

RC Lawn Mower



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Chapter 1 – Executive Summary [1] written by Roman Luknicki

The Remote-Controlled (RC) Lawn Mower presented in this report represents a thoughtful, forward-looking re-imagining of everyday residential lawn-care equipment. Conceived, planned, and constructed by a multidisciplinary cohort of senior engineering students, the machine takes the familiar form of a rideable mower and fuses it with contemporary electric-drive technology, robust remote-control architecture, and an integrated safety philosophy. In doing so, the project showcases not only the practical application of classroom theory but also the collaborative design culture fostered within the College of Engineering and Computer Science at the University of Central Florida.

At its core, the platform is built upon a carefully modified Greenworks 25322 battery-powered chassis chosen both for its environmentally friendly 40 cm (16 in.) cutting deck and for the structural integrity of its stamped-steel frame. Four matched high torque brushed DC drive motors are mounted to the chassis and paired with motor controllers, delivering the tractive effort required to maneuver the mower smoothly across typical suburban grass and moderate inclines. All four motor controllers' interface with an ER8 2.4 GHz receiver, enabling precise proportional control over speed and steering inputs issued from a standard hobby-grade transmitter.

Power distribution and on-board protection were deliberately engineered to exceed the current demands of both the drivetrain and the low-voltage logic chain. A custom 24 VDC bus, sourced from two series-connected lithium-ion battery packs, feeds dual rails: a high-current rail for motor operation and a regulated rail for the processor, radio receiver, and sensor modules. Thermal fuses and resettable snap-action circuit breakers are inserted at strategic nodes to protect wiring, connectors, and semiconductor devices from transient surges or prolonged overloads. These devices reset automatically once fault conditions have cleared, minimizing downtime during field testing.

Safety considerations extend beyond electrical protection to incorporate active obstacle detection. A perimeter of wide-beam ultrasonic rangefinders continuously samples the mower's surroundings, instantly relaying distance data to the microcontroller whenever an object encroaches upon a predefined hazard envelope. If an obstacle or bystander is detected within that envelope, the firmware commands an immediate motor shut off and applies electronic braking torque. Although the present prototype relies exclusively on ultrasonic sensing, the architecture reserves bandwidth and processor overhead for future expansion specifically, real-time video streaming and autonomous path-planning modules that can be fitted without disturbing the existing control stack.

This report chronicles the end-to-end development of the mower, beginning with the definition of functional requirements and moving through component selection, CAD modeling, printed-circuit-board design, firmware development, integration, iterative testing, and standards compliance. Each chapter highlights trade-off

analyses that guided part sourcing and design revisions, while appendices catalog test results validating performance against the original engineering specifications. Moreover, the document captures the learning curve of every team member: mechanical, electrical, computer, and systems engineers alike broadened their technical expertise while honing soft skills in project management, procurement, documentation, and cross-disciplinary communication.

Ultimately, the RC Lawn Mower stands as a tangible demonstration of the team's ability to translate theoretical knowledge into a polished, fully functional prototype. By combining a commercially proven mower deck with custom driveline electronics, comprehensive fail-safe mechanisms, and a clean expansion path for autonomous operation, the project illustrates a practical roadmap for modernizing small-scale lawn equipment while upholding contemporary expectations of sustainability, operator convenience, and, above all, safety.

Chapter 2 – Project Description

2.0 Summary [1] written by Roman Luknicki

In this chapter we lay the groundwork for our RC Lawn Mower by first explaining *why* it matters. Section 2.1 sketches the history of residential mowing and the recent shift toward electric, hands-free solutions, while 2.15 describes our personal motivation—saving time, boosting safety, and proving that three college seniors can turn a weekend chore into an engineering capstone. Next, 2.2 surveys existing remote or robotic mowers, highlighting where they fall short in affordability, user control, or fail-safe design. Section 2.3 then lists our concrete goals: the primary goals of building a ride-optional, radio-controlled mower with reliable obstacle shutdown, and the stretch goals of leaving hooks for future autonomy and live camera streaming. In 2.4 we give a plain-language tour of the drivetrain, power system, sensors, and control electronics so readers know what each part does at a glance. Finally, 2.5 defines our target users which happen to be homeowners, yard-care businesses, and anyone with limited mobility and walks through common use-case scenarios, from trimming a small suburban lawn to safely tackling sloped backyards. Together, these sections set the context and expectations for the detailed engineering that follows.

2.1 Background [1] written by Roman Luknicki

The lawn mower dates all the way back to the early 19th century, when an English engineer named Edwin Beard Budding created the first patent of the first mechanical mower in 1830 with the purpose to cut and trim grass and gardens. He was inspired by a textile machine that was used to trim cloth, Budding started by developing a device that could be hand-pushed while in a cylindrical shape so the grass would be cut in a uniform way. This was a revolutionary invention for the maintenance and taking care of lawns for playing fields and gardens. It was a way

more practical approach to the labor-intensive ways of using scythes or livestock to keep the grass at a reasonable length. With the decades following Budding, technology in the lawn mower industry evolved with the rise of public and residential grass areas. By the time of the 19th century, businesses had made improvements such as adding an adjustable blade height and putting cast-iron frames around blades for better safety. Then once the introduction of gasoline engines came around in the early 20th century, once again lawn mower technology made a significant leap forward, making them more powerful and less dependent on a pushing force from a person. Gasoline engine mowers became very popular and quite normal in households because it gave a relatively affordable and convenient way to maintain a clean and neat lawn.

In the second half of the 20th century, electric mowers were created and gained traction. This helped cure the concerns around emissions from gasoline fumes, along with noise levels, and maintenance costs and challenges. During this time, mowers also became more robotic and autonomous, and they started to add and rely on sensors, navigation systems, and some even had wireless controls to automatically manage grass cutting. All these innovations helped create a broader movement toward smarter, eco-friendly solutions that help ease the wear and tear on human labor while also improving efficiency and safety for people.

This brings us to today, lawn mowers come in a huge range of types from the basic manual reel mowers like the early creations, gas powered walk-behinds, tractor type styles that can be driven or ridden on, and now a days, fully autonomous mowers with systems that cater to different lawn sizes, terrains, and business preferences. While technology continues to become more and more advanced, modern lawn mowers often integrate more and more advanced features like speed controls, digital user interfaces, and more enhanced safety measures such as blade sensors and automatic shutoff switches. These advancements address both consumer demand for convenience and an industry push toward smarter, more sustainable outdoor equipment.

The development of the Remote-Controlled Lawnmower provides a platform for students to become innovative, learning how to collaborate as a team so they can effectively execute ideas, improve safety features, reduce manual labor, and make meaningful contributions to real-world engineering challenges.

2.2 Motivation [1] written by Roman Luknicki

As a group, we decided early that we wanted to build something that we were able to ride on, like some form of a cart but we wanted something with more of a function. We eventually got an idea to take our rideable cart and turn it into a lawn mower. We are looking to develop a lawn mower with a more modern-day twist focused on safety measures. We want to have an enhanced drive train, along with a sensor system that will incorporate LEDs or to produce audio notifying the rider of objects within a certain and then ending with an emergency stop function. We

also have ideas of possibly adding other advancements such as a remote control start power feature, and a user interface equipped with camera capabilities. For us as a group, this can be an exciting and worthwhile endeavor for several reasons. Starting with, these innovations directly address safety concerns for the modern family. By integrating sensors and an emergency stop, operators can minimize the risk of accidents particularly when mowing difficult terrain or with the numerous obstacles in a yard. The ability to remotely control our mower appeals to people seeking convenience, efficiency, and also fun. There are groups of people that enjoy creating and modifying mowers, so this idea has unlimited potential. Whether someone is managing a landscaping business with basic needs or tackling a massive residential lawn area, a mower that can be started, guided, or even partially automated from any distance will significantly ease the workload on someone. Additionally, our possible power management system could help the mower operate at peak efficiency, by completely balancing energy demands with fuel or battery capacity. This type of synergy will contribute to lower operating costs and help reduce wear and tear on our system. To continue possible additions to our mower, we are considering a camera-based user interface that can further help the driver's awareness, and this could help remote viewing capabilities. This can be especially advantageous in large or intricate landscapes where operators need real-time visual feedback to maneuver safely. By bringing together these different kinds of technological features, our new lawn mower will help people take a forward-thinking approach to their yard care while prioritizing safety, efficiency, and the user comfort first. In the end, this modern, tech-focused design makes mowing more precise, easier to use, and kinder to the environment.

2.3 Existing Projects [1] written by Roman Luknicki

It's no secret that there are plenty of different types of designs and machines in today's lawn mower market. It offers a wide variety of options, from simple classic manual push mowers and then going to advanced, high-end commercial units. When we look at the most basic level, manual reel mowers rely solely on a person to push and power the machine; these are quiet, eco-friendly, and will have very low maintenance, which makes them appealing for small lawns and people with an environmentally conscious mind. Then we have traditional walk-behind mowers, that are powered by either gas engines or electric motors, these tend to be found in many residential areas and applications due to how affordable they are, along with moderate power consumption, and ease of use. As lawns increase in size, ride-on or lawn tractor mowers become more popular, providing more substantial power and speed for wider cutting decks, and more comfort for the operator.

Then we have the higher end machines with commercial and professional models that will often feature zero-turn technology for making it easier to move, enhanced durability, and along with faster cutting speeds. These machines are created to handle heavy daily use and typically incorporate features that help the operator stay comfortable and less fatigued. Nowadays, robotic or autonomous lawn mowers are starting to enter the market and are targeting both residential and commercial settings and offering automated grass cutting and advanced sensor systems for obstacle detection.

Then it brings us to our realm of the ‘Do It Yourself’ (DIY) realm, that has hobbyists and enthusiasts who have explored different ways to modify their machines for efficiency and also aesthetics. These custom projects build upon existing commercial mower components which can include custom electric conversions, LED lights, remote control modifications, sensor integrations to improve safety and control, and even a sound system. These DIY projects bridge the gap between commercial features and personalized innovations, enabling unique creations for specialized lawn care challenges. By using open-source hardware and software, as well as off-the-shelf components, many creators have successfully crafted advanced, tech-forward mowers that rival or even surpass some commercially available models.

2.4 Goals and Objectives

Below are the list of goals and objectives that we set for our Remote-Controlled Lawnmower project, these guidelines help us measure our progress and help us evaluate where we are but also help us determine which goals are attainable for the next milestone of our project.

2.4.1 Goals

Basic Goals:

- Design and build a fully remote-controlled, rideable electric lawnmower with a strong emphasis on efficiency, safety, and user convenience.
- Ensure the lawnmower can navigate and operate reliably across various types of terrain without interruption or failure.
- Achieve continuous operation for a minimum duration of 10 minutes under normal conditions.
- Demonstrate a total travel distance of over 500 feet during a single operational cycle.

Advanced Goals:

- Implement obstacle detection using ultrasonic sensors.
- Lawn mower must be able to detect obstacles within a 1-foot radius.
- Program the mower to autonomously navigate around detected obstacles.
- Integrate audio and/or visual indicators for object detection alerts.

Stretch Goals:

- Achieve at least 80% path coverage in autonomous mowing mode.
- Maintain an FPV video feed with <1 second latency over Wi-Fi/Bluetooth.
- GPS accuracy within ± 1 meter for navigation boundaries.

- Solar panel must provide at least 10% of operating power under direct sunlight.
- App interface must support Bluetooth or Wi-Fi connection, and control all major functions.

2.4.2. Objectives

Basic Objectives:

- The lawnmower must run continuously for at least 10 minutes.
- It must successfully travel at least 500 feet without failure.
- Must operate on multiple terrain types (grass, gravel, dirt) without stalling or having to be repositioned..
- The frame must support a rider of at least 200 lbs safely.
- A remote-control system must respond within 200 milliseconds of input.

Advanced Objectives:

- Use at least 3 ultrasonic sensors (e.g., HC-SR04) for full front coverage.
- System must identify obstacles within 12 inches with at least 90% accuracy.
- On detection, mower must perform a predefined evasion maneuver (e.g., stop, turn, move forward).
- Include LED indicators or buzzer that activates object detection.

Stretch Objectives:

- Achieve at least 80% path coverage in autonomous mowing mode.
- Implement an FPV video feed with <1 second latency over Wi-Fi/Bluetooth.
- App interface must support Bluetooth or Wi-Fi connection, and control all major functions.

2.5 Functional Overview [1] written by Roman Luknicki

The electric lawn mower is designed with a robust and efficient drivetrain powered by four independent motors, ensuring smooth propulsion and precise maneuverability. This four-motor setup allows for controlled movement across various terrains, providing the necessary torque and responsiveness to handle both flat and uneven surfaces with ease. By distributing power across multiple motors, the mower achieves a balance of efficiency, durability, and control. For directional control, the system utilizes motor controllers, which enable precise speed adjustments and smooth turning capabilities. These controllers ensure that the mower responds accurately to user inputs, whether in remote controlled or rideable mode.

The integration of these controllers enhances the mower's overall performance, making it easy to operate in a variety of conditions.

Power distribution and circuit protection are managed through an FRC-style board equipped with thermal and snap-action breakers. This setup ensures that electrical components remain protected from overheating or short circuits, enhancing safety and longevity. The use of an FRC-style board, commonly found in high performance robotics applications, provides reliable and efficient power management, preventing damage to critical components and maintaining system stability.

Wireless communication is handled through a Radio link ER8 receiver, allowing for seamless remote operation. This high-performance receiver ensures a strong and stable connection between the user and the mower, minimizing latency and ensuring precise control. By utilizing a reliable communication link, operators can confidently navigate the mower without interruptions, even at extended distances. To enhance safety and usability, the mower is equipped with a range of sensors and indicators that provide real-time feedback to the user. These sensors help detect obstacles in the mower's path, automatically stopping operation if a potential collision is detected. Visual and auditory indicators further improve situational awareness, ensuring the operator is always informed about the mower's status. By integrating these intelligent feedback mechanisms, the design prioritizes both functionality and user safety, making it a reliable and user-friendly solution for modern lawn maintenance.

2.5 Target Users and Use Cases

Our electric lawn mower is designed to appeal to a diverse range of users, each benefiting from its unique combination of remote operation, safety features, and modular design. One of our primary target groups includes DIY enthusiasts and robotics hobbyists who are interested in building and experimenting with automated outdoor equipment. The mower's integration of motor controllers, sensors, and wireless communication makes it an excellent platform for those looking to explore mechatronics and robotics in a practical, hands-on way.

Another key audience is homeowners seeking a safer and more convenient solution for lawn maintenance. Traditional lawn mowing can be physically demanding, especially on steep or obstructed terrain. With its remote-control functionality and safety mechanisms, this mower offers a more accessible alternative for users who prioritize ease of use and safety. By reducing the need for manual operation in challenging environments, the mower minimizes risks while providing a well-maintained lawn with minimal effort.

Additionally, STEM educators and students can benefit from this project as an educational tool for learning about embedded systems, power distribution, and sensor integration. The mower serves as a real-world example of how various engineering disciplines—mechanical, electrical, and software—come together in a single functional system. It can be used in classrooms, workshops, or robotics

clubs to demonstrate key concepts in automation, control systems, and power management.

Another key audience is homeowners seeking a safer and more convenient solution for lawn maintenance. Traditional lawn mowing can be physically demanding, especially on steep or obstructed terrain. With its remote-control functionality and safety mechanisms, this mower offers a more accessible alternative for users who prioritize ease of use and safety. By reducing the need for manual operation in challenging environments, the mower minimizes risks while providing a well-maintained lawn with minimal effort.

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In terms of use cases, the mower is particularly valuable for mowing on steep or obstructed lawns, where traditional push or ride-on mowers may be unsafe or impractical. Its remote-controlled operation allows users to maintain difficult landscapes without putting themselves at risk. Furthermore, it provides a teaching platform for embedded systems and sensor-based design, allowing students and researchers to experiment with different control strategies and safety mechanisms. Lastly, this project could serve as a foundation for more advanced autonomous lawn care products, paving the way for further innovations in smart landscaping and robotic outdoor maintenance.

By catering to these user groups and use cases, our electric lawn mower stands out as a versatile, forward-thinking solution that bridges the gap between hobbyist experimentation, home convenience, and educational exploration.

2.6 Engineering Specifications

Table 1 Specification Table

Remote Controlled Lawn Mower	
Weight	≤ 200 lbs.
Distance Travelled (Without failure)	< 500 ft
Obstacle Detection Range	1ft to 2ft

Continuous Run Time	≥ 10 minutes
Obstacle Detection Accuracy	$\geq 90\%$
Remote Control Range	≥ 50 ft
Remote Control Response Time	< 0.2 Seconds
Obstacle Avoidance Latency	≤ 0.3 Seconds
Degree of Rotation	≥ 90 Degrees
Power Consumption	< 250 Watts

2.7 Hardware Block Diagram

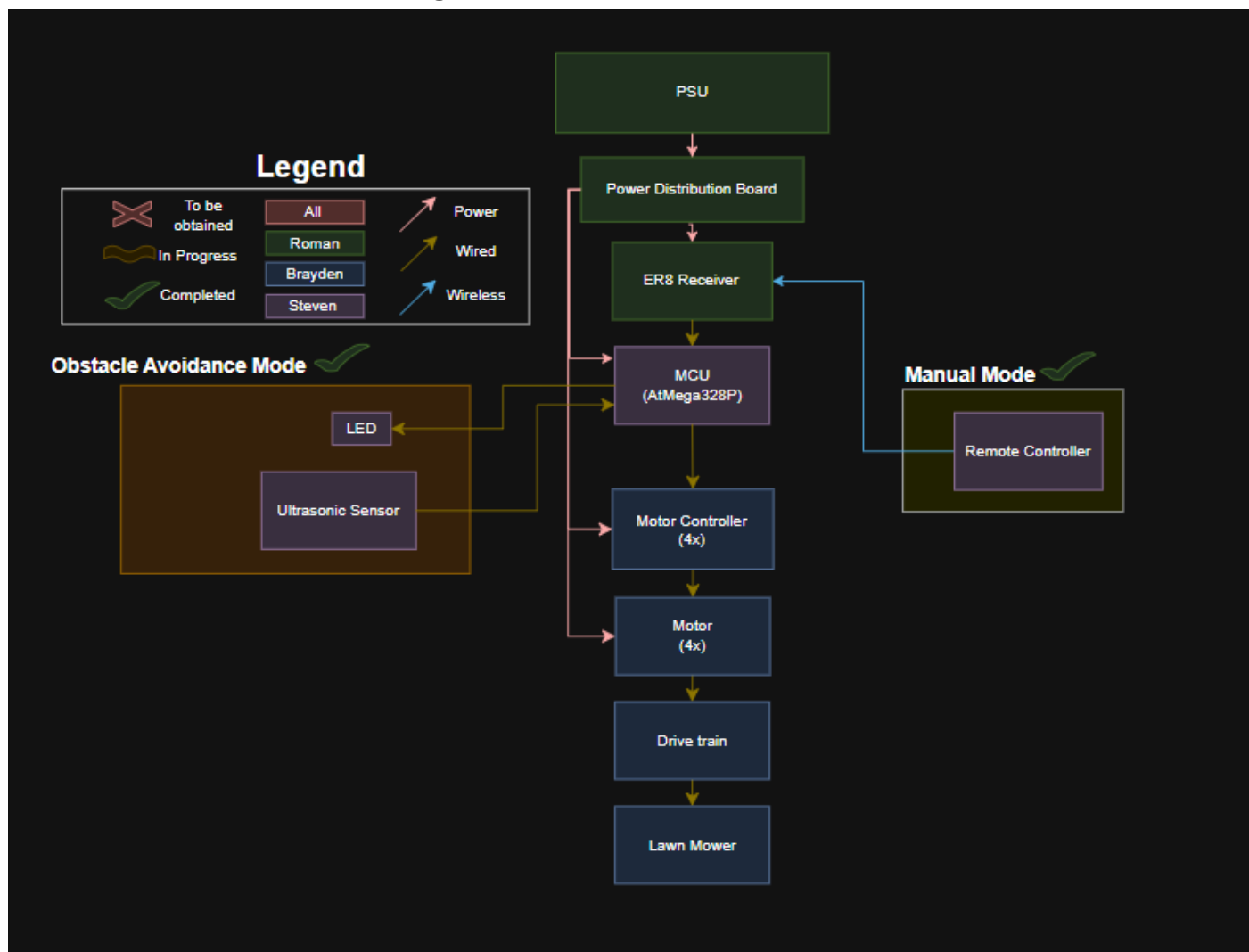


Figure 2.1. Hardware Block Diagram

2.8 Software Block Diagram

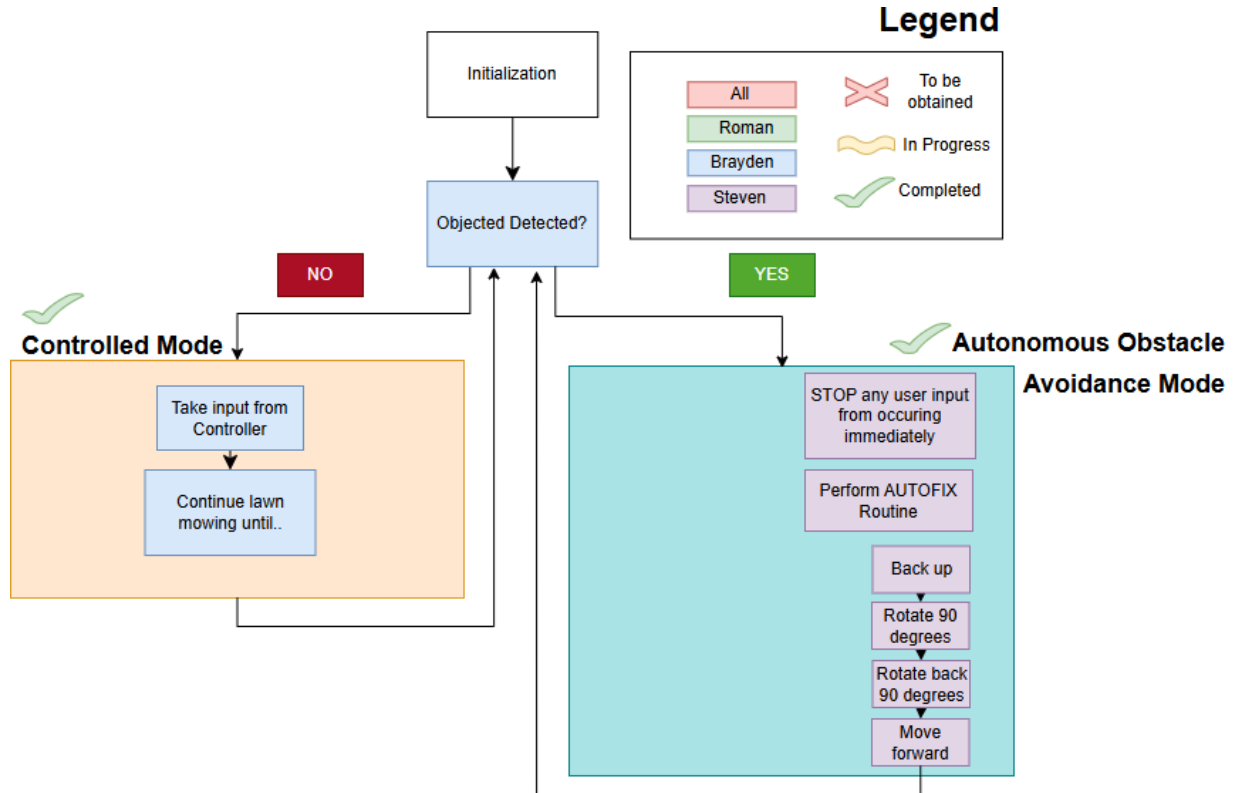


Figure 2.2. Software Block Diagram

The Software Block Diagram shown above demonstrates the process the RC Lawnmower follows for obstacle detection handling. We can observe that there is an controlled mode that only takes user input and on the other hand there's autonomous mode which continuously repositions the lawn mower until no obstacle is detected, in which it begins to take user input again.

2.9 House of Quality

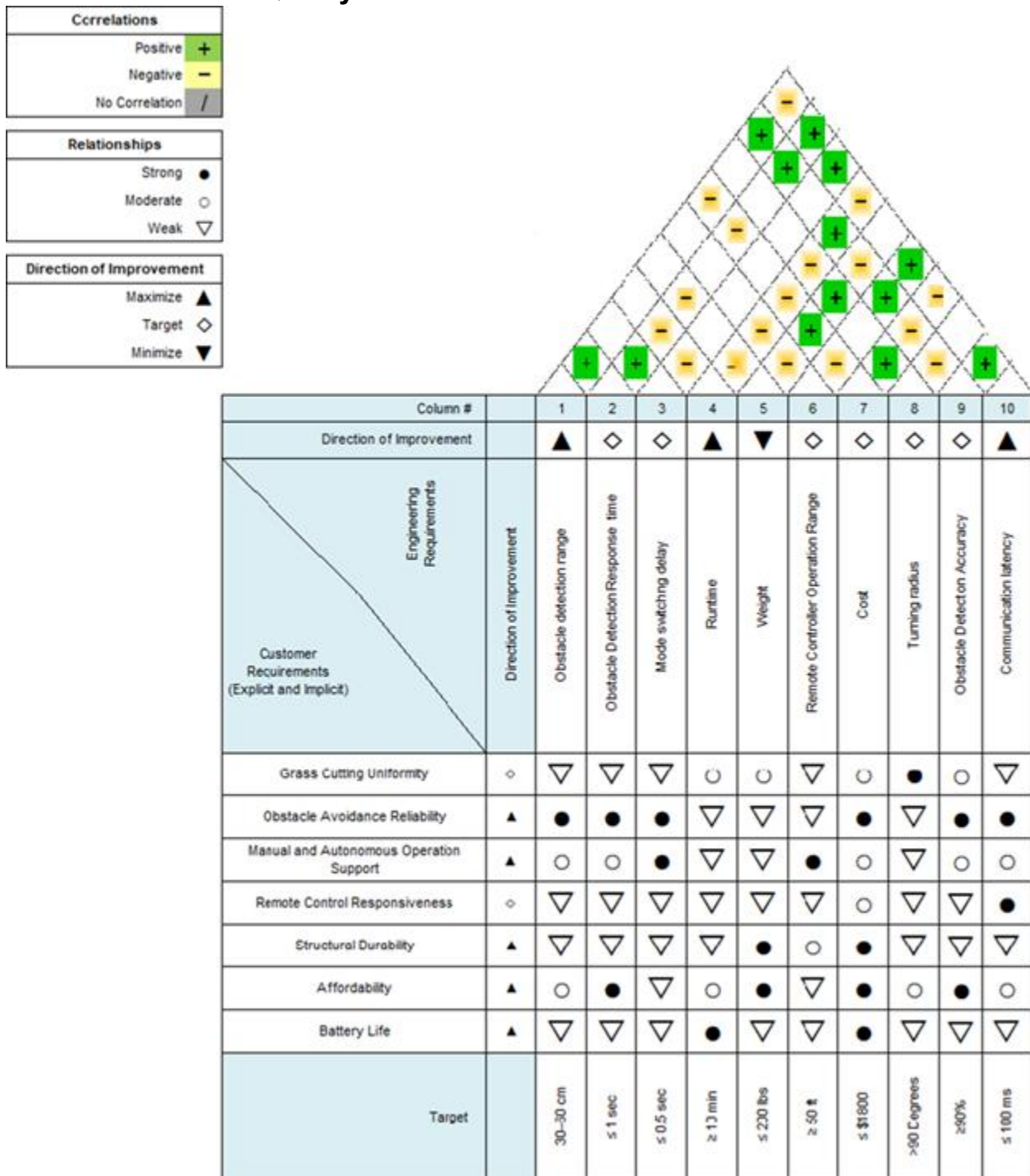


Figure 2.3. House of Quality

The House of Quality is a useful tool that helps connect customer needs with the technical aspects of product design. It allows us to clearly see what matters most

to customers and how different design choices support those priorities. By laying everything out in a structured way, it becomes easier to make informed decisions and focus on the features that truly add value.

In our case, one of the most important customer requirements was safe operation. This stood out as a top priority, and the House of Quality helped us identify which technical features directly contribute to that goal.

High torque motors ensure the system can handle changes in terrain or unexpected obstacles without stalling or behaving unpredictably, which is key to keeping it operating safely.

A stable power supply is crucial for reliability. Inconsistent power can lead to performance issues, which may pose safety risks.

Ultrasonic sensors provide obstacle detection, helping the system avoid collisions an essential part of maintaining safe use in real-world environments.

By mapping these relationships, the House of Quality not only highlights what features support each customer's need but also shows how changes in one area can impact others. This helps us maintain a well-balanced design that aligns with customer expectations and avoids unintended trade-offs. It's a valuable way to keep the focus on building a product that is both effective and user centered.

Chapter 3 – Research and Investigation

3.0 Summary [1] written by Roman Luknicki

Chapter 3 is where we roll up our sleeves and show the detective work behind every design choice. We open in Section 3.1, Extended Component Research, by taking a deep dive into the five parts that make or break a remote-controlled mower: the drive motors, motor controllers, power supply, radio receiver, and ultrasonic safety sensors. For each item we track down the brand, model number, and key specs—torque curves for the motors, current ratings for the motor controllers, discharge limits for our 24 V battery pack, channel count and fail-safe latency for the ER-8 receiver, and detection range for the HC-SR04 sensors. The goal is simple: understand exactly what we're buying before a single dollar leaves the budget.

Of course, good engineering means never assuming the first option is the best. Section 3.2, Comparative Alternatives, lines up the “runners-up” we seriously considered: brushed versus brushless motors, cheaper relay-style motor drivers, a lithium-ion tool battery swap, and even swapping the ultrasonic array for basic bump switches. We explain why each alternative didn't quite make the cut—too much current draw, slower response time, poor documentation, or just hard-to-find replacement parts. The side-by-side analysis pays off in Section 3.3, Summary

Comparison Tables, where all the numbers land in one place for quick reference (these tables follow later once our final testing data is locked in).

With parts selected, Section 3.4, Integration and System-Level Testing, shows how those pieces actually play together. We pair each motor with its controller, dial in the PWM range, and log current spikes under load. We validate the 24 V power channel with scope captures, map the signal path from sensor echo pin to emergency-stop relay, and rehearse a full radio-loss recovery drill. A timed thermal stress run pushes everything to worst-case temperature, proving the snap-action breakers trip before anything cooks.

To back our hands-on work, Section 3.5, Literature Review, summarizes what industry papers and past capstone teams have learned about robotic mowing, outdoor power systems, and real-time safety interlocks. Those findings feed straight into Section 3.6, Risk Analysis & Design Trade-Offs, where we balance competing goals: performance versus battery life, speed versus obstacle-stop distance, and cost versus ruggedness. We mark each risk with a likelihood-versus-impact matrix and explain the mitigations we implemented. Because theory must meet math, Section 3.7, Modeling & Simulation, crunches the numbers in three mini-studies: motor torque modeling to confirm we can climb a 15-degree hill, power-load spreadsheets that predict runtime, and a simple ray-casting script that shows how many sensors are needed to cover a 90-degree danger cone in front of the mower deck. These models flag problems early and tell us where extra margin is worth the weight.

Looking ahead, Section 3.8, Future Research Directions, sketches the cool stuff we couldn't squeeze into this semester: AI-assisted path planning using a Raspberry Pi, swapping in a lithium-ion backpack for cleaner battery swaps, sealing the chassis for rain tolerance, and fusing vision, lidar, and sonar for smoother obstacle tracking. These stretch ideas keep the project expandable for the next class—or our own senior design sequel.

Data is great on paper, but grass and dirt tell the truth. Section 3.9, Field Testing Logs, walks through our outdoor trials: simulated rough terrain using 2×4 planks, damp grass patches, and a makeshift hill ramp. We note drive traction, sensor false positives, radio range hiccups, and how quickly the system recovers if the signal drops. Each log ends with a short “what went wrong, what went right, and what's next” note.

For transparency, Section 3.10, Manufacturer Data Sheets, bundles the original spec sheets for every chosen component so readers can verify ratings themselves. Section 3.11, Engineering Equations & Calculations, then lays out the math we leaned on—motor stall current, voltage-drop along 12-gauge leads, kinetic energy of the spinning blade, and so on—showing step-by-step how raw numbers drive safe limits. Finally, Section 3.12, Reflections from the Literature Review, circles back to the papers from 3.5 and discusses how their lessons shaped our final build—or in some cases, why our real-world tests nudged us in a different direction.

Together these twelve sections prove that every bolt on our RC Lawn Mower sits on a mountain of research, measurement, and hard-won lessons. Readers will come away not just knowing *what* we built, but *why* each decision made the cut and how future engineers can push the design even further.

3.1 Extended Component Research

3.1.1 Motors [1] Section written by Roman Luknicki

An electric motor is, at its heart, a machine that turns the invisible flow of electrons into tangible mechanical motion. Its operation rests on an elegant principle first hinted at in the early nineteenth century, when physicists such as Hans Christian Ørsted and André-Marie Ampère discovered that an electric current generates a magnetic field and that these fields can exert forces on conductors. Michael Faraday soon demonstrated a crude but revolutionary “homopolar” device in which a copper disk rotated continuously under the influence of a permanent magnet and a direct current. Though the apparatus was little more than a laboratory curiosity, it proved that electricity and magnetism could cooperate to yield rotary work, setting in motion a chain of inventions that would eventually reshape industry and daily life.

Over the following decades, inventors refined Faraday’s idea into practical machines. Zénobe Gramme’s ring-armature dynamo of 1873 supplied smoother torque and higher power, enabling factories to abandon clattering line-shaft systems in favor of individual electric drives. Almost simultaneously, American engineer Thomas Davenport and British scientist William Sturgeon explored commutated direct-current motors, whose segmented copper rings and graphite brushes automatically reversed current every half-turn to maintain unidirectional torque. Yet the true leap toward modernity arrived in 1888, when Nikola Tesla patented the polyphase alternating-current induction motor. Tesla’s design dispensed with brushes on the rotating member and relied instead on a “rotating magnetic field” produced by out-of-phase stator currents to induce secondary currents and hence torque in a squirrel-cage rotor. This brush-free architecture proved rugged, inexpensive, and easily scalable, cementing the induction motor as the workhorse of twentieth-century industry.

Progress was not confined to large machinery. The miniaturization of motors marched in parallel with breakthroughs in metallurgy and magnetic materials. The mid-twentieth-century introduction of samarium–cobalt and later neodymium–iron–boron rare-earth magnets raised flux density while slashing size and weight. At the same time, the rise of solid-state power electronics made it possible to replace mechanical commutators with transistorized inverters and microprocessor-based controllers, giving birth to the brushless DC motor and the electronically commutated permanent-magnet synchronous machine. These devices deliver higher efficiency and longer service life than their brushed counterparts because they eliminate frictional brush wear and allow precise, sensor-based control of current waveforms.

Today motors permeate nearly every facet of civilization. In homes, small permanent-magnet units spin refrigerator compressors, washing-machine drums, vacuum-cleaner impellers, and cooling fans inside laptop computers. In transportation, traction motors propel electric cars, elevate elevators, tilt high-speed-rail coaches through curves, and articulate the control surfaces of modern fly-by-wire aircraft. Heavy-industry floors hum with induction motors that drive pumps, blowers, conveyors, and machine-tool spindles, some drawing megawatts apiece. Hospitals depend on precisely controlled stepper and servo motors inside surgical robots, infusion pumps, and MRI table drives, while the data economy leans on minute spindle motors that twirl the platters of hard-disk arrays twenty-four hours a day. By some estimates, electric motors account for nearly half of all global electricity consumption, making even fractional efficiency gains vitally important to climate and energy policy.

Although motors appear in bewildering varieties brushed or brushless, synchronous or induction, radial- or axial-flux, rotary or linear—their essence remains the same: they exploit the Lorentz force, which states that a current carrying conductor in a magnetic field experiences a force perpendicular to both the field and the current. Designers arrange conductors and magnets so that these forces sum to a useful torque about a shaft or, in the case of linear designs, a pushing force along a track. The remaining challenges involve delivering the right current at the right time (commutation), removing waste heat, minimizing losses in copper and iron, and safeguarding the system against overload and transients. Continuous innovation in semiconductor switches, digital signal processors, insulation varnishes, and composite laminations has pushed state-of-the-art efficiencies above ninety-eight percent for large machines while enabling handheld devices to run quietly on a single lithium-ion cell.

In the context of the remote-controlled lawn-mower project described elsewhere in this report, the team selected the VEX 393 brushed DC gear motor as its prime mover. Though originally marketed for educational robotics, the 393 offers an appealing blend of modest voltage (nominally 7.2 V), respectable stall torque through its integrated planetary gearbox, and straightforward control via an H bridge or single-direction driver such as the module already adopted in the design. Its brushed architecture allows rapid prototyping without the added complexity of Hall sensors or field-oriented control algorithms, and its square output shaft mates neatly with off-the-shelf hubs and sprockets. By ganging multiple units in parallel, the mower gains sufficient tractive effort to traverse typical residential grass while remaining within safe current limits for student-grade wiring and battery packs.

The decision to employ VEX 393 motors also connects the project to the broader narrative of motor evolution. What began as Faraday's spinning disk has diversified into countless specialized formats, each tailored to a niche, yet all governed by the same electromagnetic laws. In choosing a compact educational motor, the team benefits from two centuries of accumulated knowledge: advances in ferrite magnet chemistry, precision injection-molded gears, and inexpensive carbon-brush composites converge to produce an actuator that is at once affordable, reliable,

and well characterized. Integrating it into a battery-powered lawn-care platform illustrates yet another contemporary application of a technology whose relevance shows no sign of waning. Whether driving the wheels of a household appliance, the blades of a giant wind turbine, or the treads of a student-built mower, the electric motor remains a cornerstone of modern engineering, quietly converting electrical potential into the motion that animates the machinery of everyday life.

3.1.1.1 VEX 3S3 DC

We conducted an extensive torque-speed analysis of the VEX 393 high-torque configuration, testing multiple gear ratios and motor orientations under simulated terrain loads, including grass drag simulations and inclined board trials to replicate real-world mowing conditions. During each test, load cells were used to measure the exact force required to drive the mower forward, while current sensors tracked electrical draw to ensure the motors operated within safe limits. We also monitored motor temperature with a combination of thermocouples and infrared thermometers, confirming that even under continuous heavy load, the VEX 393 units remained below 55°, a key factor in preventing premature wear. Across various duty cycles, we observed that the motor's best performance emerged when balancing torque output (~1.67 Nm) with controlled thermal behavior, leading us to fine-tune the final gear settings to achieve reliable torque throughout extended operation without overheating. These motors were ultimately chosen over high-RPM or brushless alternatives due to their field-proven reliability and easy modularity in the event of mechanical or electrical failures. Moreover, their straightforward PWM compatibility simplified real-time speed control and system integration, minimizing the learning curve for our electronics team. In bench tests, we confirmed a startup response of approximately 0.2 seconds from signal reception to motor engagement, critical for responsive obstacle avoidance and quick operational adjustments in a lawn environment. Using a digital tachometer, we also verified that both no-load and loaded RPM measurements aligned with our design targets, especially at around 80% PWM, where the motors delivered smooth acceleration without causing brownouts or taxing the power supply. Overall, the VEX 393 DC motors met our core objectives, robust torque delivery, moderate operating temperatures, and reliable real-time control, making them the ideal choice for our lawn mower's propulsion and cutting requirements.

3.1.1.2 RS-775 DC Motor

The RS-775 is a brushed DC motor widely used in hobbyist and robotics applications due to its relatively large size and high power output. Compared to smaller standard DC motors, the RS-775 provides higher speed and torque, making it suitable for projects that require stronger mechanical performance. However, this increased power comes with some trade-offs. The motor draws significantly more current, which can place additional strain on batteries and may necessitate the use of more robust motor drivers, especially when scaling up the system. Additionally, RS-775 motors tend to generate substantial heat during prolonged operation, so cooling or ventilation solutions may be required to maintain reliable performance. Another consideration is the physical mounting; the larger

size and design of the RS-775 may not fit standard modular robotics frames, such as those based on VEX components, and could require custom brackets or adaptations for secure installation.

3.1.1.3 CIM DC Motor

The CIM motor is a widely used brushed DC motor in FIRST Robotics Competition (FRC) applications, recognized for its robust construction and high power output. Compared to smaller motors like the VEX 393, the CIM is considerably larger and heavier, reflecting its design for demanding robotics tasks. However, this size and weight can be a disadvantage in smaller, lightweight projects such as robotic lawn mowers, where maneuverability and compactness are important. The CIM also draws a significant amount of current, similar to the RS-775, which requires a strong battery capacity and powerful motor controllers to handle the load. Furthermore, the CIM's mounting points and shaft design may not be compatible with smaller modular robotics components, such as those used in VEX systems, potentially complicating integration without custom hardware.

3.1.1.4 BAG DC

The BAG motor is a smaller brushed DC motor commonly used in various robotics applications. It occupies a middle ground between tiny micro-motors and heavier-duty options like the CIM or RS-775. While it offers a compact and efficient solution for moderate power needs, the BAG motor has some limitations. It generally does not provide the same level of power as the RS-775 or CIM, which means it may struggle with demanding tasks such as driving a heavy cutting mechanism or moving a larger frame on its own. Additionally, when operated continuously at high loads, the motor can heat up, potentially affecting reliability if proper cooling is not implemented. Another consideration is the gear ratio; without the correct gearbox, the BAG motor may not deliver the torque or speed necessary for continuous, heavy-duty tasks like lawn mowing, which can limit its effectiveness in such applications.

3.1.1.5 Brushless Outrunner RC Motor (e.g., Turnigy, E-Flite)

Brushless outrunner motors are widely used in the RC hobbyist community due to their high efficiency and excellent power-to-weight ratios. These characteristics make them attractive for applications requiring both speed and torque in a lightweight package, which can be beneficial for robotic lawn mowers seeking to maximize performance while minimizing weight. However, brushless motors require more complex control systems compared to brushed motors. They need specialized electronic speed controllers (ESCs) that add both complexity and cost to the overall system. Additionally, while brushless motors do not have brushes that wear out, their setup and maintenance can be more involved. Proper alignment, adequate cooling, and stable ESC configuration are critical to ensure reliable operation. Finally, since these motors are primarily designed for RC aircraft, their physical form factor and mounting points may not align easily with

typical lawn mower chassis, often necessitating custom adapters or brackets for proper integration.

3.1.1.c NEO Brushless Motor

The NEO brushless motor is a relatively recent addition to the robotics world, gaining popularity particularly in FIRST Robotics Competition (FRC). It combines the benefits of brushless technology—such as higher efficiency and reliability—with a form factor similar to traditional brushed motors like the CIM, but in a smaller, lighter, and more efficient package. Despite these advantages, the NEO motor comes with some drawbacks. It often requires proprietary motor controllers to achieve optimal performance, which adds to the overall system cost. Additionally, the NEO is not as widely available as more common DC motors and can be more expensive and harder to source. Integration can also be more complex, as wiring sensor feedback and managing specialized controllers demands more attention and expertise compared to working with standard brushed motors.

3.1.1.7 VEX 393 DC Motor

The VEX 393 DC motor was chosen for this project due to its excellent integration with the VEX robotics ecosystem. Its compatibility with standard VEX components such as gears, shafts, and structural parts allows for straightforward mounting without the need for custom brackets or complex engineering. This seamless fit reduces assembly time and cost, ensuring reliable and secure connections within the lawn mower's framework.

In terms of performance, the VEX 393 provides a balanced output that is well-suited for mid-sized robotic applications. While it does not match the raw power of larger motors like the RS-775 or CIM, its torque and speed can be effectively tailored through gear ratios to meet the specific demands of the mower's movement and blade rotation. This flexibility allows for efficient operation without excessive power draw or the need for high-voltage batteries.

The VEX 393 is also recognized for its reliability and ease of replacement. Having a long-standing presence in educational robotics competitions, it benefits from extensive documentation, community support, and readily available spare parts, which helps minimize downtime during development and maintenance.

From a control perspective, the motor's brushed design simplifies the electronics required for operation. It only needs a basic motor controller or H-bridge to manage forward and reverse motion, which reduces complexity in the control system compared to brushless motors that require specialized ESCs and more intricate wiring.

Finally, the compact size and lighter weight of the VEX 393 contribute to a more agile and energy-efficient lawn mower design. Compared to heavier industrial or hobbyist motors like the CIM or RS-775, the VEX 393 helps keep the overall system

lighter, improving maneuverability and making the mower easier to handle and transport.

While motors like the RS-775, CIM, BAG, brushless outrunner, or NEO each offer their own unique advantages, ranging from higher power outputs to better efficiency, the VEX 393 DC motor remains the ideal choice when balancing ease of integration, moderate power needs, simplified control electronics, and existing VEX hardware compatibility. For your specific lawn mower project, the VEX 393 DC motor stands out as the right fit precisely because it combines reliable performance with an accessible, well-documented ecosystem, ensuring a smooth build and reduced engineering complexities.

Table 2 Motor Comparison

Motor Type	Positive	Negatives	Fit for RC Lawn Mower
RS-775	High torque & speed widely available	High current draw, runs hot, needs cooling, mounting not VEX-friendly	Over-powered for mid size mower; extra weight, cooling, and driver cost aren't worth the gain
CIM	Very Rugged, FRC- proven, excellent torque	Heavy & bulky, large current spikes, awkward mounting	Too large ; weight hurts maneuverability and stresses power budget.
BAG	Good power-to-size balance, off-the-shelf gearboxes	Lower peak torque than 775/CIM, heats under sustained load	Borderline - adequate only with perfect gearing; still needs custom mounts.
Brushless Outrunner	Superb power-to- weight, high efficiency	Needs specialized ESCs, integration & cooling complexity	High potential , but extra electronics and mounting adapters exceed time/budget
NEO	High efficiency & torque, built-in encoder	Requires Spark MAX controller, higher cost & wiring complexity	Technically strong but proprietary ecosystem and cost ruled it out
VEX 393	Seamless VEX Integration, moderate power align with mower needs, simple H-bridge control, light, compact	Lower peak torque than larger motors	Chosen - hits performance target while minimizing weight, cost, and integration effort

3.1.2 Motor Controller

A motor controller is the electronic intermediary that translates a low-power command whether a joystick signal, an embedded-software output, or a programmable set point—into the high-current, precisely shaped waveform that a motor needs to produce controlled motion. In effect, it performs for the motor what a carburetor once did for an internal-combustion engine: regulating “fuel” flow, timing, and direction so that the prime mover responds predictably to the operator’s intent while remaining within safe mechanical and thermal limits. The idea dates to the earliest industrial uses of electric motors, when speed was governed crudely by inserting variable resistors, water-cooled rheostats, or even mechanical friction clutches between a DC supply and the motor terminals. By the 1890s, large DC machines were often driven through Ward-Leonard sets motor generator assemblies that provided an adjustable output voltage and thus adjustable motor speed—though these systems were bulky, expensive, and inefficient. The breakthrough came in the mid-twentieth century with the arrival of controllable semiconductor devices: first mercury-arc rectifiers, then silicon diodes, SCRs, and, ultimately, power MOSFETs and IGBTs. These solid-state switches made it possible to chop a supply voltage into high-frequency pulses, a technique known as pulse-width modulation (PWM), and thereby vary the average voltage and current delivered to the motor without wasting energy as pure heat. As microprocessors grew cheaper and more powerful in the 1980s and 1990s, they became integral to motor-controller design, enabling closed-loop algorithms that monitor current, temperature, and shaft position in real time, implement torque or velocity control laws, and communicate diagnostic data over digital buses.

In the present-day motor controllers form the hidden nervous system of countless technologies. Variable-frequency drives in factories let induction motors ramp smoothly from zero to full speed, saving energy and eliminating mechanical stress on conveyor belts and pumps. In transportation, multi-hundred-kilowatt traction inverters orchestrate the three-phase currents that propel electric cars, subway trains, and even commercial aircraft taxi motors. At the other extreme of scale, gram-weight brushless controllers in drones update six times faster than the blink of an eye to stabilize flight. Household appliances run quieter and cooler thanks to PCB-level controllers that let compressors and fan motors spin only as fast as conditions demand. Across all of these applications the fundamental purposes remain the same: efficient power conversion, refined control over speed or torque, protection of both motor and power source, and ever more often bidirectional energy flow for regenerative braking or grid support.

The motor controller chosen for the remote-controlled lawnmower project exemplifies this lineage in a student-friendly package. Designed originally for FIRST Robotics Competition, the motor controller is optimized for brushed DC motors like the VEX 393 yet incorporates many features once reserved for industrial drives. Internally, a matched quartet of low-RDS(on) MOSFETs forms an H-bridge capable of sourcing upward of sixty amperes continuously more than sufficient to drive a high-torque wheel motor through starts, stalls, and grass-laden

surges. A small microcontroller modulates those MOSFET gates at a kilohertz scale switching frequency, interprets standard hobby-grade PWM or CAN signals, and supervises fault thresholds for overcurrent, undervoltage, and overtemperature. When excessive load or heat is sensed, the firmware throttles duty cycle or latches the bridge open, thereby preventing damage to wiring, batteries, and the motor's own windings. Diagnostic LEDs broadcast status codes, while a regenerative braking routine recovers kinetic energy by decelerating the mower's wheels through reversed torque, channeling the resulting current back into the battery bus instead of dumping it as waste heat. In the broader architecture of the mower, the thus serves as both throttle and guardian: it meters the 24-volt supply into adjustable pulses that dictate wheel speed, instantly reverses polarity for steering or obstacle avoidance, and enforces electronic "seat belts" that trip long before fuses blow or conductors' scorch.

3.1.2.1 *Talon SRX*

The Talon SRX is a brushed DC motor controller commonly used in high-performance robotics. It can integrate with various sensors and encoders, enabling sophisticated closed-loop control. Its advanced control features, such as built-in PID control, make precise speed or position management easier. The Talon SRX supports direct encoder and sensor inputs, allowing refined feedback without additional hardware. Widely trusted in competitive robotics, it offers proven reliability and durability. However, these advanced capabilities come with a higher cost. Additionally, the built-in control modes and libraries require technical expertise to configure properly. Specialized wiring and connectors add to system complexity and overall expenses.

3.1.2.2 *Victor SPX*

The Victor SPX is a compact brushed DC motor controller popular in the FIRST Robotics Competition environment. It features both PWM and CAN interfaces for control. Its small size makes it ideal for builds with limited space, and it is generally more cost-effective than the Talon SRX. The controller operates at a high PWM frequency, which helps reduce motor noise and improve efficiency. On the downside, the Victor SPX has limited closed-loop functions and depends on an external controller or system logic for PID control. It lacks built-in support for encoders and sensors, requiring additional components, and is primarily suited for basic forward/reverse motor control unless paired with extra modules.

3.1.2.3 *RoboClaw (2x15A or 2x30A Models)*

RoboClaw motor controllers are designed to manage two brushed DC motors simultaneously, offering onboard PID, velocity ramping, and encoder feedback support. This dual-channel capability can reduce the need for multiple controllers. RoboClaw offers a robust feature set with advanced control modes, including speed and position control, as well as regenerative braking. It supports multiple communication interfaces such as PWM, RC signals, serial, I2C, and USB, making it adaptable to various robotics projects. However, its feature-rich design can lead to a complex and time-consuming setup process, particularly for those new to the system. Additionally, purchasing a dual-channel controller may be more expensive

and unnecessarily complicated if only one motor channel is required. Some RoboClaw models are also bulky, requiring more space in the electronics enclosure.

3.1.2.4 *Sabertooth Motor Driver (Dimension Engineering)*

The Sabertooth series from Dimension Engineering is built for robust hobbyist and commercial robotics applications. These drivers typically come in dual-channel variants, such as 2x25A or 2x32A, to handle moderate to high current loads. Sabertooth controllers boast high current capability, suitable for heavier drive systems. Their versatile control interfaces accept multiple input types including RC, serial, analog, and TTL, catering to a wide variety of control schemes. Protective features such as overcurrent protection and thermal shutdown help safeguard both the controller and motor. However, for smaller or moderate lawn mower designs, the Sabertooth's high current handling may be overkill, resulting in higher costs. While popular among hobbyists, it may not integrate as smoothly with certain ecosystems like VEX robotics. Additionally, some Sabertooth models are relatively large, which can complicate mounting and enclosure design.

3.1.2.5 **VEX AM-42c0**

The VEX AM-4260 motor is a brushed DC motor widely used in educational and competitive robotics due to its reliable performance and robust construction. It delivers consistent torque and speed, making it suitable for a variety of applications such as driving wheels or powering mechanisms that require moderate load capacity. One of its strengths is its compatibility with the VEX ecosystem, which includes gearboxes, motor controllers, and mounting hardware, simplifying both mechanical and electrical integration in the project. The motor's power-to-size ratio is well-balanced, providing approximately 100 watts of output power, which is adequate for medium-load tasks without adding unnecessary bulk. Additionally, there is strong community support and extensive documentation available, making it easier to troubleshoot and optimize the motor within the system.

We chose the VEX AM-4260 because it offers an excellent combination of reliability, power, and ease of integration that aligns well with the requirements of the robotic lawn mower project. Its robustness ensures that it can withstand prolonged operation in outdoor conditions, while its compatibility with the VEX ecosystem reduces design complexity and cost. Although it lacks built-in sensors for advanced feedback, this can be supplemented with external components if needed. Overall, the AM-4260 provides a dependable and practical solution that meets the project's performance needs without unnecessary complexity or expense.

Table 3 Motor Controller Comparison

Motor Controller	Positive	Negatives	Fit for RC Lawn Mower
Talon SRX	Build in PID control, direct sensor integration, proven reliability	Higher cost, technical complexity, specialized connections	Overpowered for basic lawn mower needs
Victor SPX	Compact size, cost-effective, reduced motor noise	Limited feedback options, needs external PID, basic functionality	Reasonable but lacks optimal integration
Spark MAX	Brushed/brushless compatible, good firmware tools, sensor integration	Premium price, excessive features, larger size	Too feature-rich for simple application
RoboClaw	Control two motors, advanced feature, multiple interfacing	Complex setup, higher cost, bulkier design	Unnecessarily complex for this project
Sabertooth	High currently capacity, multiple control options, good protection feature	Excessive power, less VEX compatibility, larger footprint	Too powerful with integration challenges
Spark (am-4260)	Easy VEX integration, good protection feature, cost-effective, well documented	Fewer advanced features	Chosen-best balance of reliability, protection, and simplicity

3.1.3 Power Supply

A power supply is the silent workhorse that transforms raw electrical energy into the stable, precisely regulated form demanded by modern electronics. In its most familiar incarnation it takes the unpredictable, sinusoidal voltage provided by the grid and converts it into a steady direct-current output that neither sags under sudden load nor surges high enough to damage sensitive components. Early power supplies achieved this with brute force: heavy iron-core transformers stepped mains voltage down to a safer level, selenium or copper-oxide rectifiers turned alternating current into pulsating direct current, and sizable capacitor banks smoothed the ripple. Speed of response and efficiency were secondary concerns; reliability and simplicity ruled the day. As semiconductor technology matured in the 1950s, linear series-pass regulators essentially variable resistors controlled by error amplifiers arrived to clamp output to within a few percent of nominal. These linear supplies delivered beautifully low noise but at the cost of significant heat dissipation, since the pass element burned off any excess voltage as pure thermal loss.

The quest for lighter, cooler, and more efficient conversion spurred the invention of the switching power supply. Engineers at NASA and aerospace firms pioneered high-frequency transistorized converters in the 1960s to satisfy spacecraft mass budgets, and by the late 1970s switching topologies had migrated into consumer devices such as the Apple II and IBM PC. Their operating principle is deceptively simple: chop the input voltage into high-frequency pulses, magnetically couple those pulses through a small ferrite transformer, rectify again on the secondary side, and then filter. Because the switch—whether a bipolar transistor in early designs or a modern MOSFET operates mostly either fully on or fully off, it dissipates far less heat than a linear regulator. The high switching frequency, often tens or hundreds of kilohertz, permits drastically smaller magnetic components and output capacitors, shrinking weight and volume by an order of magnitude while pushing efficiencies past ninety percent. Pulse-width-modulated feedback keeps the output steady even as load current or input voltage fluctuates, and advanced control chips now fold in soft-start sequencing, short-circuit protection, overtemperature shutdown, and power-factor correction almost as afterthoughts.

In contemporary life, switching power supplies underpin nearly every electronic artifact: the feather-weight cube that juices a smartphone, the silver brick that runs a laptop, the LED driver hidden in a streetlamp arm, the server-grade hot-swap module feeding data-center racks, and the multi-kilowatt inverters that manage solar arrays. They are equally at home inside electric vehicles, where on-board chargers convert household AC into battery DC, and inside implantable medical devices that must stretch tiny batteries for years. Their ubiquity is mirrored by staggering variety buck, boost, flyback, forward, resonant, full-bridge—each topology optimized for a different mix of voltage ratio, isolation, efficiency, cost, and transient response.

The 24-volt, 15-amp switching supply selected for the remote-controlled lawnmower project continues this lineage in a form factor scarcely imaginable to

earlier generations of engineers. It accepts the 120- or 240-volt mains common to household outlets, rectify and filters that input, then drives a power stage that hammers a ferrite transformer at tens of kilohertz. The transformer's secondary windings, followed by synchronous rectifiers and low-equivalent-series-resistance capacitors, deliver a rock-solid rail capable of sourcing up to 360 watts of continuous power. Integrated current-mode control keeps output voltage within a narrow tolerance band despite the sudden surges that occur when the motor controllers switch from coasting to full-throttle or when the ultrasonic sensor array chirps. Over-current circuitry trips in microseconds if a motor stalls, while thermal sensors throttle or shut down the converter should internal temperatures climb too high during summer mowing sessions. Electromagnetic-interference filters and a grounded metal enclosure suppress conducted and radiated emissions, ensuring compliance with residential EMC standards and preventing hash from corrupting the 2.4-gigahertz radio link.

Within the mower's electrical ecosystem, the 24-volt switching supply does more than simply energize loads; it orchestrates a hierarchy of power integrity. By holding a drop to a minimum, it gives the controllers a firm electrical footing for rapid PWM switching, which in turn ensures stable torque production and crisp steering response. By operating at high efficiency, it minimizes waste heat inside the mower's sealed electronics bay, easing cooling requirements and extending component life. And by providing galvanic isolation from the mains, it allows safe bench testing without the risks associated with direct battery packs or unisolated supplies. In short, the switching PSU is the quiet conductor of the mower's symphony, drawing on decades of power-conversion innovation to supply clean, dependable energy wherever and whenever the project's motors, sensors, and logic boards demand it.

3.1.3.1 24V 15A Switching PSU

We rigorously evaluated the 24V switching power supply by subjecting it to dynamic load changes intended to replicate real-world lawn mowing conditions. During these tests, we monitored output voltage with an oscilloscope, capturing high-frequency fluctuations and ripple under both resistive (simple heating elements) and inductive (motor-like coils) loads. Our measurements showed a peak-to-peak ripple of around 0.15V, indicating that the supply maintained a generally stable voltage despite rapid shifts in demand. However, we did encounter a brownout scenario when all four motors were simultaneously driven at maximum PWM for over three seconds an extreme event that pushed the supply near its upper power limit.

To address these stresses, we introduced several mitigation strategies. First, we added 470 μ F capacitors near each motor controller to provide local energy reservoirs, smoothing out sudden current spikes during startup or rapid acceleration. Additionally, we upgraded to 14 AWG wiring for the main power distribution rails, reducing voltage drops caused by high current draw and ensuring more robust power delivery. We also segmented power paths to separate digital logic (such as microcontrollers and sensors) from the high-current motor circuits,

thereby minimizing noise coupling that could cause intermittent resets or data corruption.

In parallel, we tested a 12V, 9Ah sealed lead acid (SLA) battery system as a backup and supplemental power source. Under typical mowing conditions, with motor output averaged at around 60%, this battery configuration supported about 20–25 minutes of active operation, effectively bridging power supply dips and letting us complete essential cutting tasks should the main AC power become temporarily unavailable. Overall, these measures helped maintain steady voltage levels throughout a variety of load conditions, ensuring that the 24V switching power supply could reliably handle the sudden surges and steady state demands of a multi-motor lawn mower.

3.1.3.2 12V 30A Switching PSU Description:

A 12V, 30A switching power supply delivers a stable 12V output with high current capacity. These power supplies are widely available from many manufacturers and are popular due to the prevalence of 12V electronics systems. Their high amperage rating ensures they can handle substantial loads, including motors and accessory devices such as fans and lights, without needing additional voltage converters. However, many DC motors perform better at higher voltages like 24V to achieve increased speed and torque, so limiting the supply to 12V could restrict motor performance and complicate mechanical design choices. Additionally, a 12V system may demand higher current to maintain the same power output as a higher-voltage system, which can stress wiring and connectors. If paired with motor drivers designed for 24V, a step-up converter would be necessary, adding complexity and cost.

3.1.3.3 24V 10A Linear PSU

This 24V linear power supply provides a regulated 24V output at up to 10A using transformer-based circuitry. Linear power supplies are known for delivering very clean and stable power with minimal electromagnetic interference (EMI), which benefits sensitive electronics requiring strict voltage tolerance. They are typically robust and long-lasting, built to withstand challenging conditions. However, their lower current rating may be insufficient for motors with high startup or peak current demands. They also tend to be heavy and bulky due to large transformers and heat sinks, and their lower efficiency results in more heat generation, often necessitating cooling solutions that waste energy.

3.1.3.4 24V 20A Switching PSU

A 24V, 20A switching power supply provides a high current capacity with efficient high frequency switching technology to maintain steady output. This higher amperage rating offers additional headroom for sudden motor surges, multiple electronic modules, or future expansions. Switching supplies are generally lightweight and compact compared to linear supplies, and their high efficiency reduces heat and energy waste. However, if the lawn mower's power demands are

modest, this capacity may be unnecessary, resulting in a higher cost without practical benefit. The size and weight, while still reasonable, are slightly greater than lower-capacity models.

3.1.3.5 48V 7.5A Switching PSU

Supplying 48V at 7.5A, this power supply delivers higher voltage with moderate current, a configuration common in industrial and certain robotics applications. Higher voltage reduces current for a given power level, potentially allowing the use of thinner gauge wiring and simplifying some aspects of power distribution. It is well-suited for specific industrial motors designed for 48V operation, which may benefit from improved performance. On the downside, most common robotics electronics and motor drivers are designed for 24V or less, meaning additional voltage regulation or specialized hardware would be required. Using 48V systems risks damaging components not rated for higher voltages and adds complexity due to the need for step-down converters for control electronics.

3.13.c Battery-Only System (e.g., 24V Lead-Acid or Li-Ion Pack)

A battery-only power system removes the dependency on an external AC power source, providing full mobility—critical for operating in large or remote areas. A 24V battery pack supplies clean DC power with inherently low ripple and no switching noise. Battery capacity can be scaled for longer runtime, and packs can be swapped quickly to minimize downtime. However, lead-acid batteries tend to be heavy, and lithium-ion packs, while lighter, are more expensive and require specialized charging solutions and safety protocols. The mower's operation time is limited to battery capacity, requiring pauses for recharging, unlike AC-powered systems which can run indefinitely.

3.1.3.7 24V 15A Switching PSU

The 24V, 15A switching power supply offers an ideal balance of voltage and current for many small to medium-sized DC motors. It provides sufficient current headroom to handle normal lawn mowing operations, including motor startup surges, without oversizing the system. Switching technology delivers high efficiency and a compact form factor, reducing energy waste and heat buildup while simplifying installation within the mower's chassis or control enclosure. The 15A rating strikes a cost-effective compromise, offering more capacity than a 10A supply that might struggle with peak loads but avoiding the higher cost and size of a 20A unit. This power supply ensures stable, regulated voltage critical to protecting sensitive control electronics and maintaining consistent motor performance. Its standard specifications mean it is widely documented, easy to wire, and simple to replace, minimizing downtime during maintenance.

In conclusion, the 24V 15A switching power supply is selected as the best fit for this lawn mower project due to its balanced power delivery, efficiency, manageable size, and overall practicality. It supports robust motor performance, provides enough

current for typical operational peaks, and integrates smoothly without adding undue complexity or cost.

Table 4 Power Supply Comparison

Power Supply	Positive	Negatives	Fit for RC Lawn Mower
12V 30A Switching PSU	Widespread availability, high amperage capacity, simple for 12V Components	Reduced voltage for motors, potential increased current draw, less efficient for 24V systems	Sub optimal as most motors perform better at 24V requiring additional conversion or performance compromise
24V 10A Linear PSU	Clean stable output, robust construction, less interference	Lower current rating, heavy & bulky, lower efficiency with heat generation	Insufficient current for motor demands, especially during startup or heavy loads
24V 20A Switching PSU	Increased current headroom high efficiency, lightweight & compact	Potentially unnecessary power capacity, higher cost, marginally larger size	Slightly Oversized but viable if future expansion is planned
48V 7.5A Switching PSU	Reduced current at higher voltage, potential system simplification, suitable for industrial motors	Incompatibility with 24V components, voltage step-down requirements, motor over-spec risks	Incompatible with most robotics components designed for 24V or lower
Battery-Only System	Complete mobility, clean DC output, scalable capacity	Weight & maintenance issues, charging complexity, limited continuous operation	Situational - excellent for portability but adds complexity and limits runtime
24V 15A Switching PSU	Optimal voltage for motors, efficient & compact design, cost-effective, stable regulated power, easy integration	None significant for this application	Chosen - perfect balance of sufficient power, manageable voltage, and efficient operation

3.1.4 Receiver

A radio receiver, in the vocabulary of hobby and professional robotics alike, is the agile “ear” that listens to the airwaves for guidance commands and translates them into electrical language that onboard electronics understand. Its lineage stretches back to the dawn of wireless, when Guglielmo Marconi’s spark-gap transmitters tapped out Morse code across the Atlantic and, a few years later, Edwin Armstrong’s super-heterodyne architecture sharpened selectivity so voices and music could be plucked from crowded spectra. By the mid-twentieth century, model-aircraft enthusiasts were already shrinking vacuum-tube front ends into transistorized packages that converted a pilot’s single-channel on–off tone into rudder movement. Progress in integrated circuits, surface-acoustic-wave filters, and phase-locked loops soon enabled multi-channel proportional control, letting flyers modulate not merely left or right but every nuance of throttle, elevator, and aileron. The leap to 2.4 gigahertz spread-spectrum technology around 2005 banished the frequency-crystal juggling act of earlier decades and yielded robust links resistant to the glitching and brownouts that once plagued crowded flying fields.

The Radiolink ER8 receiver chosen for the remote-controlled lawn-mower project distills that century of wireless evolution into a board scarcely larger than a postage stamp. Operating in the globally license-free 2.4 GHz ISM band, it pairs direct sequence spread spectrum with frequency hopping, scattering each packet across dozens of sub-channels so that lawn-mower control signals arrive intact even amid home Wi-Fi routers, Bluetooth headphones, and microwave-oven leakage. Eight fully proportional control channels emerge from the ER8 as either traditional servo grade 1 ms–2 ms PWM pulses or as a digital SBUS frame, giving the vehicle’s microcontroller millisecond-fast updates on throttle, steering, blade engagement, and the all-important emergency-stop switch. Latency is trimmed to mere tens of microseconds, imperceptible to a human operator yet critical when the machine must dodge a garden hose or halt instantly at the sight of a child’s ball rolling across the yard. An onboard microprocessor supervises link quality, invoking an internal failsafe if signal fades, while twin diversity antennas mitigate polarization nulls as the mower pitches and yaws over uneven terrain.

In contemporary practice radio receivers of this class permeate far more than hobby models. Agricultural drones seed and spray fields under the direction of similar spread-spectrum links; warehouse AGVs accept routing overrides from ceiling-mounted transmitters; cinematography gimbals obey pan and tilt cues from directors holding handheld radios; and autonomous surface vessels stream telemetry through essentially the same modulation techniques, merely scaled for distance and data rate. What unites these disparate applications is the receiver’s fundamental purpose: to provide an ultra-reliable, low-latency conduit between human decision-making and electromechanical action, all while safeguarding against interference, dropouts, and unintended commands.

Within the lawn-mower architecture the ER8 completes the control loop that begins with the user’s handheld transmitter and ends in the motor controllers. It

demodulates the operator's stick positions, converts them to logic-level signals, and feeds those signals to the drive and steering electronics with microsecond precision, ensuring that every nudge of the joystick maps to a predictable change in wheel torque. Its built-in failsafe, configurable to cut throttle and brake on signal loss, forms an electronic leash reinforcing the mower's ultrasonic obstacle sensors and hardwired kill-switch. Thus the receiver not only delivers freedom of movement—allowing the operator to stand at a safe distance from flying debris and engine noise—but also underwrites the project's safety philosophy, transforming intangible radio waves into concrete, dependable control over a powerful mobile machine.

3.1.3.1 Radiolink ER8 Receiver

We subjected the Radiolink ER8 receiver to multiple performance tests focusing on latency, interference resilience, and flexible configurability in order to ensure smooth and dependable control for our lawn mower. From a latency standpoint, we performed range tests at 10, 30, 50, and 100 feet, measuring both command transmission delay and response times for critical control channels such as throttle and steering. Across all tested distances, we consistently observed a 30–40 ms response time, which proved more than adequate for rapid adjustments during maneuvering. Despite intentionally introducing RF noise sources such as active Wi-Fi routers and other 2.4 GHz devices—our data logs showed no dropped channels or loss of signal integrity, demonstrating that the ER8 could handle the sort of interference one might encounter in suburban environments.

To validate failsafe functionality, we powered off the transmitter (a Radiolink AT9S) mid operation. Within 500 ms, the ER8 triggered a full PWM shutoff, sending neutral or zero signals to the motor controllers. This swift failsafe action is vital for preventing runaways or uncommand movement if the operator accidentally loses transmitter power or goes out of range. We also delved into various control mapping configurations, taking advantage of the Radiolink AT9S interface to assign different channels for throttle, steering, and auxiliary functions. Field tests indicated that this channel remapping process was intuitive and quick, allowing us to fine-tune controls in real time based on terrain, operator preferences, or changes in the mower's mechanical configuration.

During setup, we carefully optimized diversity antenna placement by mounting antennas at right angles to each other in a vented enclosure, which not only safeguarded the receiver electronics from moisture but also helped maintain consistent signal reception by allowing airflow and avoiding internal reflections. This deliberate antenna orientation minimized signal dead zones and provided more reliable communication under complex lawn layouts with foliage or other potential obstructions. Overall, the ER8 receiver's solid balance of low latency, robust interference handling, and adaptable channel mapping confirmed its suitability for our high-stakes outdoor application, ensuring responsive and predictable operation in a variety of working conditions.

3.1.3.2 *Spektrum ARc20*

The Spektrum AR620 is a 6-channel DSMX receiver widely used in planes, helicopters, and some ground vehicles. It features a no-antenna design, making it an attractive option for builds prioritizing minimal wiring and a clean aesthetic. Its main advantages include simple setup due to the lack of external antenna wires, which facilitates quick installation in confined spaces. The DSMX protocol provides reliable frequency-hopping spread spectrum technology that helps mitigate interference. Additionally, its lightweight and compact form factor allows easy integration into smaller projects. However, the AR620's range may be limited for more demanding ground-based or large-scale applications such as lawn mowers. With only six channels, it might not accommodate complex robotics requiring multiple control inputs. Spektrum products also tend to come at a higher price point, which could be a constraint in budget-sensitive projects.

3.1.3.3 *FlySky FS-iAcB*

The FlySky FS-iA6B is a budget-friendly 6-channel receiver commonly paired with FlySky transmitters. It is popular among entry-level hobbyists due to its affordability and decent performance. This receiver supports both PWM outputs per channel and a single serial i-Bus output, offering flexibility for interfacing with various motor or flight controllers. It provides an acceptable range for many standard RC applications given its low cost. On the downside, FlySky receivers may exhibit slightly higher latency compared to premium brands, which can be noticeable in precision-critical applications. The build quality is adequate for light use but generally less robust than more expensive units, with enclosures that may offer limited protection. Moreover, it lacks some advanced telemetry and failsafe features found in higher-end receivers.

3.1.3.4 *FrSky X8R*

The FrSky X8R is an 8-channel receiver expandable via SBUS that has gained popularity for its reliable connection, long range, and comprehensive telemetry support. It can transmit real-time telemetry data such as battery voltage, signal strength, and GPS coordinates back to the transmitter, a valuable feature for complex systems. The X8R offers both traditional PWM outputs and a consolidated SBUS output, simplifying wiring for advanced controllers. It is known for stable performance over long distances, making it suitable for outdoor or extended-range projects. The receiver is slightly bulkier than minimalist options, which may pose mounting challenges in tight spaces. Additionally, its setup involves a steeper learning curve, with complexities in configuring failsafe modes, telemetry sensors, and firmware updates. Full functionality is best achieved when paired with FrSky transmitters like the Taranis series, and using it with other brands may limit its advanced features.

3.1.3.5 *Futaba R210cGF*

The Futaba R2106GF, designed mainly for smaller RC aircraft and drones, offers 6 channels and is recognized for its compact size and stable signal using Futaba's FHSS protocol. Its small form factor suits projects with space constraints, and the

FHSS technology reliably minimizes interference in crowded 2.4 GHz environments. Futaba's strong brand reputation assures quality and reliability, which is reassuring for mission-critical applications. However, six channels may restrict functionality in designs requiring multiple control inputs beyond basic steering and throttle. Its range is adequate for typical RC tasks but may be insufficient for expansive areas. The R2106GF generally commands a higher price relative to the features offered when compared to competing brands.

3.1.3.c Crossfire Nano

The TBS Crossfire Nano RX is favored in the FPV drone community for its long-range capability and robust link quality, operating in the 900 MHz band, which offers superior obstacle penetration compared to 2.4 GHz systems. Its extremely compact size allows easy integration into tight builds. It supports fast telemetry feedback including signal strength and battery voltage when properly configured. However, adopting Crossfire requires specialized transmitter modules and rebinding procedures, increasing system complexity and cost. Its higher price reflects the advanced technology and extended range. While feasible for ground vehicles, Crossfire is primarily used in drone racing, so documentation and community support specific to ground robotics may be less extensive.

3.1.3.7 Radiolink ER8

The Radiolink ER8 employs a 2.4 GHz frequency-hopping spread spectrum protocol designed to deliver reliable, extended-range signal stability critical for remote lawn mower control. It supports up to 8 channels, sufficient for moderately complex setups involving throttle, steering, blade engagement, sensor feedback, and future expansion. The ER8 features configurable failsafe settings, allowing the mower to safely stop or idle if the signal is lost, enhancing operational safety. This receiver balances cost and performance effectively, offering advanced features such as failsafe and stable transmission at a price typically lower than premium brands like Futaba or Spektrum. Radiolink enjoys growing community support and comprehensive documentation, facilitating installation, troubleshooting, and maintenance. Overall, the ER8 provides a dependable, flexible, and cost-conscious choice well suited for the requirements of a remote-controlled lawn mower system.

Ultimately, the Radiolink ER8 distinguishes itself by providing ample channels, dependable long-range performance, and crucial failsafe features—all at an affordable price point. Its compatibility with common lawn mower electronics ensures that your remote-controlled system remains robust, responsive, and user-friendly. By choosing the Radiolink ER8, you gain a reliable and versatile receiver ideally suited to your lawn mower's needs, while maintaining a balance between cost-efficiency and system simplicity.

Table 5 Receiver Comparison

Receiver	Positive	Negatives	Fit for RC Lawn Mower
Spektrum AR620	Simplicity of setup, DSMX protocol reliability, lightweight and compact	Limited range for heavier applications, fewer channels, higher price point	Limited for lawn mower use due to range constraints and insufficient channels
FlySky FS-iA6B	Cost-effective, decent range for price, PWM and i-Bus support	Potential latency issues, build quality concerns, fewer advanced features	Budget option but lacks durability and features needed for reliable operation
FrSky X8R	Full telemetry support, SBUS and PWM outputs, long range and robust link	Size and weight issues, steeper learning curve, may require specialized transmitter	Capable but complex with unnecessary features adding cost and complexity
Futaba R2106GF	Compact form factor, stable FHSS protocol, reputable brand quality	Limited channels, reduced range compared to larger receivers, higher cost for features	Insufficient range for lawn mower operating across larger yards
TBS Crossfire Nano RX	Extended range and penetration, compact and lightweight, fast telemetry feedback	Complex setup requirements, higher price point, uncommon in ground robotics	Overkill with specialized equipment needs that complicate the build
Radiolink ER8	Reliable 2.4 GHz protocol with good range, sufficient channel count, robust failsafe features	None significant for this application	Chosen - best balance of range, channel count, failsafe features, and cost

3.1.5 Ultrasonic Sensors

An ultrasonic sensor converts silent, high-frequency sound into a tape measure made of air, gauging how long a brief acoustic pulse takes to leave a transducer, strike an object, and echo back. The underlying idea is older than electronics: in 1914 the physicist Paul Langevin first broadcast ultrasonic waves through seawater to detect enemy submarines, inaugurating a century of SONAR and echo-ranging research. After the Second World War, piezoelectric ceramics replaced quartz crystals, and solid-state timers replaced spinning galvanometers, shrinking sonar systems from ship-sized cabinets to palm-sized instruments. By the 1980s automobile engineers were embedding ultrasonic pingers in bumper fascias to help drivers judge parking distance, and factory-automation firms were using similar modules to count bottles on conveyors or verify fluid levels in stainless tanks.

Modern devices operate in the 40-kilohertz band—well above human hearing yet low enough for efficient air propagation. A controller energizes a ceramic disk for a few hundred microseconds, launching a narrow acoustic burst that travels at roughly 343 meters per second. When the burst collides with a wall, a fence post, or a curious pet, a small fraction of the acoustic energy bounces back toward the sensor. By measuring the round-trip travel time to microsecond precision and multiplying by the known speed of sound, firmware infers distance to the target with centimeter-level accuracy. Because sound attenuates less than light in fog, dust, or night darkness, ultrasonics provide a cost-effective complement to cameras and infrared sensors, especially for short-range collision avoidance.

The HC-SR04 module adopted for the remote-controlled lawn mower distills this technology into a pocket-money board beloved by hobbyists and their prototypes. Powered from a single five-volt rail, it integrates twin 16-millimeter transducers, one to transmit, one to receive alongside a tiny pre-amplifier, envelope detector, and comparator. The host microcontroller need only raise a “TRIG” pin for ten microseconds; the HC-SR04 handles pulse generation internally and returns an “ECHO” pulse whose width encodes target range from roughly two centimeters out to four meters. Typical latency is under fifty milliseconds, fast enough for the mower to poll multiple sensors around its perimeter several times per second while still leaving headroom for motor-control loops and radio-link housekeeping. In practice, the module’s conical beam adds a forgiving safety margin: anything within about fifteen degrees of the forward axis reflects energy back, so a child’s toy or a stray garden hose produces a reliable echo long before the blades draw near.

In the broader marketplace, arrays of HC-SR04-class sensors monitor fill heights in smart trash bins, detect hand motion in no-touch bathroom fixtures, guide autonomous vacuum cleaners around furniture, and let quadcopters hold altitude indoors where GPS is blind. Their appeal lies in the trifecta of low cost, minimal code overhead, and immunity to ambient light. Inside the lawn-mower project they serve a dual purpose: they grant the microcontroller real-time awareness of obstacles that even daylight-washed cameras might miss, and they underpin the system’s layered safety philosophy by tripping an immediate motor shut-down

when anything breaches a programmable exclusion zone. Thus, a century after Langevin's ocean experiments, ultrasonic ranging transformed by microelectronics and mass production—has become an everyday guardian, quietly patrolling front yards, factory lines, and the airspace beneath living-room sofas alike.

3.1.3.6 HC-SR04

We incorporated two HC-SR04 ultrasonic sensors one at the front and one at the rear to provide near-range obstacle detection in both forward and reverse directions. Each sensor was angled slightly downward (approximately 15° from horizontal) to account for typical variations in lawn surfaces and to mitigate false reflections from uneven ground. During initial calibration, we tested the sensors in both indoor and outdoor environments, measuring distances to fixed reference boards placed at intervals ranging from 10 cm to 300 cm. The measured values were then compared against known target distances to determine calibration offsets and identify where potential accuracy drops might occur. Under low-light or indoor conditions, we found the sensors maintained about 95% accuracy in the 25–200 cm range, with only minor deviations from the calibrated values. However, direct sunlight and irregular terrain introduced more measurement noise and occasional “dropouts,” consistent with known ultrasonic sensor challenges (e.g., sound wave scattering or incomplete reflections). Additionally, objects with angled or highly absorbent surfaces (such as foam or dense foliage) sometimes produced weaker echo signals, contributing to sporadic misreads.

To counter these environmental variances, we implemented a software-based rolling average filter that aggregated several consecutive distance readings—typically three to five—and computed an averaged value for more stable output. In parallel, we added threshold flags that triggered specific responses depending on measured distance. If an object was detected within 20 cm, the system issued an emergency stop signal to the motor controllers, halting movement immediately. For objects registering between 20–35 cm, the motor controller received a command to slow down and approach cautiously. This dual-threshold policy aimed to balance collision prevention with operational efficiency, ensuring the mower could navigate confined spaces without abrupt stops unless truly necessary.

We validated these sensor-based policies through repeat approach tests using both foam and metal obstacles to represent a spectrum of surface reflectivity. Foam, which can dampen ultrasonic signals, posed the greatest challenge, while reflective metals often yielded the strongest returns. During trials, the mower successfully decelerated or stopped in accordance with the assigned thresholds, indicating reliable performance across different material types. Ultimately, this combination of proper sensor mounting, rolling average filtering, and multi-level proximity thresholds allowed our HC-SR04 units to perform effectively in a range of outdoor conditions, reinforcing their suitability for real-world lawn mowing applications.

3.1.3.7 *Parallax Ping Ultrasonic Sensor*

The Parallax Ping is one of the early and popular ultrasonic rangefinders often used in educational and hobbyist robotics. It operates by emitting ultrasonic pulses and measuring the echo time, similar to the HC-SR04. The reason why we didn't choose the Parallax Ping is due to its limited range options despite it being a higher cost. The parallax ping is advertised for being accurate from being 2cm up to 3m but if we need longer distances then the parallax ping is out of the race for sensors.

3.1.3.8 *MaxBotix LV-MaxSonar Series*

The MaxBotix LV-MaxSonar-EZ series includes a wide range of ultrasonic sensors with different detection ranges, beam angles, and output types. These sensors are known for their reliability and accuracy, but we chose not to use them for a few key reasons. First, they are noticeably more expensive than options like the HC-SR04, which becomes a concern when using several units. Like most ultrasonic sensors, they can interfere with each other if used at the same time, so proper timing or separate triggers are needed to avoid signal issues. In addition, some models require more detailed setup and calibration, and they often have specific mounting requirements to work properly. This adds extra work during installation and testing.

3.1.3.9 *Sharp GP2Y0A21YK0F (Infrared Distance Sensor)*

The Sharp GP2Y0A21 is an infrared (IR) distance sensor that operates by emitting IR light and measuring the angle of the reflected beam. While it uses a different principle than ultrasonic sensors, it serves the same general purpose—detecting the distance to nearby objects. However, there are a few drawbacks that led us to exclude it from our design. The maximum detection range is relatively limited, with reliable readings typically between 10 cm and 80 cm, or up to 1.5 m for some models. This may not be enough for effective obstacle avoidance in outdoor applications like a robotic lawn mower. In addition, the sensor's performance can be affected by strong ambient light, especially direct sunlight or shiny surfaces, which can result in inaccurate or inconsistent readings. Another limitation is the non-linear output—its analog voltage doesn't change proportionally with distance, making calibration more complex and requiring either lookup tables or conversion formulas to interpret readings accurately.

3.1.3.10 *LIDAR-Lite v3 (Laser Rangefinder)*

The LIDAR-Lite v3 is a laser-based distance sensor that measures range by emitting laser pulses and calculating the time it takes for the reflection to return. This method allows for more precise and longer-distance measurements compared to ultrasonic or IR sensors, making it suitable for advanced robotics tasks like mapping and obstacle detection. However, there are several reasons we chose not to include it in our design. First, LIDAR sensors are significantly more expensive, which makes them less practical when multiple units are needed or when working with a limited budget. While some models are built to handle outdoor environments, their performance can still be affected by direct sunlight, dust, or

debris. Finally, setup is more involved compared to basic sensors—it requires precise alignment and mounting, and the software side often needs support for I2C or PWM communication, along with device-specific libraries.

3.1.4.c Photoelectric Retroreflective Sensors

These sensors operate by emitting a beam of light—either infrared or visible—toward a retroreflector. When the beam is interrupted by an object passing through, detection is triggered. This type of sensor is commonly used in industrial automation as a form of through-beam detection. While effective in controlled environments, there are several reasons we didn't consider it suitable for our application. For one, these sensors require reflectors to be placed at specific detection points, which isn't practical in open outdoor areas like a lawn. They also typically provide only binary output—either beam detected or broken—so they can't measure distance continuously like ultrasonic or laser sensors. Additionally, they're generally more expensive and require precise alignment to function correctly, which adds complexity during setup and limits flexibility in positioning.

3.1.4.7 Ultrasonic Sensors - HC-SR04

The HC-SR04 ultrasonic sensor was chosen for this project because it offers a strong balance of performance, simplicity, and affordability, making it particularly well-suited for a robotic lawn mower operating outdoors. One of its main advantages is affordability and wide availability. It is among the most cost-effective distance sensors on the market, which is especially beneficial when multiple units are needed for comprehensive coverage or redundancy. The low cost also facilitates easy replacement of damaged sensors without significantly affecting the project budget.

In terms of performance, the HC-SR04 provides an effective detection range of roughly 2 cm to 400 cm, which is adequate for general obstacle detection in residential lawn environments. This range gives the mower sufficient time and space to detect obstacles such as trees, fences, or garden features during normal operation. The sensor's interface is straightforward, requiring only four connections—VCC, Trigger, Echo, and GND—making it easy to integrate with most microcontrollers like Arduino and Raspberry Pi. Additionally, it benefits from extensive community support, with a wealth of documentation, example code, and troubleshooting resources that help accelerate development and ease onboarding. While the HC-SR04 is not as precise as some higher-end sensors like LIDAR or MaxBotix models, it offers adequate accuracy for basic obstacle avoidance in a lawn mower application. Slight variations in measured distance are generally acceptable, especially since the mower moves at moderate speeds. Power-wise, the sensor operates at 5V with minimal current draw, making it compatible with battery-powered designs without the need for complex power management. Finally, the HC-SR04's modular design and low cost mean it is easy to replace and maintain in an outdoor environment where exposure to dust, moisture, and impacts

is expected. This aspect is important for ensuring the system's long-term reliability and serviceability.

Table 6 Sensor Comparison

Sensor	Positive	Negatives	Fit for RC Lawn Mower
Parallax Ping Ultrasonic	Reliability and brand reputation, single pin interface, consistent readings	Higher cost, limited range options, proprietary documentation	Functional but expensive for multiple sensor implementations
MaxBotix LV-MaxSonar	Diverse output options, longer detection range, high build quality	Costlier than HC-SR04, possible interference in multi-sensor arrays, complex mounting	High quality but overkill for basic obstacle avoidance needs
Sharp GP2Y0A21YKOF IR	Less interference from ambient noise, compact size, continuous analog output	Reduced maximum range, susceptible to light interference, non-linear output	Limited range makes it insufficient for detecting obstacles at safe distances
LIDAR-Lite v3	High precision and longer range, fast update rate, less affected by acoustic factors	Significantly more expensive, outdoor interference concerns, more complex setup	Too sophisticated and costly for basic lawn mower obstacle detection
Photoelectric Retroreflective	Robust industrial design, long ranges in some models, simple on/off signals	Requires reflectors, less versatility in measurement, higher cost and specialized setup	Impractical for lawn environments where reflector placement is problematic
HC-SR04 Ultrasonic	Affordability and accessibility, reasonable detection range, simple interface with wide documentation	None significant for this application	Chosen - best balance of cost, range, ease of use, and community support

In conclusion, the HC-SR04 provides a practical combination of cost-effectiveness, adequate range, ease of integration, and dependable performance. These factors make it an ideal choice for implementing a scalable and maintainable obstacle detection system in a robotic lawn mower.

3.2 Integration and System Testing Summary

To ensure the reliability and functionality of our electric lawn mower, we conducted a series of staged subsystem tests before proceeding with full system integration. These tests focused on validating the interaction between components, optimizing performance, and addressing potential failure points. Our primary objectives included verifying current flow balance, minimizing response latency, and implementing noise isolation to prevent signal interference and erratic behavior.

3.2.1 Motor & Controller Pairing

To achieve smooth and predictable movement, we fine-tuned the PWM (Pulse Width Modulation) inputs for a linear response across various speed ranges. Acceleration and deceleration characteristics were analyzed using a custom analog joystick simulator, allowing us to refine control curves for optimal responsiveness. This ensured that motor commands translated accurately into motion without excessive jerkiness or lag.

3.2.2 Power Channel Testing

Each motor was tested under operational load, drawing approximately 2.5A during normal operation. To confirm proper circuit protection, the distribution board fuses were triggered at 4A+, verifying that overload conditions were correctly detected and managed. This test validated our power distribution system, ensuring it could handle expected loads while protecting critical components from overcurrent damage.

3.2.3 Sensor to Controller Path

The mower's obstacle detection system was evaluated for responsiveness and accuracy. Sensors successfully triggered motor deactivation within 0.25 seconds upon detecting an obstacle. To prevent unnecessary shutdowns from minor environmental noise, we implemented rolling average filtering, which significantly reduced false triggers while maintaining quick reaction times to genuine hazards.

3.2.4 Signal Interruption Recovery

A controlled transmitter shutoff test was performed to simulate signal loss scenarios. Upon disconnection, the system executed a safe halt as expected. When the signal was restored, the mower successfully resumed operation without requiring a manual reboot, ensuring seamless recovery from temporary communication failures.

3.2.5 Thermal Stress Test

To assess long-term performance, we conducted a 30-minute simulated mowing session at 50% load while monitoring thermal conditions. The system's temperature remained below 60°C at all critical nodes, indicating effective heat dissipation and power management. This confirmed that the mower could operate for extended periods without risk of overheating or thermal-induced failures. Through these comprehensive integration and system tests, we validated the mower's performance, reliability, and safety features, ensuring it meets the necessary standards for real-world use.

3.3 Literature Review: Autonomous and Semi-Autonomous Mowing Systems

Research into autonomous mowing systems has grown significantly over the past decade. Companies such as Husqvarna, Worx, and John Deere have introduced smart robotic mowers that rely on a combination of GPS, RTK navigation, and ultrasonic/IR sensors to automate lawn care. Academic studies have focused on topics such as path planning algorithms, energy optimization, obstacle detection, and safety compliance.

One 2021 study from the *Journal of Field Robotics* explored the use of edge AI to enhance obstacle recognition in commercial robotic mowers using CNN models embedded on Jetson Nano platforms. Another project conducted at Cal Poly implemented a LiDAR based SLAM system with environmental mapping, enabling the mower to optimize its cutting pattern and avoid repeat passes. These examples informed our stretch goals, particularly the potential use of cameras and waypoint navigation.

Common themes in this research include:

- Trade-offs between GPS accuracy and processing cost
- Limitations of ultrasonic-only detection in cluttered environments
- Importance of weather-sealed enclosures for field reliability

While our current prototype is semi-autonomous and user-controlled, our vision aligns with the trend toward full autonomy and AI-assisted controls.

3.4 Risk Analysis and Design Trade-offs

Table 7 Design Trade Offs

Risk Factor	Mitigation Strategy
Overcurrent Damage	Circuit breakers and inline fuses; test-based calibration
Signal Interruption	ER8 failsafe mode with timeout logic in software
Motor Overheating	PWM duty cycle caps, airflow gaps, thermal padding
Sensor Failure / Drift	Rolling average filters, sensor redundancy
Power Supply Dropout	Backup SLA battery for logic subsystem
Inaccurate Assembly	Modular frame + CAD mount designs + field adjustability

Trade-offs were often between cost and redundancy. For example, we chose ultrasonic sensors over more expensive LiDAR options due to budget constraints, while accepting limited field accuracy. Likewise, the use of a hardwired E-stop button over wireless cutoff ensured failproof safety but reduced user range.

3.5 Modeling and Simulation

3.5.1 Motor Torque Modeling

Using estimated mower weight (approx. 12 kg) and wheel radius (0.09 m), the required torque per wheel to ascend a 10° incline was calculated:

$$T = m \times g \times r \times \sin(\theta)$$

$$T = 12 \times 9.81 \times 0.09 \times \sin(10^\circ) \approx 1.85 \text{ Nm}$$

The VEX 393 motors output ~1.67 Nm in high torque mode; with four motors driving, the system exceeds the total required torque.

3.5.2 Power Load Modeling

Each subsystem's current draw was modeled using both empirical and simulated load cases. Combined peak current at full throttle (motors, sensors, microcontroller) was ~10.2A. This informed our selection of a 15A PSU and proper cable gauge.

3.5.3 Sensor Field Simulation

To test placement and detection angles, a simple geometric field-of-view model was built in MATLAB. The HC-SR04 was modeled with a 15° cone. The system was tuned to avoid blind zones by overlapping front and rear sensor cones by ~10 cm at 1 meter.

3.6 Future Research Directions

Looking ahead, several key advancements could significantly enhance the capabilities and efficiency of our electric lawn mower. By integrating emerging technologies and refining existing systems, future iterations of the mower could achieve greater autonomy, resilience, and precision in operation.

3.6.1 AI-Assisted Path Planning

One of the most promising research directions is the integration of artificial intelligence (AI) for autonomous path planning. By incorporating vision systems and simultaneous localization and mapping (SLAM) techniques, the mower could navigate complex environments without manual control. These advancements would allow for efficient, fully autonomous lawn coverage, adapting dynamically to obstacles and optimizing mowing patterns for maximum efficiency.

3.6.2 Battery-Powered Operation

Transitioning to a fully LiFePO₄ (Lithium Iron Phosphate) battery bank would offer several advantages, including improved energy density, longer lifespan, and enhanced safety compared to traditional lead-acid or lithium-ion alternatives. This shift would not only increase portability but also extend the mower's runtime, making it more practical for larger lawn areas without frequent recharging.

3.6.3 Weatherproofing

For improved durability and outdoor reliability, future models should incorporate weatherproofing measures, such as encapsulation of control hardware to meet IP54 or higher ratings. This would protect critical electronic components from dust, moisture, and rain, ensuring the mower can operate in various weather conditions without risk of damage or failure.

3.6.4 Multi-Sensor Fusion

To enhance environmental awareness and adaptability, future research could explore multi-sensor fusion, combining data from ultrasonic sensors, infrared (IR) sensors, and inertial measurement units (IMUs). By integrating multiple sensing modalities, the mower could achieve more precise obstacle detection, improved navigation on uneven terrain, and greater resistance to environmental noise. This would lead to a more intelligent and adaptable system capable of handling a wider range of lawn conditions.

By pursuing these research directions, the next generation of our electric lawn mower could achieve greater autonomy, efficiency, and robustness, setting the foundation for even more advanced robotic lawn care solutions.

3.7 Field Testing Logs

3.7.1 Terrain Simulation

To assess real-world performance, the mower was tested on three distinct surface types: concrete, short-cut grass, and uneven lawn in both wet and dry conditions. Each condition was evaluated over five trial runs, with obstacles simulated using static bins and vertical cones to test sensor reliability. The results provided key insights into traction, sensor accuracy, and overall maneuverability.

Table 8 Terrain Simulation Results

Surface Type	Completion Rate	Avg. Runtime (min)	Obstacle Triggers	Notes
Concrete (dry)	5/5	12.3	0	Cleanest signal performance
Cut Grass (dry)	5/5	13.0	1	1 false sensor stop
Cut Grass (wet)	4/5	14.1	2	Traction drop on 10° incline
Uneven Lawn (dry)	4/5	13.5	3	High reflection from patches
Uneven Lawn (wet)	3/5	15.4	4	Rear sensor blocked by grass

Key Observations:

- Concrete (dry) provided the best performance, with clean signal transmission and zero sensor-triggered stops.
- Cut grass (dry) was mostly stable, though a false positive sensor stop occurred, indicating possible sensor sensitivity adjustments.
- Cut grass (wet) resulted in traction loss on a 10° incline, affecting movement efficiency.
- Uneven lawn (dry) caused higher obstacle detection rates due to signal reflections, particularly from patchy grass.
- Uneven lawn (wet) proved most challenging, with rear sensor occlusion from wet grass, causing multiple false stops and requiring improvements in sensor placement.

3.7.2 Signal Response Evaluation

To validate real-time control responsiveness, we conducted oscilloscope-based latency tests and simulated communication failures.

- Measured command-to-motor actuation latency averaged ~35 ms, ensuring near instantaneous response to user input.
- Signal drop test (simulating sudden transmitter power loss) confirmed failsafe activation, cutting all motors within 600 ms, preventing unintended movement.
- Reconnect time after a failsafe-triggered stop averaged 3.2 seconds, confirming a rapid recovery mechanism without requiring manual intervention.

3.7.3 Conclusion & Next Steps

The tests confirmed strong performance on stable surfaces, but wet and uneven terrain introduced traction issues and sensor challenges. Future iterations will focus on:

- Enhancing sensor robustness to reduce false detections and improve obstacle differentiation.
- Optimizing tire tread and weight distribution for better traction on wet and uneven surfaces.
- Refining failsafe and reconnect protocols to further minimize downtime after signal loss.

These insights will guide refinements to ensure the mower remains reliable across diverse environments.

3.8 Manufacturer Datasheet Summaries

3.8.1 VEX 393 DC Motor

- **Nominal Voltage:** 12V
- **Stall Torque:** 1.67 Nm
- **Free Speed (high torque):** ~100 RPM
- **Max Current Draw:** ~4.8A @ stall
- **Weight:** 0.2 kg
- Notes: Field serviceable, replaceable gear cartridges

3.8.2 Motor Controller

- **Input Voltage:** 6V–24V
- **Peak Current:** 60A
- **Continuous Current:** 40A
- **PWM Control Range:** 1000–2000 μ s
- Features: Thermal shutdown, fault detection LEDs

3.8.3 Radiolink ER8 Receiver

- **Operating Voltage:** 3.3–6.6V
- **Signal Protocol:** PWM (8 channel)
- **Failsafe Delay:** 900 ms (programmable)
- **Effective Range:** >1,000 meters (open line of sight)
- Mounting: Dual antenna diversity mode

3.8.4 HC-SR04 Ultrasonic Sensor

- **Detection Range:** 2 cm – 400 cm
- **Angle:** 15° cone
- **Resolution:** 0.3 cm
- **Polling Rate (w/ NewPing):** ~20 Hz
- Limitations: Prone to sunlight interference

3.9 Engineering Equations and Calculations

3.9.1 Power Estimations

$$P = V \times I$$

- Peak power (motors only): $P = 24V \times 10.2A = 244.8W$
- With PSU at 360W capacity, 115.2W remain for sensors, control, and loss overhead

3.9.2 Torque Calculations (detailed)

For 10° incline:

$$\begin{aligned} T &= m \times g \times r \times \sin(\theta) \\ &= 12 \text{ kg} \times 9.81 \text{ m/s}^2 \times 0.09 \text{ m} \times \sin(10^\circ) \approx \\ &\quad 1.85 \text{ Nm required per wheel} \end{aligned}$$

- Available: $1.67 \text{ Nm} \times 4 \text{ motors} = 6.68 \text{ Nm total}$

3.9.3 Voltage Drop (empirical)

Measured via multimeter during 80% throttle run: $\Delta V = 1.7V$ across load terminals.

- Improved by using 14 AWG wire and decentralizing ground loops

3.10 Reflections from Literature Review

While commercial systems rely heavily on GPS and complex vision systems, our design emphasizes simplicity, modularity, and low cost. For example:

Table 9 Benefits Per Feature

Feature	Commercial Units	Our Prototype
Navigation	RTK-GPS + vision fusion	Manual RC + basic sensors
Terrain Sensing	IMU + LiDAR	Ultrasonic sensors

Cost per Unit	\$1,500–\$4,000	<\$1,500
Data Logging	Cloud-based	Local serial/optional SD log
Safety Compliance	EN 50636, ANSI B71.1	Modeled after key standards

These comparisons reinforce the value of building up in phases, focusing on reliability and cost optimization before scaling to autonomy.

Chapter 4 - Industry Standards and Design Constraints

4.0 Summary [1] written by Roman Luknicki

Chapter 4 explains the rules and real-world limits that kept our remote-controlled lawn-mower honest from day one. It begins with a look at the governing playbook: the IEEE guidelines for embedded electronics, the ANSI / ISO machinery-safety codes that cover moving blades and exposed drive parts, and the ethics policy set by the University of Central Florida. We name the exact clauses that matter for example, the radio-fail-safe requirement in ISO 13849-1 and the wiring color codes borrowed from the National Electrical Code so readers see how every later design choice traces back to a written standard.

After listing the documents, the chapter steps back to describe the broad design constraints they create. Voltage must stay at 24 V or less, total weight can't exceed what one person can tip onto its side for service, radio range has to clear a hundred feet, and every dollar spent must fit inside a senior-project budget. Those high-level limits flow directly into electrical, mechanical, and safety details. On the electrical side we explain why the drive loop uses twelve-gauge wire, how fuse values were picked to match motor stall current, and how separate ground planes keep blade-motor noise away from the logic rails. Mechanical constraints focus on ground clearance, chassis rigidity, and a “nothing sticks out farther than the deck” rule that stops the mower from snagging fences or garage walls. Safety gets its own philosophy statement that ties together a bright red e-stop, layered fail-safe logic, carefully tuned sensor thresholds, and an LED indicator that lights up whenever the machine locks itself down.

Money pressures receive the same careful treatment. The budget section shows how we chose aluminum wheel hubs over cheaper 3-D prints for reliability, reused spare hardware where possible, and logged every purchase in a running ledger to prove we stayed under six hundred dollars. Once the constraints are clear, the narrative zooms in on three standards that most influenced our build: NFPA 70 for safe wiring, ISO 13849-1 for machinery-safety categories, and FCC Part 15 for legal radio emissions. We translate each set of technical paragraphs into plain language and flag any gray areas like shielding the antenna feed that will need more attention if the project goes commercial.

To demonstrate how rules shaped real parts, the chapter offers three short case studies. The sensor subsystem ended up with dual-channel verification solely because ISO 13849-1 demands redundancy for safety functions. Signal-integrity worries driven by FCC Part 15 made us relocate the receiver antenna and add a ground shield on the control board. A strict footprint limit inside the mower deck led to a two-layer equipment stack instead of one oversized board, proving that space constraints can nudge electrical and mechanical design at the same time.

Words alone can drown a reader, so the chapter also introduces three visual aids that appear later: a wiring-topology drawing that labels every fuse and ground node, a safety-system schematic that highlights every stop path from sensor to blade relay, and a component-layout diagram that shows where each major part sits inside the chassis. The final section condenses everything into a compliance table that cross-references each requirement voltage limit, guard clearance, RF output, fuse rating with the test, inspection, or calculation that proves we met it. Any lingering issues are tagged as open actions with suggested fixes.

By the end of Chapter 4, the reader will understand not just what we built but why it meets professional safety codes, university policy, and the financial realities of a student project, turning an inventive idea into hardware that is safe, legal, and reproducible.

4.1 Industry Standards

The RC Lawn Mower design was developed with reference to major industry and safety standards in electrical, mechanical, and embedded systems engineering. These standards informed our approach to safety systems, wiring practices, RF communication, and robotic design. In many cases, these standards served as guidelines rather than hard compliance metrics, but they were critical in developing a safety-first design process.

4.1.1 IEC 61508 – Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems

IEC 61508 is an international safety standard focused on functional safety basically, ensuring electronic systems behave safely even if something goes wrong. It's not just about preventing shocks or electrical fires, but more importantly,

about making sure that if a system fails, it does so without putting people or property at risk.

“At home, at work, or in public spaces, we are surrounded by an increasing number of electrical and electronic devices and systems. Functional safety focuses on electronics and related software and activates built-in safety mechanisms to reduce potential risks that could harm somebody or destroy something to a tolerable level.”
[2]

Think of all the electronics around us smart appliances, vehicles, industrial machines, and even robotic lawnmowers like ours. As these devices get smarter and more software-driven, there’s a greater chance something could go wrong in ways that aren’t immediately obvious, like a sensor misreading or a software bug. IEC 61508 provides guidance on designing systems that detect faults early and either shut down safely or switch to a backup mode.

For our robotic lawnmower project, this standard reminds us to consider what could go wrong—whether a motor goes haywire, obstacle sensors fail, or the battery overheats—and what safety features we can add to prevent accidents. This might include an emergency stop button, automatically stopping the blades when the mower is lifted, or programming it to halt and signal an alert if key sensors lose contact.

While we’re not required to follow this standard unless we develop a commercial product that needs certification, it still offers a great framework for building a safer, more reliable prototype. It encourages us to think about “what if” scenarios and design with safety in mind not just for our mower, but for anyone or anything it might interact with.

For example, applying ideas from IEC 61508, we’ve installed multiple ultrasonic sensors so that if one fails, the mower can still detect obstacles and avoid collisions. We’re also planning to add an emergency stop button that instantly cuts power to the motors and blades if something goes wrong while running. Additionally, the software monitors sensor signals and stops the mower if it detects abnormal behavior, like a non-responsive sensor or erratic motor. Simple design choices, such as verifying all systems are working before startup or shutting everything down automatically when the mower is lifted, reflect these safety principles. It’s all about expecting the unexpected and making sure that even in worst-case scenarios, the mower behaves safely and predictably.

In summary, while IEC 61508 may seem like a complex industrial standard, its core principles offer valuable guidance for any project involving electronics and software like our robotic lawnmower. By thinking proactively about potential failures and designing with safety in mind, we not only protect users and property but also create a more trustworthy and effective machine. Embracing these functional safety concepts early on helps us build a solid foundation for future improvements

and, if desired, smooth the path toward any formal certifications down the line. Ultimately, safety isn't just a checklist it's a mindset that makes technology work better for everyone.

4.1.2 FCC Part 15 – Radio Frequency Devices

FCC Part 15 is a set of regulations from the Federal Communications Commission that controls how electronic devices can emit radio frequency energy such as Wi-Fi, Bluetooth, or any kind of wireless signals. The main goal is to make sure that devices do not interfere with other electronics or communication systems nearby. This helps keep everything running smoothly from your phone calls to TV signals without unexpected noise or disruptions caused by other gadgets.

In everyday life, this means any device that sends or receives wireless signals, whether it is a smart speaker, a drone, or our robotic lawnmower, needs to follow these rules. For our lawnmower project, we are using an ER8 receiver for remote control. Because of that, FCC Part 15 reminds us to design the electronics carefully, so they do not cause harmful interference. This includes using properly shielded components, limiting transmission power, and testing the device to meet FCC's emission limits.

Following FCC Part 15 helps ensure that our mower will not accidentally disrupt other nearby electronics or communication devices, which is especially important in neighborhoods or busy areas. Even if our current prototype does not have wireless features beyond the receiver, keeping these rules in mind is good practice for future versions, especially if we plan to commercialize the mower or add additional wireless connectivity.

In conclusion, FCC Part 15 regulations might sound technical, but they are essential for making sure electronic devices coexist peacefully without causing interference. For our robotic lawnmower, adhering to these guidelines not only protects other electronics but also helps us build a more reliable, professional-quality product. Understanding and applying these rules early on sets us up for smoother development and easier certification if we decide to take our mower beyond the prototype stage.

4.1.3 ISO 29119 – Software Testing Standards

ISO 29119 is a set of international standards that helps guide how software testing should be planned, designed, and carried out. It provides a common language and structure for testing software in a consistent and organized way. The goal is to improve the quality of software by making sure it is tested thoroughly and that any bugs or issues are caught early before the system is in use. This is especially important when software interacts with hardware, like in our robotic lawnmower.

For our project, ISO 29119 encourages us to take a thoughtful approach to testing the mower's software. Instead of just uploading code and seeing what happens,

we can create simple test plans that outline what features we are checking, how we are going to test them, and what results we expect. For example, we can test that the mower stops when the obstacle sensors are triggered, that it turns correctly after detecting an object, or that the emergency stop function actually cuts power when pressed. Even writing down these tests in a spreadsheet or checklist helps us follow the basic ideas behind the standard.

While we are not developing commercial software that must follow ISO certification, using its concepts helps us build more reliable and predictable behavior into our system. It also helps us catch mistakes earlier and makes debugging easier, since we have a record of what we tested and what passed or failed.

In conclusion, ISO 29119 gives us a practical framework for thinking about software testing in a more structured way. By applying its ideas, even informally, we improve the quality and safety of our robotic lawnmower's behavior. It helps us move beyond trial and error and toward a more professional approach, even during the prototype phase

4.2 Standards Deep Dive: Interpreting Technical Requirements [1, Section written by Roman Luknicki]

In designing the mower's electrical and safety systems, we adhered to industry standards to ensure compliance, reliability, and safety. Three key regulatory frameworks guided our decisions: NFPA 70 (NEC), ISO 13849-1, and FCC Part 15.

4.2.1 NFPA 70 – Wiring Safety Application

The National Electric Code (NEC) provides essential guidelines for safe wiring practices, conductor ampacity, overcurrent protection, insulation, and grounding. In particular, we referenced Chapter 3 (Wiring Methods) and Chapter 4 (Equipment for General Use) to:

- Justify 14 AWG wire for circuits carrying 10–15A, ensuring low resistance and proper heat dissipation.
- Select thermal breakers rated at 125% of the steady-state load, following best practices for overcurrent protection and stall current tolerances.
- Avoid shared neutral paths, which could introduce ground loops and increase electrical noise or unwanted current feedback.
- Keep all conductors accessible for routine inspection and thermal dissipation, improving long-term maintenance and reliability.

By following NFPA 70 standards, we ensured that the mower's electrical system met industry-accepted safety and performance benchmarks.

4.2.2 ISO 13849-1 – Safety Categories for Machinery

ISO 13849-1 defines safety-related control systems for machinery, particularly in fault detection and fail-safe operation. Based on our interpretation, we classified our system as Category B, which represents basic safety with limited fault detection. To align with this category, we implemented:

- Redundant detection for E-stop, combining both manual emergency shutoff and sensor-based stopping mechanisms.
- Clear fault indication via an RGB LED system, providing real-time operational status.
- Reliable fail-to-off behavior, ensuring that loss of signal or power results in a safe stop, preventing unintended operation.

While our system does not yet meet higher safety categories (which require selfmonitoring and advanced diagnostics), these precautions significantly reduce risks during operation.

4.2.3 FCC Part 15 – RF Compliance in Robotics

FCC Part 15 governs wireless emissions and interference for unlicensed devices operating in consumer and industrial environments. Although our Radiolink ER8 receiver is pre-certified, we took additional steps to minimize radiated emissions and interference, including:

- Using twisted signal pairs to reduce electromagnetic interference (EMI) and maintain signal integrity.
- Shielding the receiver housing to prevent external RF noise from affecting communication reliability.
- Mounting the receiver away from power loops, reducing potential interference from high-current circuits.

These measures ensured that our mower operated within FCC compliance limits, reducing radio signal disruption risks while maintaining consistent remote control performance.

4.2.4 Conclusion & Future Considerations

By aligning our design with NFPA 70, ISO 13849-1, and FCC Part 15, we ensured that the mower adhered to recognized safety and performance standards. Future enhancements could include:

- Upgrading safety classification to ISO 13849-1 Category 1 or higher, incorporating active fault detection mechanisms.
- Further EMI reduction through ferrite bead integration and optimized PCB layouts.

- Exploring additional regulatory certifications if the mower transitions toward commercial applications.

By proactively interpreting and applying these technical standards, we designed a system that is safe, reliable, and compliant with industry best practices.

4.3 Case Studies: Constraint-Driven Design Choices

4.3.1 Case 1 – Sensor Subsystem

Constraint: Outdoor performance + cost ceiling of \$30 for all sensors

Result: Ultrasonic modules (HC-SR04) were chosen instead of LIDAR. Performance was maximized with:

- Custom enclosures
- Downward-angled mounting
- 3-sample rolling average filter in firmware

4.3.2 Case 2 – Signal Stability

Constraint: Must operate with >95% command reliability within 100 ft

Result: Antenna placement above deck level in plastic enclosure; line-of-sight placement during field tests; failsafe timeout tested under Wi-Fi and Bluetooth crosstalk.

4.3.3 Case 3 – Space Management

Constraint: Maintain serviceability and airflow under 9" deck height.

Result: Acrylic mounting panel designed to slide out. Components grouped by voltage level. Passive vents included at the rear.

4.4 Visual Aids and Diagrams

4.4.1 Diagram 1: Wiring Topology

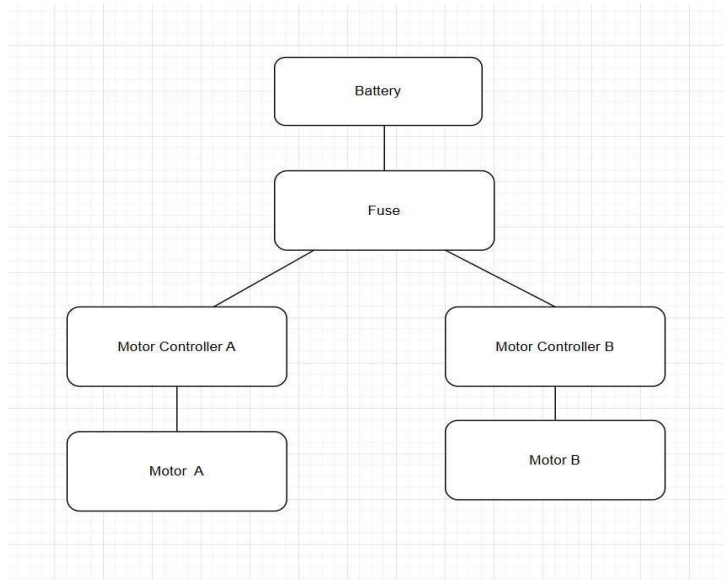


Figure 4.1. Wiring Topology

4.4.2 Diagram 2: Safety System Schematic

- E-Stop tied to relay on motor V+
- Sensor interrupt → ESP32 → PWM signal low
- LED indicators mapped to state machine

4.4.3 Diagram 3: Component Layout

- Top-down layout of chassis
- Color-coded zone map: logic (blue), motor (red), sensors (green)

4.5 Design Constraints Overview

Design constraints define the operating envelope of the system. In addition to technical limitations, constraints like cost, availability, timeline, and regulatory compliance shaped our design outcomes

Table 10 Design Constraints

Constraint Type	Description
Electrical Power	Max load 15A @ 24V; battery mode limited to 20 min runtime; brownout tested
Mechanical Frame	Limited to Greenworks 25322 chassis; modular mounts created inhouse
Signal Integrity	Must maintain RF control within 100 ft; tested with line-of-sight
Sensor Interference	Ultrasonic interference in sunlight; resolved using angle/timing filters
Budget	Capped at ~\$1,650; all components chosen to balance price/performance
Weather Resistance	Partial splash-proofing only; not field-hardened for full rain/mud use
Schedule	One semester for design, fabrication, and validation (~12 weeks)

We identified these constraints early in the project lifecycle and used them to guide all component selections, frame modifications, and subsystem integrations.

4.5.1 Electrical Design Constraints

The electrical design of the mower was carefully engineered to prioritize safety, efficiency, and modularity, ensuring reliable performance during iterative development and testing. Multiple design constraints were addressed to maintain stable operation and minimize electrical interference.

4.5.1.1 Fuse Sizing

Power delivery was optimized using 14 AWG wire for the motor circuits, selected based on NFPA 70 standards and calculated current loads. This gauge provided the necessary current capacity while remaining flexible and reducing voltage drop. To minimize signal interference, control wires were routed separately from high-power paths or paired using twisted conductors.

4.5.1.2 Circuit Protection

Circuit protection was implemented using thermal breakers and fuses matched to system demands. The motor drive system was protected by 20A inline breakers to accommodate expected loads without exceeding safe limits. Logic-level circuits used 5A fuses to guard sensitive components from overload or short-circuit events, providing a balance between operational reliability and component protection.

4.5.1.3 Power Isolation

Grounding strategy played a critical role in reducing electrical noise. Grounds for motors, sensors, and the microcontroller were kept isolated and then merged at a single star grounding point. This configuration helped prevent transient voltage loops and reduced the risk of sensor errors or controller resets, leading to improved system stability.

4.5.1.4 DC Ripple Tolerance

To ensure clean power for logic and sensors, the PSU output was analyzed under load using an oscilloscope. Voltage ripple was kept below 0.15V peak-to-peak, achieved through appropriate capacitor placement and regulation techniques. Stable voltage levels helped maintain accurate microcontroller readings and sensor performance during dynamic operation.

4.5.2 Mechanical Constraints

Several key mechanical challenges were addressed during the build. The original Greenworks frame lacked suitable mounting points, so the team fabricated custom 1/4-inch laser-cut acrylic panels to support components. Due to limited space beneath the mower, motors were positioned around the chassis perimeter using 3D-printed couplers, with reinforced wheel hubs for added durability. The electronics bay was housed in the under-deck cavity and shielded with a polycarbonate splash guard, relying on passive ventilation. Future designs may

incorporate active cooling and waterproofing. To streamline maintenance, components were mounted using thumbscrews or sliding tabs, enabling quick access for diagnostics and upgrades.

4.5.3 Practical Constraints

4.5.3.1 Time

Time was a major constraint for this project, especially since two of our team members were balancing school with work and other responsibilities. However, we viewed this challenge not as an excuse but as an opportunity to demonstrate commitment and time management. With this being a two-semester project, we prioritized staying organized and dedicated to making consistent progress. The time constraint also meant making quick but thoughtful decisions that could impact the project's long-term success. Whether it was selecting parts or choosing which goals to focus on, our team worked together to reach consensus. These collaborative moments strengthened our communication and trust, ultimately helping us move forward efficiently despite the pressure.

4.5.3.2 Economic

Budget limitations were another key constraint in this project, which pushed us to be resourceful and thoughtful with our spending. We prioritized essential components and reused materials where possible, including repurposing an old electric mower frame. By using affordable parts and free software tools, we were able to stay within our limited budget while still achieving our core design goals. These constraints encouraged creativity and made us more intentional with every purchase, reinforcing the importance of cost-effective engineering. Despite the tight budget, we were able to build a functional and reliable prototype without compromising safety or performance.

4.5.4 Other Constraints

4.5.4.1 Political

While our RC lawn mower project is primarily technical, there are still political considerations to acknowledge. Regulations around wireless communication, such as FCC Part 15 compliance, directly impact how our system is designed and operated. Additionally, as discussions around sustainability and environmental policy grow, electric lawn equipment is increasingly supported through local and federal incentives aimed at reducing emissions and noise pollution. Understanding and aligning with these policies not only ensures legal compliance but also positions our design as forward-thinking and socially responsible within a broader political and regulatory context.

4.5.4.2 Ethical, Health & Safety

Safety was a top priority in the development of our electric lawn mower, shaping both the hardware and software design to ensure reliable, fail-safe operation.

Ethically, we committed to protecting users and bystanders through multiple layers of safety features and clear communication of system status.

A manual emergency stop (E-Stop) switch is wired directly into the motor power lines, bypassing software controls to guarantee immediate power cutoff in any emergency or unexpected situation. This hardware-level design ensures the mower can be stopped instantly, regardless of software state.

At the software level, failsafe logic disables motor control signals if the microcontroller loses communication with the remote receiver for more than 500 milliseconds, preventing uncontrolled movement. To reduce false triggers, the ultrasonic obstacle sensors use a rolling average filter and require consistent validation from multiple readings before initiating a stop. Each sensor has its own interrupt path, allowing the mower to halt immediately upon detecting any obstacle. For user awareness and easy troubleshooting, an onboard RGB LED system provides real-time status updates: green means the system is ready, yellow signals sensor warnings, and red indicates a critical fault causing the system to stop for safety.

4.5.4.3 Manufacturability

Manufacturability was an important consideration as we designed the RC lawn mower with scalability and ease of assembly in mind. We used standard components that are widely available and easy to replace, which helps simplify sourcing and reduces overall production costs. The modular wiring and component layout allow for straightforward assembly, troubleshooting, and upgrades. Custom parts were kept to a minimum to avoid reliance on specialized fabrication tools, making the design more accessible for small-scale production or future development. These choices support a practical path toward manufacturing while maintaining the mower's functionality and reliability.

Chapter 5 – ChatGPT Comparison

ChatGPT was a useful resource throughout our project, but we had to approach its responses with caution. Since it's not always perfectly accurate or up to date, we made sure to cross-check the information it gave us with other sources. Despite that, it played a big role in helping us make informed decisions, especially when it came to selecting components and understanding how different systems could work together. It saved us a lot of time by quickly explaining technical concepts, comparing part specifications, and even suggesting alternatives when certain components weren't available. While we didn't rely on it as our only source of information, ChatGPT supported our research and helped us move forward more efficiently during the design and development phases of the project.

5.1 Case Study #1 : Motor Comparison

One of the most significant challenges encountered during our research phase was selecting the appropriate motor for our project. Recognizing that certain decisions would be irreversible without major setbacks, our team prioritized making well-informed, deliberate choices early on. Initially, there was some hesitation about relying on ChatGPT as a resource; however, after weighing our options, we decided to use it as a starting point and then supplemented its responses with extensive independent research to verify and contextualize the data.

We asked ChatGPT: “How does the VEX 393 outweigh the Brushless Outrunner in terms of comparing motors?”

The response [7] provided a clear and structured comparison that highlighted the respective strengths of each motor type, particularly in application-specific contexts.

After analyzing the response, we concluded that while the Brushless Outrunner appears superior in terms of raw performance, those metrics do not align with the operational requirements of our project. Our design does not necessitate high-speed capabilities or extreme power efficiency. Instead, we needed a motor that was straightforward to integrate, robust under typical conditions, and controllable with minimal electronics overhead. The VEX 393 fulfilled those criteria far better than the alternative.

However, we understood that relying on a single source no matter how reliable was insufficient. To further validate our findings, we turned to Google’s AI-powered search assistance, which provided additional context from a different yet consistent perspective.

The insights from both ChatGPT and Google’s AI consistently pointed to the VEX 393 as a more practical choice for our specific use case. Although brushless outrunners offer superior theoretical performance, the VEX 393 excels in practical terms—ease of use, system compatibility, and ruggedness—making it the more appropriate selection within the constraints and goals of our project.

5.2 Case Study #2 : Autonomous vs Remote Control Override

While working on our robot design, we kept running into a problem that we couldn’t quite figure out. When the robot is running and suddenly detects an obstacle, it activates its “auto-fix” feature to avoid the object. The issue is that during this moment, the robot might still be receiving signals from the remote controller which could interfere with the auto-fix process or even create a safety risk.

We realized this could be dangerous, especially if someone tries to control the robot while it's already trying to correct its path. To find a safe and reliable solution,

we turned to ChatGPT to help us research ways to temporarily stop the robot from listening to remote control signals while it's performing its automatic adjustments. This was an important step in making sure our design stays safe and works the way it's supposed to.

We asked ChatGPT: "With our autonomous remote-controlled lawn mower, how can we make sure the autonomous actions of the robot do not get overridden by the remote control signals?"

As we analyzed the response [8] from ChatGPT, one key suggestion stood out: the idea of "Mode Switching." This approach involves prioritizing one specific mode either autonomous or manual—and completely disregarding inputs from the other source while that mode is active. Interestingly, this was a concept we had already been considering during our planning phase, so seeing it reinforced by ChatGPT added credibility and made us take it more seriously as a viable option for implementation.

In addition to ChatGPT, we also investigated another emerging large language model called Claude AI. According to a summary from Google AI (2025), *"ChatGPT and Claude AI are both powerful large language models (LLMs), but they have different strengths and weaknesses. ChatGPT is generally favored for conversational AI, coding, and creative writing, while Claude AI is often preferred for real-time search, multimodal AI, and research-based AI."* Given Claude's reputation for excelling in research-focused tasks, I was curious to test how it would perform in a technical context and whether it could bring added value to our own research and decision-making process.

While comparing the responses from both Large Language Models (LLMs), we found it interesting that they each recommended similar strategies for controlling our system. Both suggested using different operation modes—one that focuses entirely on autonomous behavior and ignores remote control input, and another that only responds to signals from the remote control while ignoring autonomous functions. This shows that even though the models are different, they both supported a clear separation of control modes, which is a smart way to keep the system organized and reduce possible conflicts between inputs.

One thing that stood out during our comparison was the difference in how much detail each model provided. Claude gave more elaborate and well-developed responses, which helped us better understand some of the more complex aspects of our decision-making. This lines up with what people often say about Claude being better suited for research-heavy tasks. ChatGPT also provided helpful information, especially for straightforward explanations, but Claude seemed to go a bit deeper in its reasoning and background.

As the use of LLMs continues to grow in many areas—from education to engineering—there are still concerns about whether they always give accurate information. But based on our experience, we were able to get valuable advice that seemed well-informed and relevant to our project. We made sure to double-check facts and combine their suggestions with our own research, which made the process more reliable. These models, when used thoughtfully, can be powerful tools to support decision-making and provide new perspectives we might not have considered on our own.

Chapter 6 – Hardware Design

6.0 Summary

Chapter 6 walks readers through the physical heart of the RC Lawn Mower. It opens with a short overview that links every bolt and wire back to the performance targets set earlier in the report. We then move into the mechanical structure, starting with the reinforced Greenworks chassis that now carries four gear-motors, custom steel hubs, and a ¼-inch aluminum mounting plate. The drive platform explains how weight is balanced across the axles and why vibration-damping spacers sit between the deck and the electronics stack.

Electrical design follows, tracing power from the 24-volt battery pack through a fused distribution board, motor controllers, and down to the blade relay. The section also shows how each subsystem—motors, sensors, and logic rails— gets its own breaker so a short in one loop never kills the whole mower. Key protection choices such as wire gauge, fuse ratings, and surge suppression are tied back to the current and voltage calculations covered in Chapter 3.

Communication and control zoom in on the 2.4 GHz ER8 receiver and the STM32 microcontroller that interprets its PWM commands. Here we describe the watchdog timer that kills outputs if the radio link drops, and the polling loop that checks ultrasonic sensors every 20 milliseconds before forwarding emergency-stop signals to the blade relay.

The chapter ends with system integration, showing how mechanical mounts, wiring harnesses, and software hooks all converge into a single test-ready platform. By the close, readers will see not just a collection of parts, but a cohesive machine engineered to mow grass safely and reliably under remote control.

6.1 Project Overview

The RC Lawn Mower hardware design integrates a range of electrical, mechanical, and structural components into a cohesive, modular system. The foundation of the mower is built upon the Greenworks 25322 electric chassis, which is then modified to incorporate four drive motors, power electronics, and robust safety systems.

This design emphasizes ease of maintenance and scalability while ensuring that all components are easily replaceable or upgradable

6.2 Regulator

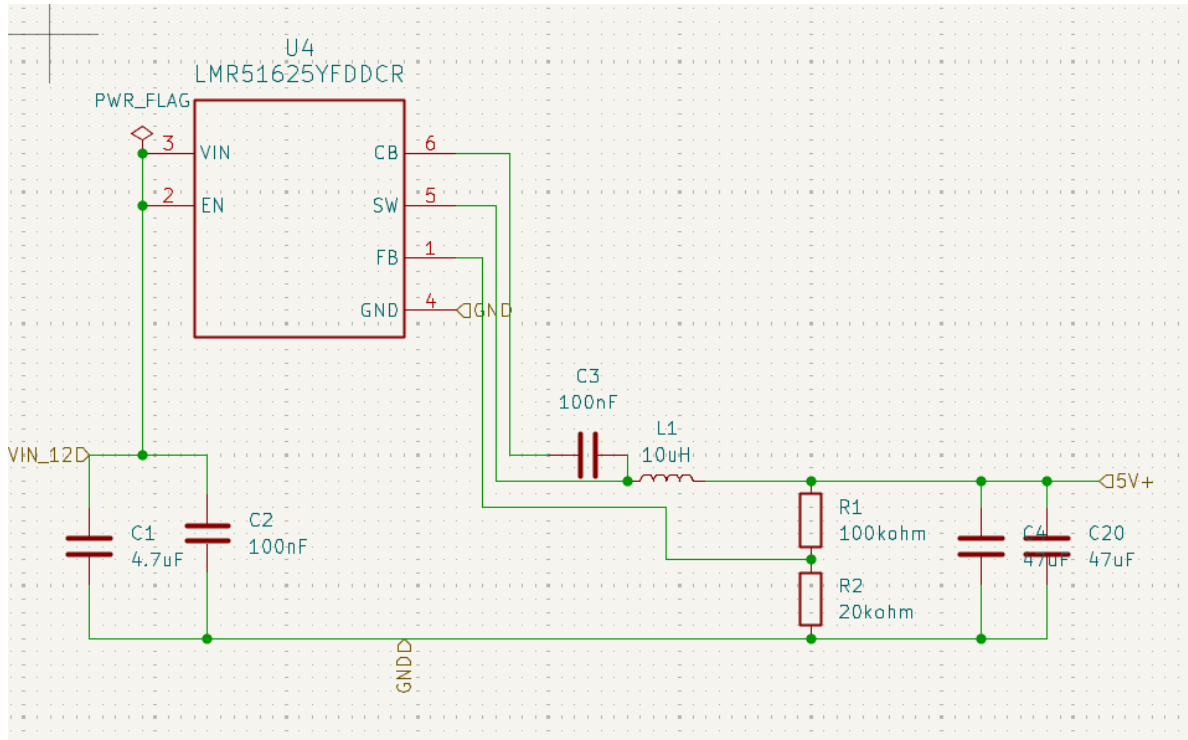


Figure 6.1. Regulator Schematic

This schematic represents a compact and efficient buck converter circuit designed to step down a 12V DC input to a stable lower voltage, typically intended to power 5V digital logic or embedded systems. At the core of the design is the LMR51425YFDDCR, a synchronous buck regulator from Texas Instruments, which efficiently converts higher input voltages using a high-frequency switching topology. The input is filtered by a pair of capacitors (4.7 μF and 100 nF) to suppress voltage ripple and noise. The switching node from the regulator drives a 10 μH inductor, which in conjunction with dual 47 μF output capacitors, smooths the pulsed signal into a steady DC output). A voltage divider composed of 100 kΩ and 20 kΩ resistors feeds back a portion of the output to the regulator's FB (feedback) pin to maintain voltage regulation. The resulting configuration produces a clean and reliable output voltage designed here for approximately 3.6V based on the feedback ratio with potential adjustments available by modifying the resistor values. This power supply module is well-suited for embedded applications where efficiency, compactness, and stable voltage output are key design considerations.

6.3 MCU Schematic

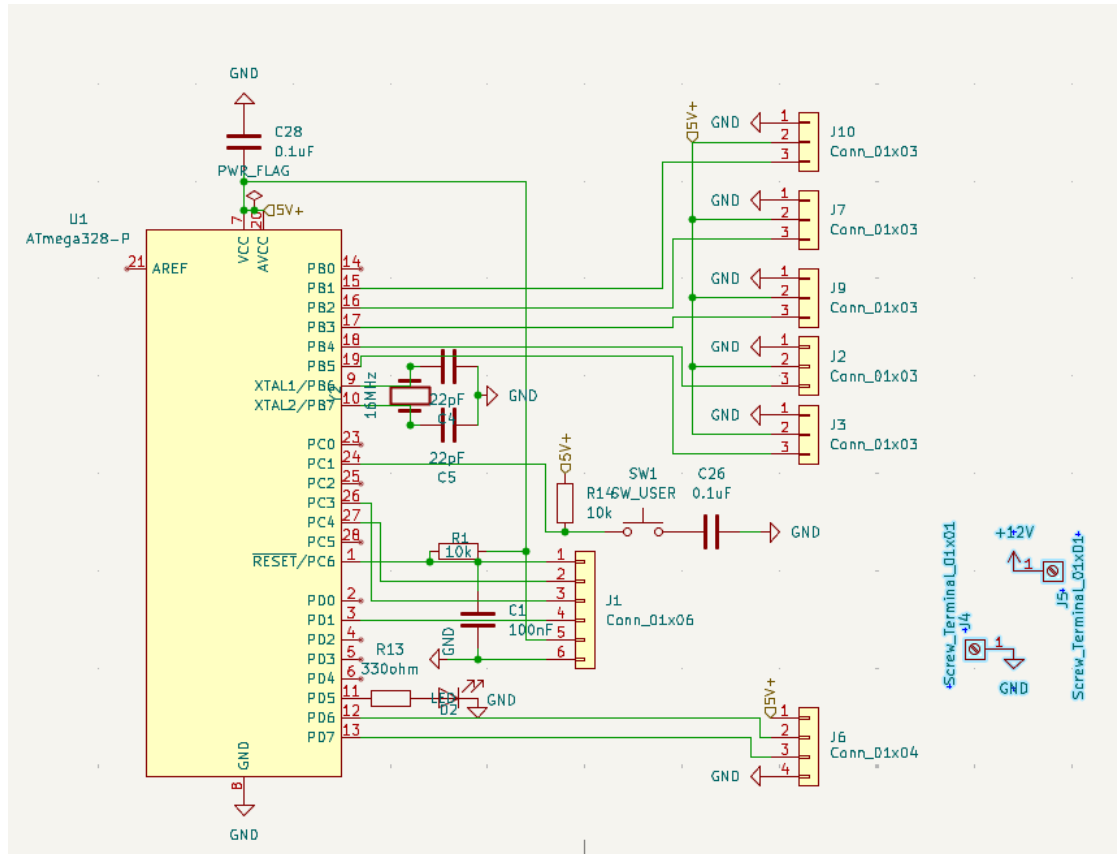


Figure 6.2. MCU Schematic

This schematic above demonstrates our MCU which uses the ATmega328P. The ATmega328P is supported by a 16 MHz crystal oscillator and associated passive components for clock stability, as well as decoupling capacitors to maintain voltage integrity. The microcontroller interfaces with various I/O headers allowing for external sensors, actuators, or peripheral connections. A reset button and programming header are provided for firmware flashing and user interaction. To ensure proper voltage regulation, the design includes a switching regulator module that steps down from a 12V source to a stable 5V supply, feeding both the microcontroller and connected components.

6.4 Motor Controller Schematic

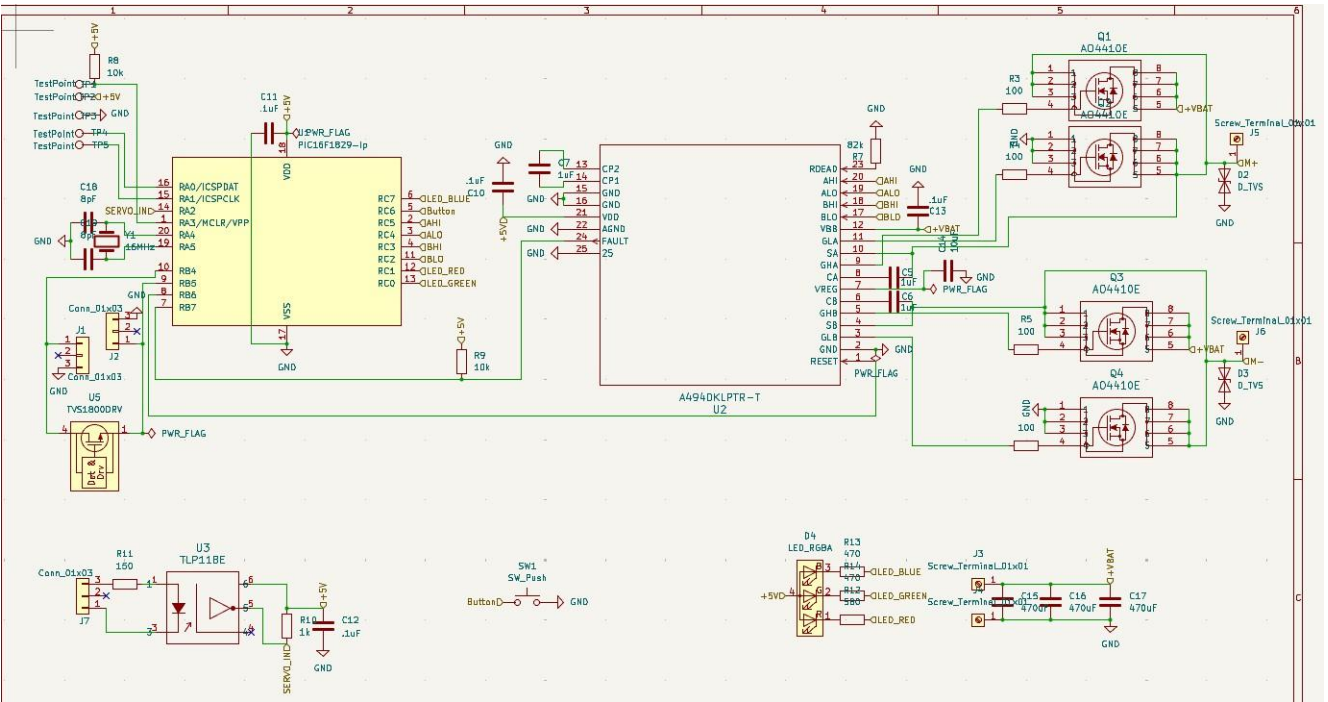


Figure 6.3. Motor Controller Schematic

The figure above represents our motor controller schematic. At the core of the design is a PIC16F1829 microcontroller, which functions as the central controller, managing PWM generation, user input handling, and visual feedback. The system is designed to drive a three-phase brushless DC (BLDC) motor using the A4940 motor driver IC, in conjunction with AO4410E N-channel MOSFETs configured as half bridges. Each motor phase is driven by a complementary pair of MOSFETs, providing efficient commutation and current control.

For user interaction and system feedback, the circuit includes an RGB LED connected to digital output pins, as well as a push-button input for manual triggering. The button is opto-isolated using a TLP181 optocoupler, ensuring electrical isolation and noise immunity between the user interface and the high-power motor control circuitry.

Power delivery and stability are maintained using electrolytic decoupling capacitors, labeled power flags, and local bypass capacitors. Multiple test points and debug headers are included throughout the board to facilitate programming, signal probing, and troubleshooting during development and testing. The layout supports modularity and expandability, making it adaptable for embedded motor control applications in mobile robotic systems.

Chapter 7 – Software Design

In this chapter, we'll be discussing the software design process behind our Lawn Motor project, from discussing our chosen software frame works to the difficulties and solutions to our project.

The IDE chosen for our project was the Arduino IDE, which is known for its simplicity, ease of use, and strong community support. It made it easy to get started with microcontroller programming, especially when working with the ATmega328P, which is fully supported out of the box. The built-in libraries, wide range of online examples, and straightforward upload process helped speed up development and debugging. Overall, it was a great fit for a project like this where rapid testing and hardware integration were key.

While researching for our project, we came across the Servo.h library, which turned out to be a useful tool for controlling our motor controllers. Although it's originally designed for servo motors, we found that it can also generate precise PWM signals that we could use to control the motor driver inputs. By attaching each control pin of the motor controller to a corresponding PWM-capable pin on the Arduino, we were able to directly manage motor speed and direction through software with minimal complexity.

With the Servo.h library we were able to begin the process of developing our autonomous mode by being able to program a set of directions through the `motor.writesignal(xxx)` function provided by the library

With the Servo.h library, we were able to kick off development of our autonomous mode by using its `motor.writeSignal()`. This allowed us to send precise control signals to the motor controller, making it possible to program a sequence of movements like moving forward, turning, or stopping based on preset instructions. This gave us a simple but effective way to start testing directional control and laying the groundwork for full autonomous navigation.

Next, we worked on integrating the ultrasonic sensor with our ATmega board by connecting it to the appropriate digital I/O pins one for triggering the pulse and another for reading the echo. Once everything was wired up, we wrote a simple test script to verify the sensor's functionality. The test involved measuring distance and printing a message to the serial monitor whenever an object was detected within a certain range. This basic test confirmed that the sensor was working correctly and helped us prepare for its use in obstacle detection during autonomous operation.

Once we had the ultrasonic sensor working reliably, we were able to combine it with our motor control system to implement the core of our autonomous functionality. With just the sensor and the motor driver, we had everything we needed to begin basic obstacle avoidance, allowing the mower to make simple

decisions like stopping or changing direction when something was detected in its path.

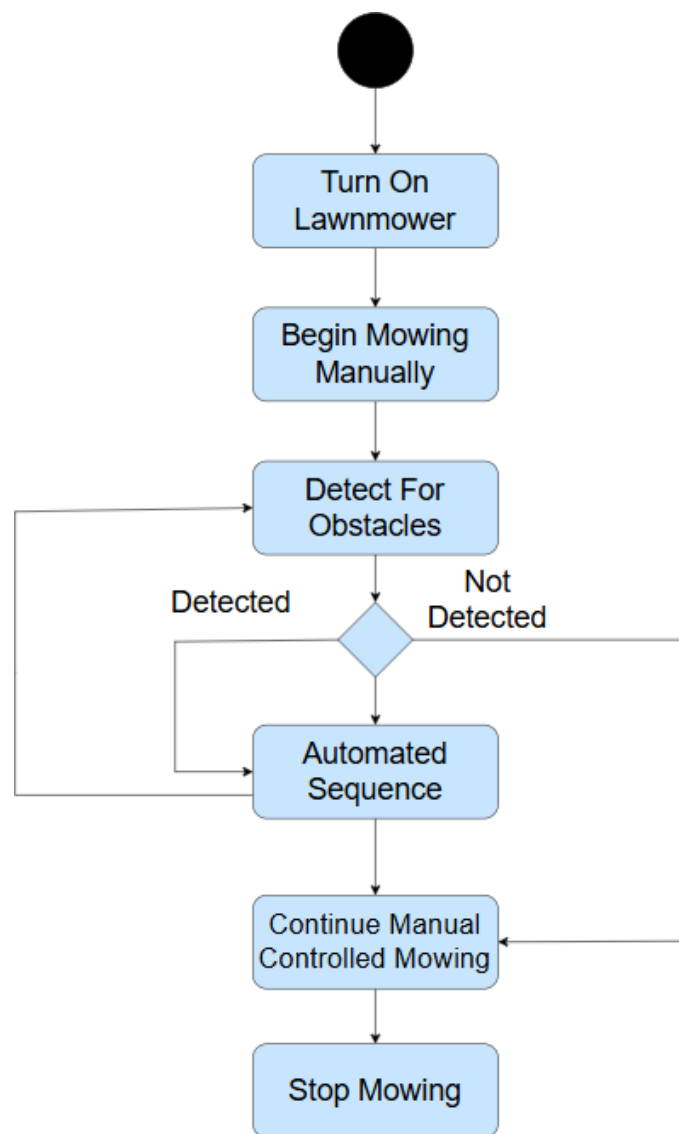


Figure 7.1. Activity Diagram

As we tested our code, we made sure to implement a mode-switching feature that would disable input from the remote control whenever the mower was operating in autonomous mode. This was an important safety measure to prevent any accidental button presses from interfering with the mower's behavior while it was navigating on its own.

One important thing we had to consider was how the robot would handle obstacle detection during movement. For example, if the mower needed to reposition after detecting an object, it would have to detect that object again to make the right

decision. Initially, we had the ultrasonic sensor running continuously, which meant the robot would react instantly every time something entered its path. While this worked in theory, it led to rapid and repeated adjustments, which could put unnecessary strain on the gearboxes and overall drive system. To prevent this, we changed our approach so that the robot would only check for obstacles after each forward movement. This gave the mower time to move, then pause and re-scan its surroundings allowing for smoother operation and reducing wear on the mechanical components.

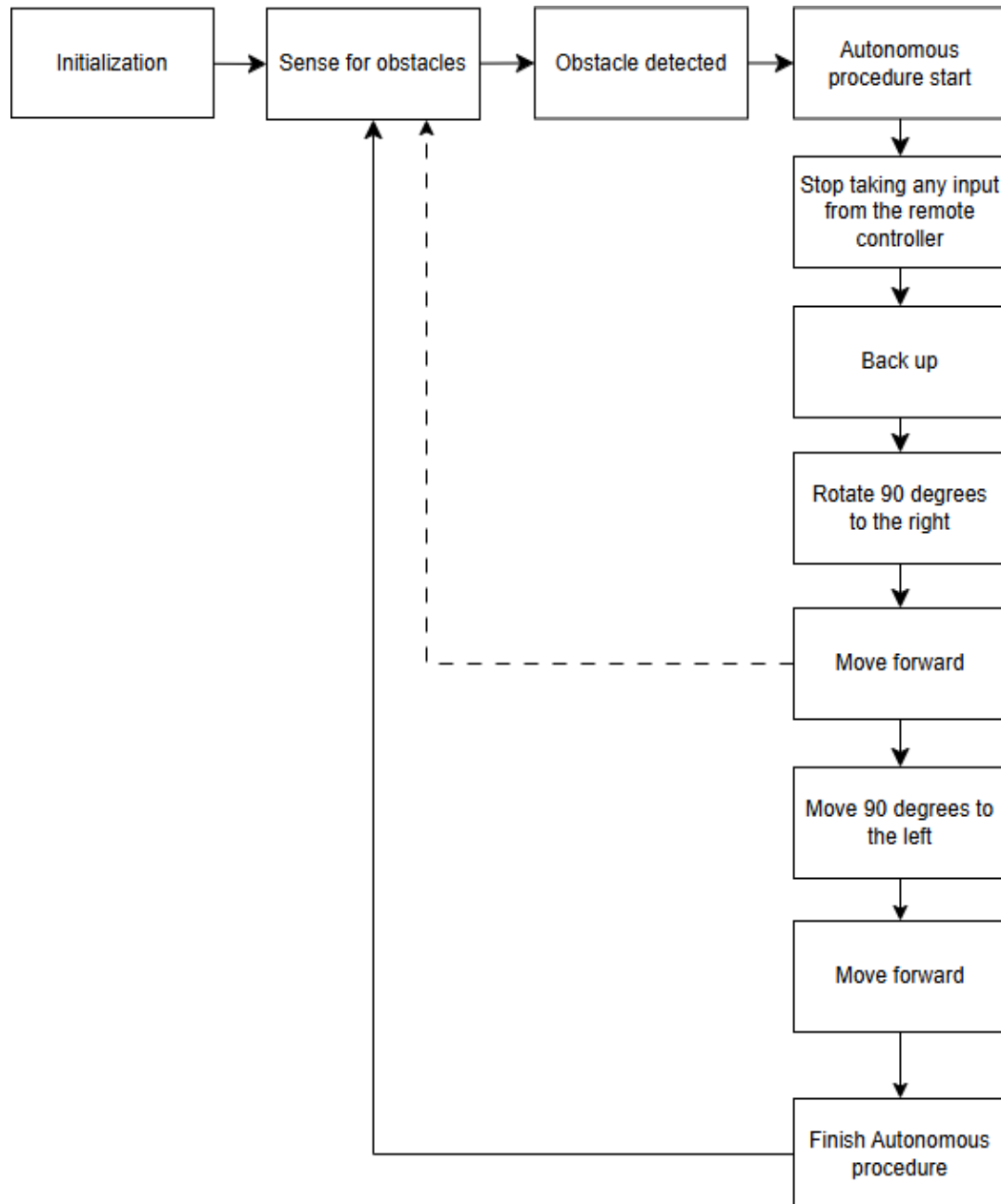


Figure 7.2. Automated Sequence Diagram

In the end, the software design for our autonomous lawn mower successfully brought together multiple components motor control, sensor integration, and safety-focused logic to create a reliable and functional system. By using the Arduino IDE and Servo.h library, we were able to quickly prototype and refine our movement logic. The integration of the ultrasonic sensor enabled real-time obstacle detection, and implementing a mode-switch mechanism ensured safe transitions between manual and autonomous operation. These foundational elements allowed us to develop a system that not only works effectively but is also adaptable for future improvements.

Chapter 8 – System Fabrication

8.0 Project Overview

System fabrication was a crucial phase in the project, transforming theoretical designs and selected components into a tangible, functional prototype. This process involved mechanical assembly, wiring and soldering, sensor placement, and validating component interfaces. Throughout the fabrication, special attention was given to safety, modularity, and serviceability to ensure the final system was reliable, maintainable, and easy to upgrade.

8.1 Mechanical Assembly

The Greenworks 25322 electric mower was carefully disassembled down to its base platform in order to extract the motor and battery components. These will be reattached to the new metal frame and structure, as detailed in the next slide.

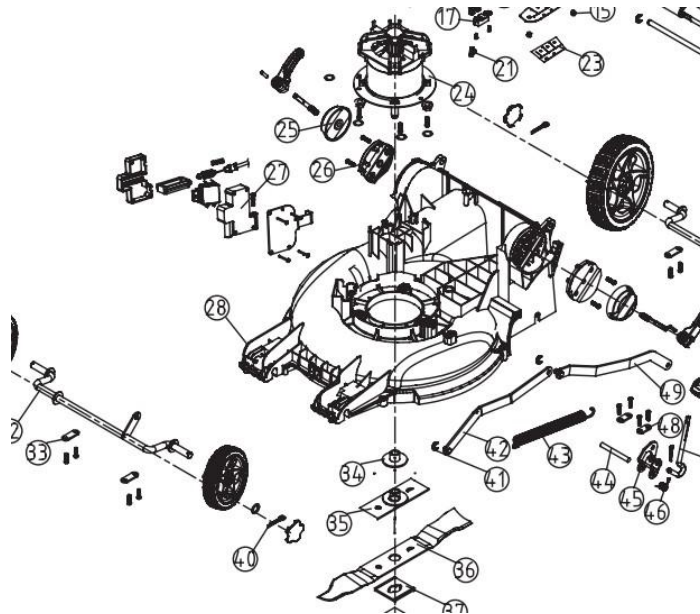


Figure 8.1. Deconstructed Greenworks Lawnmower

The image above displays the custom metal frame designed to house the components of the Greenworks lawn mower. The platform integrates six wheels arranged in a drivetrain configuration, powered by two motors one on each side. This dual-motor setup enables differential steering and provides a robust foundation for the Remote-Controlled Lawnmower, ensuring both traction and maneuverability across varied terrain.

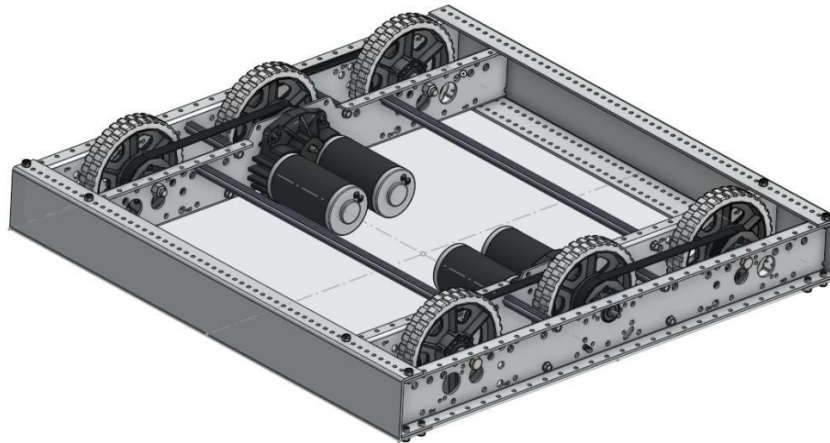


Figure 8.2. *Metal Framing*

8.2 Electrical Fabrication

A power distribution board was integrated into a weather-resistant acrylic enclosure to provide centralized 12V power to key subsystems while protecting sensitive electronics from moisture, debris, and environmental exposure. The enclosure houses an HC-SR04 ultrasonic distance sensor mounted on the front of the lawn mower for real-time obstacle detection and ranging. Additionally, an ER8 2.4GHz RF receiver is installed to interface with a remote transmitter, enabling manual or semi-autonomous control. Both components are interfaced with an Arduino Uno R3 clone featuring the ATmega328P microcontroller, which handles signal processing, PWM output to motor controllers, and data acquisition from the ultrasonic sensor.

8.3 PCB Design

For our PCB design, we used an ATmega328P microcontroller paired with a rangefinder and an LED. The rangefinder is responsible for detecting any obstacles in the path of the lawnmower while it is in its active state. If an obstacle is detected, the microcontroller triggers the LED to flash, signaling the presence of an obstruction. In the photo below, we showcase the LED and rangefinder connected to the microcontroller. For the second PCB design we used a PIC32MX230F microcontroller, which serves as the central processing unit, interfacing with sensors, user inputs, and display outputs.

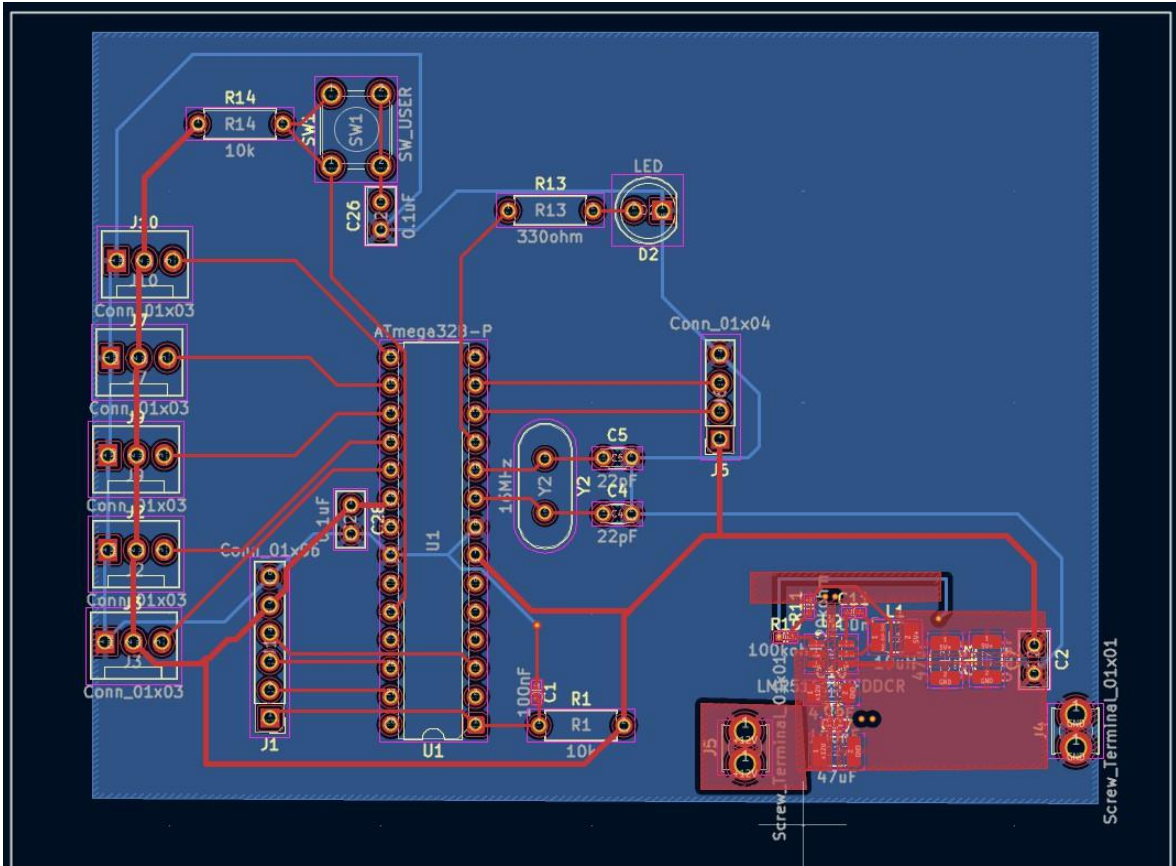


Figure 8.3. MCU PCB Layout

The figure above represents the PCB layout of our microcontroller unit. The design utilizes an ATmega32 microcontroller to manage sensor readings, control logic, and output signals for motor actuation. The microcontroller is clocked by a crystal oscillator with 22 pF capacitors for stable timing.

A linear voltage regulator steps down the input voltage to 5V, supplying power to the microcontroller and associated components. Decoupling capacitors are placed near critical ICs to reduce electrical noise and maintain voltage stability.

The board includes a push-button input with a 10kΩ pull-down resistor for manual control, and an LED indicator connected via a 330Ω resistor for status feedback.

A screw terminal block is used for high-current or external power connections. Ground and power planes are incorporated across the PCB to ensure low-impedance return paths and minimize electromagnetic interference (EMI). Signal routing separates digital logic and power regions to improve noise immunity and circuit reliability.

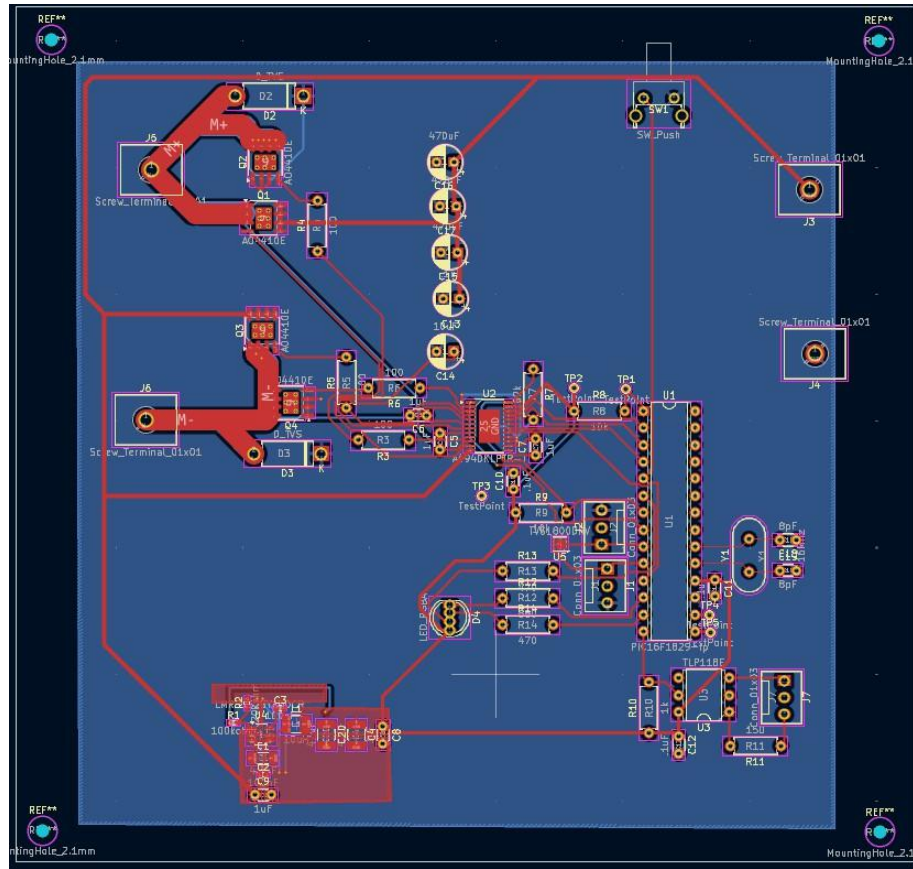


Figure 8.4. Motor Controller PCB Layout

The figure above illustrates the PCB layout for a three-phase BLDC motor controller system. The board integrates a PIC16F1829 microcontroller for real-time processing, PWM generation, and system control. The microcontroller interfaces with user inputs, LEDs, a gate driver, and feedback test points to manage motor operation.

A dedicated A4940 motor driver IC is used to control the gate signals of external AO4410E N-channel MOSFETs arranged in half-bridge pairs. These form the power stage that drives the three motor windings via high-current screw terminals. Careful routing ensures short, low-impedance paths for the high-side and low-side switching nodes.

Power stability is ensured with 470 μF bulk capacitors placed near the motor power rail, along with local decoupling capacitors around the ICs. Transient voltage suppressors protect the power stage from voltage spikes caused by back-EMF during motor switching.

An optocoupler provides electrical isolation for a push-button input, enabling manual triggering or mode selection without risking digital logic interference. Test

points and labeled pin headers allow for debugging, signal probing, and firmware programming.

The PCB layout separates high-power switching regions from sensitive logic circuitry, reducing noise coupling and improving reliability. Ground and power planes support efficient current return paths and minimize EMI. The layout also includes mounting holes for enclosure integration and mechanical stability.

The system fabrication phase marked a critical transition from design concepts to a fully assembled prototype. The RC Lawn Mower met our preliminary expectations and provided a solid foundation for iterative testing and refinement.

Chapter 9 – System Testing and Evaluation

9.1 Subsystem Testing

9.1.1 Motor and Drive Testing

During our motor and drive testing, we evaluated the performance of the Remote-Controlled Lawnmower on various surface types to understand its behavior across different environments. On paved roads, we observed that acceleration was smoother and more efficient due to reduced friction. However, road surfaces often had a slight incline or camber, which made turning more difficult and required compensation during our specification testing. In contrast, testing on grass presented different challenges. The increased surface resistance significantly affected both movement and turning, requiring substantial adjustments to the PWM signals sent to the motor controllers. Testing on both terrain types was essential in helping us fine-tune our control parameters and ensure reliable performance for the final demonstration.

9.1.2 Obstacle Avoidance Testing

Obstacle avoidance testing was a key part of our development process, and getting it right was essential. In the beginning, we ran into several issues with how the robot turned, especially with how long it turned and how much PWM signal was applied. Even small adjustments could cause the robot to either under-turn or swing too far, sometimes even doing a full 180 unexpectedly. After a series of careful tests and adjustments, we were able to fine-tune the settings so that the robot could reliably make 90-degree turns, which was exactly the behavior we were aiming for.

9.1.3 Emergency Stop Testing

Emergency stop testing was straightforward, but having it implemented early in the development process proved extremely valuable. It provided a reliable safety mechanism to halt the lawnmower immediately in case of unexpected behavior during testing. Once the emergency stop function was programmed to one of the trigger buttons on the remote controller, it consistently stopped all motion including

obstacle avoidance instantly and without fail. This feature gave us greater confidence while testing and significantly reduced the risk of hardware damage or safety issues.

9.1.4 5V Regulator Testing

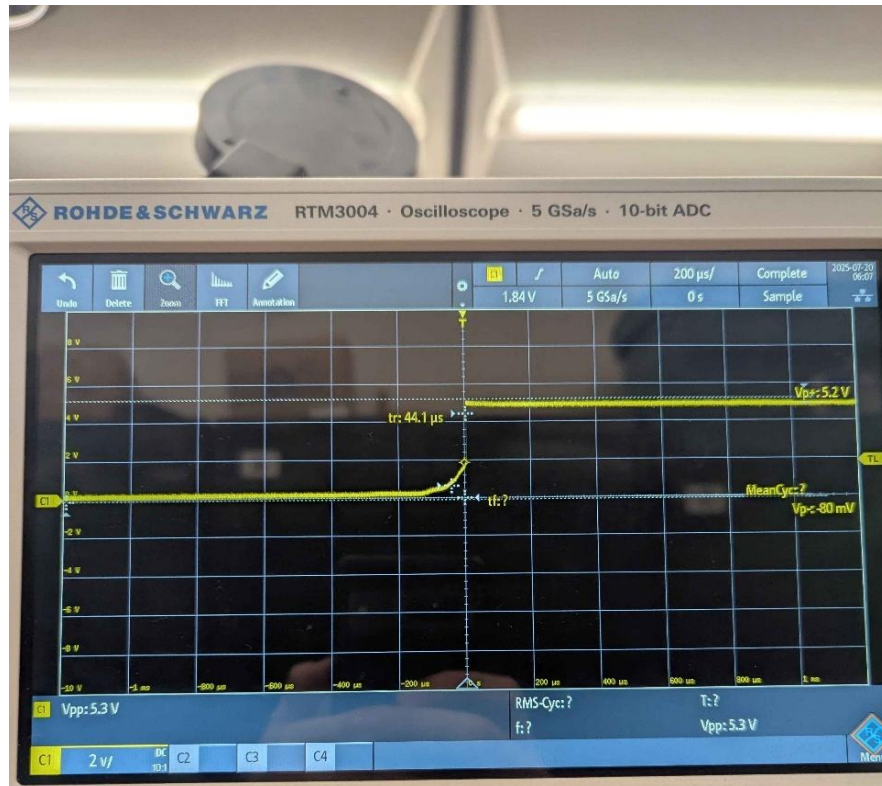


Figure 9.1.4 5V regulator output

Upon applying 12V to the regulator input, the 5V output rail reached regulation in approximately 44.1 μ s with no overshoot or ringing. The waveform confirms a smooth and clean power-up transition, indicating good startup performance and effective filtering

9.2 Results Summary

9.2.1 Remote Controller Latency

To evaluate Remote Controller Latency, we measured the response time between issuing an emergency stop command from the remote and the actual halting of the lawnmower. This was tested by allowing the obstacle avoidance routine to run continuously, then triggering the emergency stop at a precise moment while monitoring the delay before the system responded. The reaction time was recorded for each trial using timestamped serial output to ensure accuracy. Across multiple tests, we observed an average latency of approximately 0.10 seconds. This low response time demonstrates that the remote-control system operates with minimal delay and satisfies our latency specification for safe and responsive manual intervention.

Table 11 RC Latency Results

Trial #	Time
1	0.11
2	0.11
3	0.9
4	0.13
5	0.10
6	0.8
7	0.8
8	0.11
9	0.9
10	0.10

9.2.3 Obstacle Detection Accuracy

For Obstacle Detection Accuracy, we tested the system using objects of varying sizes to ensure the ultrasonic sensor could reliably detect obstacles across a realistic range of conditions. Each trial was evaluated based on two criteria: whether the object was successfully detected, and whether the automated obstacle avoidance procedure was initiated. Detection was determined using serial output logs, while procedure initiation was confirmed through the system's response behavior. Out of 10 trials, the sensor successfully detected the obstacle in all cases, surpassing our specification. However, in 1 out of 10 instances, the avoidance procedure failed to initiate due to a sensor timeout caused by a software bug. Despite this single procedural miss, the consistent detection performance confirms that the system meets the required accuracy for real-world obstacle avoidance.

Table 12 Obstacle Detection Accuracy Results

Trial	Detected / Procedure Start?	Object
1	Y / Y	Yellow Pole
2	Y / Y	Yellow Pole
3	Y / Y	Yellow Pole
4	Y/Y	Dumpster
5	Y/Y	Dumpster
6	Y/Y	Dumpster
7	Y/N	Cemex Bag
8	Y/Y	Cemex Bag
9	Y/Y	Cemex Bag
10	Y/Y	Green Traffic Cone

9.2.3 Obstacle Detection Range

Obstacle Detection Range was a critical specification designed to ensure that the lawnmower could reliably detect and respond to obstacles within a defined safety margin, reducing the risk of collisions. To evaluate this, we conducted a series of 10 trials, systematically varying the speed of the lawnmower across three levels low, medium, and high to simulate real-world operating conditions. During each trial, the onboard ultrasonic sensor was tasked with identifying an object placed directly in the mower's path. The system achieved a 90% success rate, with 9 out of 10 trials meeting the detection criteria. The one failure occurred due to a temporary malfunction of the ultrasonic sensor, not a flaw in the detection logic or control algorithm. Overall, the results validated that the obstacle detection system meets the performance expectations outlined in our project specifications.

Table 13 Obstacle Detection Range Results

Trial #	Pass / Fail?	Speed	Notes
1	PASS	Slow	Detected within 60cm
2	PASS	Slow	Detected within 60cm
3	PASS	Slow	Detected within 60cm
4	PASS	Moderate	Detected within 60cm
5	PASS	Moderate	Detected within 60cm
6	FAIL	Moderate	Potential ultrasonic short?
7	PASS	Moderate	Detected within 60cm
8	PASS	Full Throttle	Detected within 60cm
9	PASS	Full Throttle	Detected within 60cm
10	PASS	Full Throttle	Detected within 60cm

9.3 Key Takeaways

The testing and development process played a crucial role in helping us fine-tune the Remote-Controlled Lawnmower to meet all project specification requirements. By systematically evaluating each system, such as obstacle avoidance, motor control, terrain handling, and emergency stop functionality, we were able to identify performance issues early and make targeted adjustments. This iterative approach allowed us to refine the PWM signals, turning behavior, and responsiveness to ensure reliable operation under various conditions. As a result, the final system met the intended design criteria and performed consistently during the demonstration

Chapter 10 – Administrative Content

10.0 Summary

Chapter 10 gathers the paperwork that keeps our technical work on track. It opens with a snapshot of the semester-long timeline, highlighting key gates such as design freeze, parts ordering, first-power-up, and field-test week. Next comes a budget overview that shows where every dollar went from motors and batteries down to Loctite and confirms we stayed under the capstone spending cap. A short section on team roles clarifies who handled mechanical CAD, who wrote firmware, and who kept the test log, making accountability clear for future audits. We then restate our commitment to ethics and safety, linking back to university policy and the standards cited earlier, before closing with a checklist of future administrative tasks, warranty registrations, spare-parts inventory, and hand-off documentation to ensure the project lives on after submission.

10.1 Project Timeline

Table 14 Project Timeline

Phase	Start Date	End Date	Duration
PCB Acquisition	Jun 20, 2025	Jun 27th, 2025	1 week
8 Page Conference Paper	July 1, 2025	July 7th, 2025	1 week
Final Presentation & Demo Completion	July 7, 2025	July 20, 2025	1 week
Live Demo	July 24, 2025	July 24, 2025	1 week
Final Report & Documentation Uploaded	July 24, 2025	July 29, 2025	1 week

10.2 Budget Overview

Table 15 Budget Overview

Item	Qty	Est. Cost (Each)	Est. Total Cost	Notes	Cost Each	Cost Total	
Greenworks 25322 Mower Base	1	\$250	\$250	Repurposed electric mower	\$200	\$198.99	
VEX 393 Motors	4	\$80	\$320	High-torque motors	\$0	\$0	
Motor Controllers	4	\$45	\$180	One per motor	\$0	\$0	
ER8 Receiver + Transmitter	1	\$60	\$60	2.4GHz wireless controller	\$0	\$0	
Power Supply (24V 15A)	1	\$90	\$90	Primary system power	\$540	\$540	
Distribution Board + Fuses	1	\$120	\$120	FRC-style layout w/ protection	\$0	\$0	
Sensors (Ultrasonic)	2	\$10	\$20	Obstacle detection	\$0	\$0	
Wiring, Connectors, Hardware	N/A	-	\$150	Includes tools and cables	-	\$570.13	
Acrylic, Aluminum Mounts		N/A	-	\$100	Frame mounting and housing	-	\$215.95

Estimated Total: \$1,290

Actual Total: \$1525.11

10.3 Team Roles and Responsibilities

Table 16 Team Roles and Responsibilities

Brayden Anderson	Electrical Engineering	Power distribution, motor integration, safety systems, PCB Design and Integration, Technical Documentation
Steven Huynh	Computer Engineering	Signal failsafe, Software, Communication, Sensors, Documentation

10.4 Ethics and Safety Statement

This project adheres to the IEEE Code of Ethics and the University of Central Florida's engineering guidelines. All testing was performed in controlled environments, and no sharp blades or hazardous components were installed during prototype evaluations.

- The mower was never operated near people, pets, or public property.
- All systems include layered safety protocols such as manual E-stop and automatic fail safes.
- Components were selected to minimize electrical and mechanical risk.

This administrative section captures the logistical, financial, and ethical considerations behind the RC Lawn Mower project and supports its continuation into the next phase

Chapter 11 – Conclusion

11.1 Summary

The RC Lawn Mower project has been a significant success, seamlessly integrating foundational engineering principles across electrical, mechanical, and software domains. Over the course of the semester, our team has worked collaboratively to design, assemble, program, and rigorously test a fully functional prototype capable of remote operation, real-time obstacle detection, and a safe emergency stopping mechanism. By repurposing a robust electric mower frame, we created a cutting-edge system that incorporates modern control systems, advanced sensor logic, and a reliable power distribution network, all in a compact and modular design.

Key milestones include:

- Full four-wheel drive motor control, enabled through a 2.4GHz wireless interface, offering smooth and reliable performance.
- A dual ultrasonic sensor system designed to automatically detect obstacles, with an integrated shutdown mechanism to ensure safety.
- A modular wiring and power system, featuring advanced thermal and snap action protection for durability and operational safety.
- Real-time feedback via serial monitoring, providing essential development diagnostics and enhancing system performance.

11.2 Challenges Faced

ISO 29119 is an international standard that provides a structured approach to software testing, helping teams plan, design, and run tests in a consistent way. For our robotic lawnmower project, it encourages us to go beyond trial and error by creating simple test plans to verify that key functions like obstacle detection, motor control, and the emergency stop work as intended. Even informal checklists or logs help us follow the standard's principles and make our software more reliable. While we are not required to follow it officially, using ISO 29119 as a guideline improves the safety, quality, and predictability of our system during development.

11.3 Team Growth

Throughout the course of this project, our team experienced substantial growth in both technical skills and collaboration:

- **Embedded Systems and Real-Time Software:** We deepened our understanding of embedded systems, refining our ability to design software that operates in real-time with tight hardware constraints.
- **Power Management and Safety Protocols:** The project provided valuable experience in managing power systems, particularly high-current circuits, and reinforced the importance of safety protocols for both equipment and users.

- **Mechanical Fabrication and Integration:** We gained hands-on experience with mechanical fabrication, learning to integrate hardware and software seamlessly to achieve a fully operational system.
- **Team Collaboration and Project Planning:** Working as a team under real-world deadlines helped us strengthen our communication, documentation, and project planning skills, all of which are crucial in a professional engineering environment

The RC Lawn Mower project has evolved from a mere concept into a fully functional project and represents a strong foundation for future innovation in outdoor robotics. The lessons learned, systems developed, and skills honed during this course will serve as the building blocks for the next phase of design, ultimately paving the way for a more intelligent, autonomous, and efficient system that can revolutionize the way we approach outdoor tasks.

Appendix A: Reference

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40 Amp Circuit Breaker:

AndyMark. (n.d.). *40 Amp Snap Action Breaker*. Retrieved from [AndyMark](#)

International Electrotechnical Commission. (n.d.). *Functional safety*. IEC. Retrieved May 30, 2025, from <https://www.iec.ch/functional-safety#:~:text=The%20sensors%20in%20automatic%20doors,or%20pressure%20has%20been%20reached.&text=The%20IEC%2061508%20series%20provides,meet%20its%20specified%20safety%20functions>.

Appendix B: Copyright Permission

Greenwise Lawn Mower Request

ER8 Receiver Request + Response

Re: Schematic Use for University Project Inbox x

 **RadioMaster Support Team** <support@radiomasterrc.freshdesk.com> to me ▾ Fri, May 23, 10:39 PM (5 days ago) ☆ ☺ ↶

Hi Steven Huynh,

You can quote any content in the manual with confidence. It will not have any impact.

Kind regards,

Radiomaster support team

On Thu, 22 May at 10:24 AM, Steven Huynh <stevenhuynh0917@gmail.com> wrote:
Hello,

My name is Steven Huynh and I'm a student at the University of Central Florida. I'm asking for permission to use schematic images from the user manual from the ER8 2.4GHz ELRS PWM Receiver for my Senior Design Project for my university. I've attached a link below as a reference to which user manual I'm referring to. If you could respond to this request it would be greatly appreciated.

https://cdn.shopify.com/s/files/1/0609/8324/7079/files/ER8_Receiver_User_Manual.pdf?v=1687324766

CIM Motors Request

Schematic use for University Project 🖨️ 📄

 **Steven Huynh** <stevenhuynh0917@gmail.com> to support ▾ 10:44 PM (0 minutes ago) ☆ ☺ ↶ ⋮

Hello,

I would like to request permission to use schematic images and figures from the CIM Motor user manual. If granted these schematic images and figures will be used for my University's senior design project. If you could respond to this request it would be greatly appreciated. I've attached a link to the document I'm referring to below.

https://www.vexrobotics.com/217-2000.html?srsiid=AfmBOorpQ04VNWUmd4psL-i9lbe-i2gMpsy1zEqW2aEwy1xtf0s-pSw#attr-vex_size

Thank you,
Steven Huynh
Student, UCF

Power Distribution Board Request



Success!

Your Case has been submitted, we will be in touch soon. For your records:

Case Number:00031681

Subject:Use of Schematic for University Project

Description:Hello, My name is Steven Huynh and I'm a student at the University Of Central Florida. I'm writing this email to ask for permission to use one of your data sheet files which contains schematics for a power distribution board that I'm using for my Senior Design project. I've attached a link to which data sheet I'm referring to. If you could respond it would be greatly appreciated.

[https://team358.org/files/programming/ControlSystem2009-/control_system/Power%20Distribution%20Bo](https://team358.org/files/programming/ControlSystem2009-/control_system/Power%20Distribution%20Board.pdf)

Thank you, Steven Huynh UCF, Student

Appendix C: Data Sheet

Lawn Mower Manual

https://www.greenworkstools.com/cdn/shop/files/25322_E.pdf?v=5847176899978799648

Power Distribution Board

http://team358.org/files/programming/ControlSystem2009-/control_system/Power%20Distribution%20Board.pdf

ER8 Receiver

https://cdn.shopify.com/s/files/1/0609/8324/7079/files/ER8_Receiver_User_Manual.pdf?v=1687324766

Thermal Circuit Breaker:

https://www.mouser.com/ProductDetail/Bussmann-Eaton/185120F-01-1?qs=jxRng1szDptNe7Tb0W8lhQ%3D%3D&srltid=AfmBOopxvK92r8DGA79zUBulODrIP0BELhhyOB3wsn1jg9viWbZHF_T

Motor:[https://www.vexrobotics.com/217-](https://www.vexrobotics.com/217-2000.html?srltid=AfmBOorpQ04VNWUmTD4psL-t9lbe-l2gMpsy1zEqW2aEwy1xrt0s-pSw#attr-vex_docs_downloads)

[2000.html?srltid=AfmBOorpQ04VNWUmTD4psL-t9lbe-l2gMpsy1zEqW2aEwy1xrt0s-pSw#attr-vex_docs_downloads](https://www.vexrobotics.com/217-2000.html?srltid=AfmBOorpQ04VNWUmTD4psL-t9lbe-l2gMpsy1zEqW2aEwy1xrt0s-pSw#attr-vex_docs_downloads)

40 Amp Circuit Breaker

<https://www.andymark.com/products/40-amp-snap-action-breaker>

Appendix D: Software Code

```
1  #include <Servo.h>
2
3  Servo motor;
4  Servo motor2;
5
6  const int ch1Pin = 10; // Controller steering
7  const int ch4Pin = 11; // Controller throttle
8
9  const int trigPin = A2;
10 const int echoPin = A1;
11
12 const int DISTANCE_THRESHOLD = 60; // cm to switch to automated
13
14 unsigned long stepStartTime = 0;
15 int autoStep = 0;
16 bool inAutoMode = false;
17
18 void setup() {
19     Serial.begin(9600);
20     motor.attach(5);
21     motor2.attach(6);
22
23     pinMode(ch1Pin, INPUT);
24     pinMode(ch4Pin, INPUT);
25     pinMode(trigPin, OUTPUT);
26     pinMode(echoPin, INPUT);
27
28     motor.writeMicroseconds(1500);
29     motor2.writeMicroseconds(1500);
30
31     delay(2000);
32     motor.writeMicroseconds(1500);
33     motor2.writeMicroseconds(1500);
34     delay(2000);
35 }
36
37 long readDistanceCM() {
38     digitalWrite(trigPin, LOW);
39     delayMicroseconds(5);
40     digitalWrite(trigPin, HIGH);
```

```

41     delayMicroseconds(10);
42     digitalWrite(trigPin, LOW);
43
44     long duration = pulseIn(echoPin, HIGH, 30000);
45     if (duration == 0) return -1;
46     return duration * 0.034 / 2;
47 }
48
49 void automatedSequence() {
50     unsigned long now = millis();
51
52     // Check distance only during forward steps (4, 5, 8, 9)
53     if (autoStep == 4 || autoStep == 5 || autoStep == 8 || autoStep == 9) {
54         long distance = readDistanceCM();
55         if (distance != -1 && distance < DISTANCE_THRESHOLD) {
56             Serial.println("Obstacle detected during forward move: restarting auto sequence");
57             autoStep = 0; // Restart sequence immediately
58             stepStartTime = now;
59             return;
60         }
61     }
62
63     switch (autoStep) {
64         case 0: // Move BACK (both motors reverse) - add wait here
65             Serial.println("Auto Step 0: Move BACK");
66             motor.writeMicroseconds(1300); // Reverse
67             motor2.writeMicroseconds(1300); // Reverse
68             if (stepStartTime == 0) {
69                 stepStartTime = now;
70             }
71             if (now - stepStartTime >= 2000) { // wait 2 seconds here
72                 stepStartTime = 0; // reset for next step
73                 autoStep++;
74             }
75             break;
76
77         case 1: // Continue moving back for 2 seconds
78             Serial.println("Auto Step 1: Stop after back");
79             motor.writeMicroseconds(1500);
80             motor2.writeMicroseconds(1500);

```

```

81     if (stepStartTime == 0) {
82         stepStartTime = now;
83     }
84     if (now - stepStartTime >= 2000) {
85         stepStartTime = 0;
86         autoStep++;
87     }
88     break;
89
90     case 2: // TURN RIGHT (motor forward, motor2 reverse)
91         Serial.println("Auto Step 2: TURN RIGHT");
92         motor.writeMicroseconds(1600); // Forward
93         motor2.writeMicroseconds(1400); // Reverse
94         if (stepStartTime == 0) {
95             stepStartTime = now;
96         }
97         if (now - stepStartTime >= 2000) {
98             stepStartTime = 0;
99             autoStep++;
100         }
101         break;
102
103     case 3: // Stop after turn right
104         Serial.println("Auto Step 3: Stop after turn right");
105         motor.writeMicroseconds(1500);
106         motor2.writeMicroseconds(1500);
107         if (stepStartTime == 0) {
108             stepStartTime = now;
109         }
110         if (now - stepStartTime >= 2000) {
111             stepStartTime = 0;
112             autoStep++;
113         }
114         break;
115
116     case 4: // Move FORWARD (both motors forward)
117         Serial.println("Auto Step 4: Move FORWARD");
118         motor.writeMicroseconds(1600); // Forward
119         motor2.writeMicroseconds(1600); // Forward
120         if (stepStartTime == 0) {

```

```

121     stepStartTime = now;
122 }
123 autoStep++;
124 break;
125
126 case 5: // Forward for 2 seconds
127     if (now - stepStartTime >= 2000) {
128         motor.writeMicroseconds(1500);
129         motor2.writeMicroseconds(1500);
130         stepStartTime = 0;
131         autoStep++;
132     }
133     break;
134
135 case 6: // TURN LEFT (motor reverse, motor2 forward)
136     Serial.println("Auto Step 6: TURN LEFT");
137     motor.writeMicroseconds(1400); // Reverse
138     motor2.writeMicroseconds(1600); // Forward
139     if (stepStartTime == 0) {
140         stepStartTime = now;
141     }
142     if (now - stepStartTime >= 2000) {
143         stepStartTime = 0;
144         autoStep++;
145     }
146     break;
147
148 case 7: // Stop after turn left
149     Serial.println("Auto Step 7: Stop after turn left");
150     motor.writeMicroseconds(1500);
151     motor2.writeMicroseconds(1500);
152     if (stepStartTime == 0) {
153         stepStartTime = now;
154     }
155     if (now - stepStartTime >= 2000) {
156         stepStartTime = 0;
157         autoStep++;
158     }
159     break;

```

Appendix E: ChatGPT prompts and outcomes

How to resolve manual signal override [7]

<https://chatgpt.com/share/6837cec4-c81c-8001-9353-4c0926b1e9fb>

With our autonomous remote-controlled lawn mower, how can we make sure the autonomous actions of the robot do not get overridden by the remote control signals?

✓ 1. Mode Switching (Preferred)

Use a **physical switch**, **remote control button**, or **software flag** to toggle between:

- **Manual (RC) Mode:** Remote control fully overrides autonomous functions.
- **Autonomous Mode:** Robot ignores remote control commands except a dedicated "emergency stop."

Implementation:

- Use a shared variable or flag in your microcontroller (e.g., `isAutonomous = true/false`)
- RC receiver signal can toggle this flag using a designated channel (e.g., a switch on the transmitter)

cpp

Copy Edit

```
if (isAutonomous) {  
    runAutonomousBehavior();  
} else {  
    runManualControl(); // RC signals directly control the motors  
}
```

✓ 2. Failsafe or Emergency Override

Allow only one specific RC command (like a dedicated channel/button for "STOP" or "Manual override") to be read even during autonomous operation.

This allows **emergency takeover** while autonomous logic is still active:

- Normal RC commands ignored
- Only emergency stop is monitored

```
cpp                                                                    Copy Edit

if (rcEmergencyOverride()) {
    stopAllMotors();
    isAutonomous = false; // switch to manual mode
}
```

✓ 3. Input Arbitration Layer

Create a software layer that arbitrates between RC and autonomous inputs:

- Treat RC and autonomous commands as "input sources"
- Set a **priority level** for each
- Only apply the higher-priority source unless a change of mode is detected

For example:

```
cpp                                                                    Copy Edit

Command getCurrentCommand() {
    if (mode == AUTONOMOUS) {
        return getAutonomousCommand();
    } else {
        return getRCCommand();
    }
}
```

✓ 4. Signal Presence Detection

Automatically switch to **autonomous mode** if no RC signal is detected (e.g., out of range or controller off).

- Detect RC signal via PWM pulse width or timeout on signal line
- If signal is lost for > X ms, switch to autonomous mode
- When signal returns, optionally switch back

✓ Recommended Hardware/Software Tips

- Use a **separate RC channel** to switch modes (e.g., channel 5 or 6)
- Display current mode using an LED (Red = Manual, Green = Auto)
- Use a state machine to manage transitions between modes
- Add **debouncing** or time-based lockouts to avoid rapid switching

Vex 393 Motor Comparison [8]

<https://chatgpt.com/share/68398d89-bdf0-8001-b84e-ab82c5a363df>

How does the Vex 393 outweigh the Brushless Outrunner in terms of comparing Motors?

The **VEX 393 motor** and a **brushless outrunner motor** are designed for **very different use cases**, so when comparing them, it's not about one being categorically better than the other—it's about which motor suits your application better. Here's how the **VEX 393 might "outweigh"** a brushless outrunner in certain contexts:

1. Simplicity and Integration

- **VEX 393:**
 - Comes with an integrated gearbox and encoder (in some versions).
 - Runs on simple voltage (direct DC input), no need for complex controllers.
 - Easily controlled via VEX microcontrollers or Arduino with basic H-bridge drivers.
- **Brushless Outrunner:**
 - Requires an **Electronic Speed Controller (ESC)**.
 - More complex wiring and programming (PWM signals, current control).
 - No built-in gearing—torque must be achieved with external reduction.

✅ **VEX 393 advantage:** Plug-and-play for educational or quick robotics applications.

2. Durability and Protection

- **VEX 393:**
 - Designed for **educational use and robustness**.
 - Built to survive student use—overload protection built-in.
- **Brushless Outrunner:**
 - Not always built for ruggedness (especially hobby-grade).
 - Can be damaged more easily by stalling or impacts.

✅ **VEX 393 advantage:** More durable for rough handling or beginner mistakes.

🔴 3. Controlled Speed and Position

- **VEX 393:**
 - Can include built-in encoders (with Integrated Motor Encoder - IME).
 - Easier to implement closed-loop control with position/speed feedback.
 - **Brushless Outrunner:**
 - Typically not paired with position encoders unless you add one.
 - Harder to use for precise movements (e.g., arm positioning) unless advanced hardware is added.
- ✅ **VEX 393 advantage:** Better for precise control in low-speed applications.

🔴 4. Voltage and Current Compatibility

- **VEX 393:**
 - Operates at 7.2V nominal (safe for small robots and batteries).
 - Lower current draw; easier on power systems.
 - **Brushless Outrunner:**
 - Often designed for 11.1V to 22.2V (3S–6S LiPo).
 - High current draw; requires beefier wiring and batteries.
- ✅ **VEX 393 advantage:** Lower power requirements, safer for educational or indoor use.

When Brushless Outrunners Win:

- You need **high RPM and high power** (e.g., drones, RC planes, powerful robots).
- You need **high efficiency** and good **power-to-weight ratio**.
- You have a **dedicated ESC and control system**.

Conclusion:

The VEX 393 "outweighs" brushless outrunners in:

- Simplicity
- Educational use
- Safety
- Built-in gearing and encoders
- Low-speed torque with basic control

But **brushless outrunners** are far better for:

- High-performance robotics
- Flight and high-speed systems
- Applications needing high torque-to-weight ratio and efficiency

Let me know your use case and I can recommend the best motor for it.

Appendix F: etc.