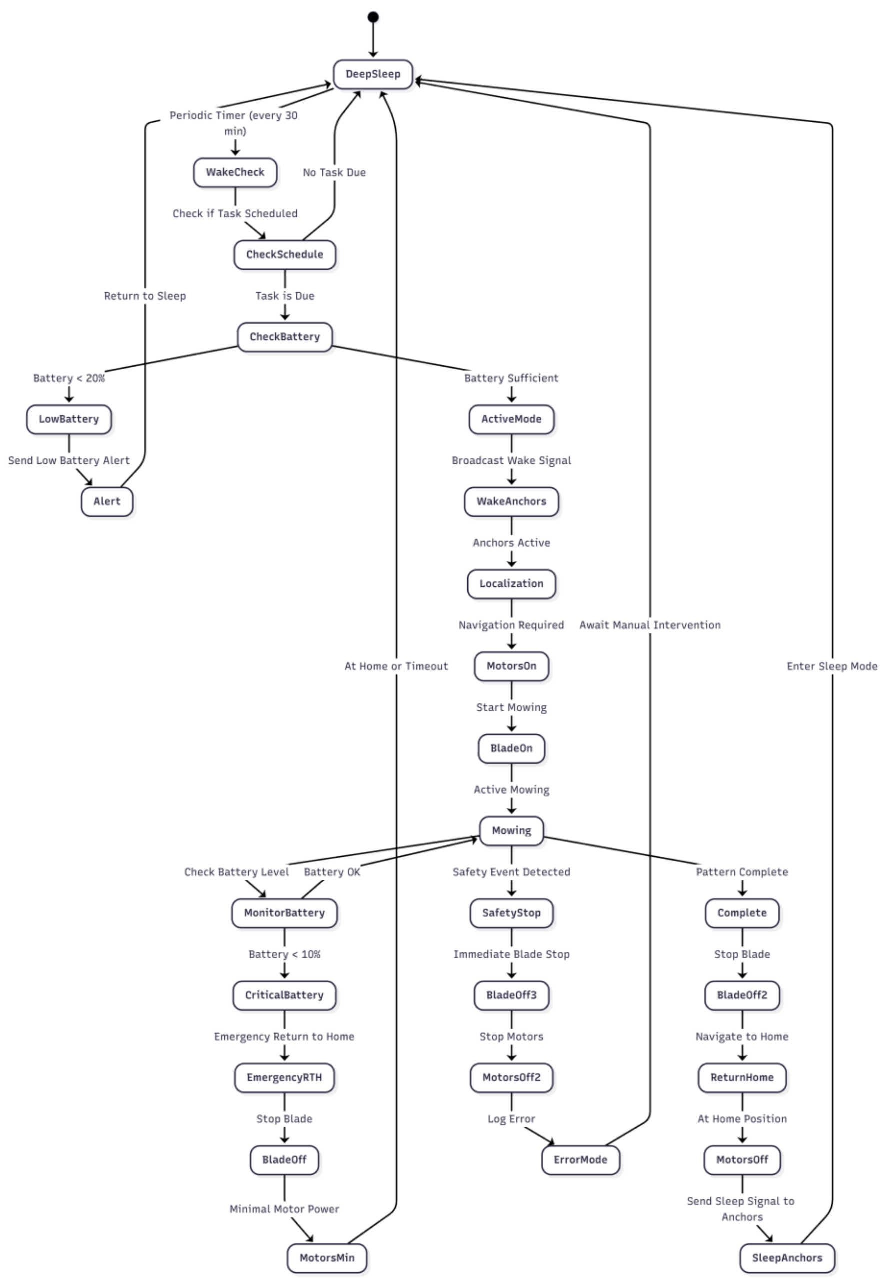


Figure 23: Power Management

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.

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 12: 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 13: 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 14: 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 15: 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

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