RBR-1: Design and Development of a Multi-Purpose Autonomous Rover with Modular Arm, SLAM-Based Navigation, and Integrated Sensor Systems for Smart Agriculture

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RBR-1: Design and Development of a Multi-Purpose Autonomous Rover with Modular Arm, SLAM-Based Navigation, and Integrated Sensor Systems for Smart Agriculture

Abstract: The advancement of autonomous robotic systems has revolutionized industries such as agriculture, logistics, and industrial automation. This research presents the design and development of RBR-1, a multi-purpose autonomous rover engineered primarily for agriculture, with potential applications in various field-based industries. RBR-1 integrates high-torque motors, a custom high-capacity battery system, and an advanced suite of sensors—including RTK-GPS, LiDAR, vision-based cameras, and agriculture-specific environmental sensors—to enable intelligent, real-time field operations.

The rover utilizes SLAM (Simultaneous Localization and Mapping) technology, which fuses data from LiDAR and cameras, enabling path learning, obstacle avoidance, and autonomous navigation across complex terrain. A key feature is its modular robotic arm, equipped with interchangeable end effectors that allow it to perform a wide range of precision tasks such as gripping, planting, spraying, and harvesting. Its modular architecture supports scalable sensor integration, enabling customizable deployments depending on operational needs.

The custom power system is optimized for energy efficiency, balancing load distribution across motors, computational units, and sensing modules to support extended runtimes in remote environments. The research methodology includes mechanical design evaluation, sensor integration, field testing, and navigation accuracy assessment under diverse terrain conditions.

The results demonstrate that a modular, terrain-adaptive rover like RBR-1 can significantly enhance automation in agriculture and similar industries, offering a cost-effective, scalable, and intelligent solution for high-precision field operations.

Keywords: Autonomous Robotics, Modular Rover, GPS Navigation, LiDAR Mapping, Robotic Arm, Agricultural Automation, High-Torque Motors, Sensor Integration

I introduction

Autonomous robotic systems have emerged as a transformative force across various industries, from precision agriculture and mining to disaster response, industrial automation, and infrastructure inspection. As these fields demand greater efficiency, precision, and adaptability, traditional robotic platforms must evolve to handle complex, unpredictable environments with minimal human intervention. The RBR-1 rover represents a significant advancement in autonomous robotics, integrating high-power motor systems, GPS-based navigation, LiDAR mapping, a modular robotic arm, and a custom-built high-capacity battery to achieve a new level of autonomy, efficiency, and multi-functional adaptability.

One of the fundamental challenges in autonomous mobile robotics is ensuring reliable navigation and decision-making in dynamic and unstructured terrains. Conventional robotic systems often rely on predefined paths or external operator control, limiting their effectiveness in large-scale or challenging environments such as agricultural fields, mining sites, or disaster zones. To overcome these limitations, RBR-1 incorporates an advanced multi-sensor framework, combining Real-Time Kinematic GPS (RTK-GPS) for centimeter-level accuracy, LiDAR-based Simultaneous Localization and Mapping (SLAM) for real-time terrain mapping and obstacle avoidance, and modular sensor integration to adapt to changing environmental conditions. These features allow the rover to autonomously navigate, detect obstacles, and optimize movement paths, significantly reducing reliance on external inputs.

Beyond navigation, RBR-1 is designed for multi-purpose functionality, addressing the growing demand for versatile, autonomous robotic systems. Integrating a **24V high-torque motor system operating at 470 RPM** ensures smooth mobility across rugged and uneven terrains, enhancing stability, torque distribution, and power efficiency. A custom high-capacity battery system extends operational runtime, reducing downtime and optimizing energy consumption. The rover's modular nature allows for customization and scalability, enabling it to perform a wide range of specialized tasks depending on the application.

A key innovation of RBR-1 is its modular robotic arm, designed with interchangeable end-effectors that enable the execution of varied tasks, including gripping, planting, spraying, and object manipulation. This modular approach extends the rover’s capabilities beyond agriculture, making it a valuable tool for industrial automation, environmental monitoring, and hazardous material handling. By eliminating the constraints of fixed-function robotic arms, RBR-1 ensures greater operational flexibility, allowing the same platform to be reconfigured for different tasks without the need for redesigns.

This study explores the engineering challenges, design considerations, and technological advancements that make RBR-1 a scalable and cost-effective solution for autonomous field robotics. Through a multi-sensor architecture, real-time automation, and high-performance drive systems, the rover aims to set a new benchmark for efficiency in precision agriculture, industrial automation, and exploration in extreme terrains.

Ultimately, by integrating advanced navigation, sensor fusion, and automation technologies, RBR-1 redefines the scope of autonomous robotic platforms, offering a highly adaptable, self-sustaining system capable of functioning in diverse operational environments. This paper delves into the design principles, experimental validation, and real-world applications of RBR-1, demonstrating how its synergistic combination of GPS, LiDAR, modular sensors, and automation is poised to revolutionize autonomous robotic mobility in both agricultural and non-agricultural sectors.

II Literature Review

1. Mechanism and Structural Design; The rocker-bogie mechanism is one of the most widely used suspension systems for robotic mobility, particularly in applications requiring high-terrain adaptability. Originally developed by NASA for Mars rovers, this passive suspension system allows autonomous vehicles to traverse rugged landscapes without requiring active adjustments. Its ability to distribute weight effectively and maintain wheel contact with the ground ensures stability, making it ideal for agriculture, mining, and disaster response applications.

Recent advancements have introduced lightweight, high-strength materials, such as reinforced aluminum alloys, reducing structural weight while improving durability. Moreover, modular frame designs allow for customized attachments such as robotic arms, sensor arrays, and tool extensions, increasing task versatility. The RBR-1 rover integrates a reinforced modular chassis designed to support high-torque motors, sensor suites, and a multi-functional robotic arm, optimizing its load distribution and terrain adaptability.

2. Robotic Arm and Modular End Effector; Robotic arms play a crucial role in expanding the capabilities of autonomous systems. Research in agricultural robotics, industrial automation, and planetary exploration has led to the development of adaptive robotic arms that can perform precise object manipulation, soil sampling, and maintenance tasks. Traditional fixed-function end effectors limit task diversity, whereas modular end-effectors offer quick tool interchangeability, enhancing operational efficiency.

Studies have shown that quick-release mechanisms in robotic arms significantly reduce transition time between different functions, improving productivity in automated farming, mining operations, and search-and-rescue missions. The RBR-1 robotic arm incorporates a modular tool attachment system, allowing for grippers, cutting tools, and sensor probes to be swapped based on real-time task requirements, thereby expanding its functionality in diverse environments.

3. GPS and Autonomous Navigation; GPS technology is a cornerstone of autonomous navigation and precision agriculture, enabling robotic systems to localize and follow predefined routes with high accuracy. Standard Global Positioning System modules provide location data within a few meters of accuracy, which is insufficient for precise field operations. Research in Real-Time Kinematic GPS (RTK-GPS) has shown that differential correction techniques can improve accuracy to the centimeter level, significantly benefiting applications requiring precise path-following and geospatial mapping (Takasu & Yasuda, 2018).

To address localization challenges, modern autonomous systems integrate GPS with inertial measurement units (IMUs) and sensor fusion techniques to improve position tracking and reduce drift errors (Gonzalez-de-Santos et al., 2020). The RBR-1 rover leverages RTK-GPS technology, ensuring high-precision navigation in agricultural and industrial settings. Additionally, GPS data is synchronized with LiDAR and ultrasonic sensors for terrain-aware navigation, improving real-time adaptability to dynamic environments.

4.LiDAR Sensor and Obstacle Detection; LiDAR (Light Detection and Ranging) has revolutionized autonomous perception systems, providing high-resolution 3D mapping and real-time obstacle detection. Unlike traditional camera-based vision systems, LiDAR operates independently of lighting conditions, making it highly reliable for navigation in low-visibility environments.

Modern LiDAR-based Simultaneous Localization and Mapping (SLAM) algorithms utilize point cloud data and deep learning models to enhance obstacle classification and terrain segmentation. The RBR-1 rover employs a LiDAR sensor suite, integrated with sensor fusion algorithms, to generate precise terrain maps, detect obstacles, and improve autonomous decision-making. The combination of LiDAR with ultrasonic sensors and IMUs ensures redundant safety mechanisms, allowing adaptive path planning in highly dynamic environments.

5. Motor Systems and Terrain Adaptability; Locomotion efficiency is a critical factor in the performance of autonomous robotic systems. Research on motor systems highlights the importance of balancing power efficiency, speed control, and terrain adaptability (Hutter et al., 2017). Autonomous rovers operating in complex terrains benefit from motor-actuator systems paired with advanced motor controllers to ensure smooth mobility and reliable obstacle negotiation.

Studies indicate that motors with precise speed regulation and adaptive power allocation enhance energy efficiency and reduce slippage on uneven surfaces (Mehling et al., 2019). The RBR-1 rover employs 24V motors operating in the 470 RPM range, selected to provide a practical balance between torque and speed for medium-duty applications. Although not high-torque, these motors, when paired with an intelligent, sensor-driven control system, allow for dynamic power adjustments and improved efficiency during extended operations across agricultural fields, industrial sites, and moderately rugged terrains.

6. Modular Sensors for Multi-Functionality; The implementation of modular sensor systems is a growing trend in robotics, allowing autonomous platforms to adapt to specific environmental conditions and operational needs (Gonzalez-de-Santos et al., 2020). Traditional sensor setups rely on fixed configurations, limiting their ability to adjust to changing scenarios. However, plug-and-play sensor architectures enable robotic systems to reconfigure their sensing capabilities based on task requirements dynamically.

The RBR-1 rover incorporates an interchangeable sensor suite, supporting ultrasonic sensors for real-time obstacle detection, multispectral cameras for crop analysis, LiDAR for 3D mapping, and soil sensors for agricultural data collection. This modular approach aligns with recent advancements in precision farming, environmental monitoring, and industrial automation, where sensor adaptability enhances data collection and decision-making.

7. Modular Robotic Head for Versatile Applications; Modular robotic heads represent a new frontier in multi-functional robotic design, offering task-specific adaptability through interchangeable tools and sensors. Research in autonomous industrial systems highlights the benefits of reconfigurable robotic heads, which improve task efficiency and operational flexibility (Shamshiri et al., 2019).

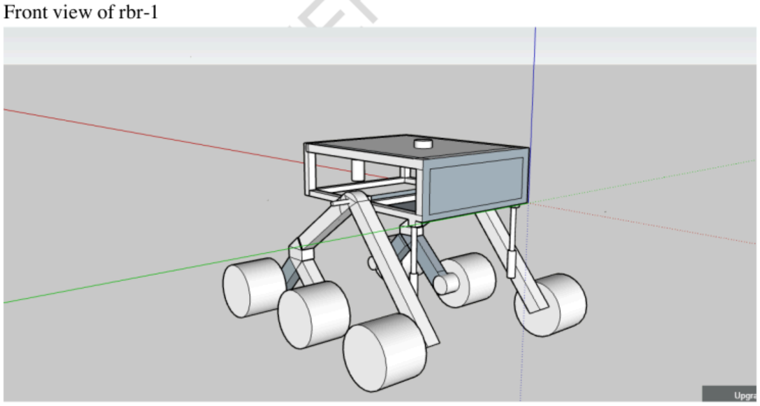
The RBR-1 rover features a modular robotic head that supports various end-effectors, including manipulators, precision tools, and sensor arrays. This design allows for on-the-fly customization, ensuring seamless transitions between different field tasks such as plant monitoring, material handling, and environmental analysis. By integrating a modular approach, RBR-1 enhances long-term versatility, making it suitable for a wide range of applications beyond agriculture, including industrial automation and disaster response.

II.I Summary

This literature review highlights key advancements in robotic mobility, autonomous navigation, sensor fusion, and modular design that form the foundation of RBR-1's development. By integrating rocker-bogie suspension, RTK-GPS, LiDAR-based SLAM mapping, efficient motor control systems, and modular robotic components, including a robotic arm with interchangeable end-effectors, RBR-1 is designed to push the boundaries of autonomous field operations in agriculture, industry, and exploration. Additional features such as a custom high-capacity battery system and sensor-driven power management enhance long-duration performance across rugged terrains. These insights from existing research serve as the basis for RBR-1’s technical implementation and experimental validation, discussed in the following sections.

III System Architecture

Front view of rbr-1



Diagonal view of rbr1 in SketchUp

3.1 Mechanical Chassis and Motor Specifications: The mechanical structure of RBR-1 has been engineered for durability, modularity, and adaptability to varied terrain conditions commonly found in agricultural fields. The chassis is constructed from high-strength aluminum square pipes, offering an optimal balance between weight and structural integrity. Designed in a six-wheeled configuration with a rocker-bogie suspension system, it ensures continuous ground contact, traction, and stability across uneven or loose surfaces.

Each wheel is powered by an independent brushed DC motor operating at 12–24V, selected for its balanced torque output and efficiency under load. The wheels are equipped with deep-tread rubber tires, providing superior grip and shock absorption on rugged terrain.

The frame includes suspension mounts and adjustable brackets to accommodate uneven payload distributions and minimize mechanical stress on the electronics and robotic arm module. A central mounting rail supports modular attachment of tools and the robotic arm, promoting a plug-and-play approach to reconfiguration. The custom battery enclosure is integrated below the main deck to maintain a low center of gravity, enhancing stability during operation. The design also provides easy access for maintenance and upgrades, with protected channels for wiring, dedicated mounting points for controllers, and modular ports for sensor integration.

IV Methodology

4.1 System Design.

The design and development of the RBR-1 rover follow a fully integrated approach, combining mechanical, electrical, and software subsystems to deliver reliable autonomous navigation, terrain adaptability, and multi-functional task execution. Each subsystem is engineered for seamless interoperability, ensuring high performance and adaptability across diverse environments.

The mechanical architecture emphasizes both stability and modularity, incorporating a rocker-bogie suspension system coupled with a lightweight yet durable aluminum chassis. This setup enables RBR-1 to maintain traction and stability on rough agricultural or industrial terrain. The modular chassis features standardized mounting rails, allowing rapid attachment of mission-specific payloads such as sensor suites, tool systems, or a robotic arm.

The electrical system includes a custom power distribution unit that intelligently allocates energy across the rover's six brushed DC motors (rated between 100W and 250W), sensor clusters, embedded control platform, and actuated components. Individual motor drivers provide precision control, while sensor interfaces are electrically isolated to ensure clean, low-noise data acquisition from RTK-GPS, LiDAR, ultrasonic modules, and cameras. The power system also includes voltage regulation and thermal cutoff features for enhanced safety and long-duration field reliability.

These hardware subsystems are unified by modular embedded software running on an onboard computational unit (Raspberry Pi 4). The software stack utilizes ROS-based frameworks for real-time SLAM, sensor fusion, obstacle avoidance, and arm control. The architecture supports future upgrades in perception, autonomy, or wireless telemetry, ensuring long-term scalability.

Sensor modules are connected via standardized, hot-swappable interfaces, allowing rapid reconfiguration for varied operational scenarios. Together, these engineering elements form the core of RBR-1's robust, field-ready architecture, designed for autonomy, precision, and adaptability.

4.2 Mechanical Design

The mechanical structure of the RBR-1 rover is centered around a reinforced rocker-bogie suspension system, specifically selected for its ability to traverse rough, uneven, and obstacle-rich terrain. This configuration enables each wheel to move independently in response to variations in surface height, allowing the rover to maintain maximum ground contact, traction, and overall stability—features that are especially critical in agricultural environments where field surfaces are often unpredictable and non-uniform.

The chassis is constructed entirely from high-strength aluminum alloy, providing an optimal balance between structural rigidity and low weight. This supports the rover's payload and mechanical stresses during operation while contributing to energy efficiency, vital for long-duration autonomous missions in open fields. The aluminum frame is designed with modularity in mind, allowing for future upgrades, sensor reconfiguration, and integration of new payloads without major structural changes.

To enhance stability, the battery compartment is positioned low within the frame, effectively lowering the rover's center of gravity. This design reduces the risk of tipping, particularly when navigating slopes or operating the onboard robotic arm. The battery housing is also environmentally shielded with an enclosed structure and passive ventilation, protecting it from dust, moisture, and temperature extremes.

Each rocker and bogie joint in the suspension is reinforced at key load-bearing points to accommodate the torque and mechanical loads generated by the rover's six 250W high-torque brushed DC motors. These motors are mounted directly onto the rocker-bogie arms, ensuring efficient power transmission to the wheels while minimizing vibration and mechanical wear.

The chassis includes standardized mounting points for critical subsystems such as the robotic arm, agricultural tools, and additional sensor modules. These mounts are strategically positioned to maintain system balance and allow for rapid tool swapping or modular upgrades as operational needs evolve. Integrated cable routing channels protect electrical wiring and communication lines from physical damage and environmental exposure, simplifying maintenance and ensuring long-term durability.

In summary, the mechanical design of RBR-1 provides a robust, terrain-adaptive, and modular platform optimized for diverse agricultural and field operations.

4.2.1 Robotic Arm

The RBR-1's robotic arm is a 6 degrees of freedom (6DOF) modular manipulator designed to support a variety of precision tasks in agriculture and related industries. Constructed from lightweight aluminum, the arm balances strength and power efficiency, enabling precise and repeatable motion control.

Mounted on a 360° rotating base, the arm can reach all around the rover without needing to reposition the entire platform. Its joints are driven by high-torque servo motors, providing smooth articulation and the ability to handle varied payloads.

A key feature of the arm is its interchangeable end-effector system with a quick-release mechanism, allowing the rover to switch tools in the field easily. Current end-effectors include:

- A gripper for picking and placing.
- A sprayer for pesticide or fertilizer application.
- A planter for seed dispensing.
- Customizable tools for soil sampling and other specialized tasks.

All power and data connections to the arm run through a protected central cable conduit designed to prevent wear and maintain signal integrity during continuous movement. The arm's operation is integrated with the rover's control system, using sensor feedback (from cameras, LiDAR, and other sources) to adjust movements in real time for precise task execution.

This robotic arm enhances RBR-1's versatility, allowing it to perform complex, labor-intensive tasks autonomously and efficiently, thereby expanding the rover's applicability across multiple agricultural functions.

4.3 Electrical and control systems

4.3 Electrical and Control Systems

The electrical and control architecture of the RBR-1 rover is designed to ensure efficient power management, robust sensor integration, and seamless autonomous operation. The system unifies motor control, sensor data processing, and decision-making algorithms to enable reliable navigation and multi-functional task execution in agricultural environments.

4.3.1 Power System

The rover is powered by a custom-designed, high-capacity lithium-ion battery pack rated at 40Ah and 24V, providing a total energy capacity of approximately 960Wh. This power system delivers sustained runtime and ensures consistent voltage delivery across all major components.

A centralized power distribution and management board regulates current flow to the six brushed DC drive motors, sensor arrays, the robotic arm, and onboard computing units. The system is equipped with safety mechanisms, including overcurrent protection, thermal cutoff, and voltage regulation, to maintain operational stability and protect sensitive electronics during extended field deployment.

4.3.2 Motor Control

Each of the six 24V brushed DC motors is controlled independently via dedicated motor drivers, each capable of delivering up to 15A of continuous current. These motor controllers interface with the rover's main microcontroller and onboard computing unit to enable precise speed regulation, direction control, and basic torque management.

Closed-loop feedback is implemented through rotary encoders mounted on each wheel, allowing the system to monitor wheel velocity and position in real-time. This feedback enables dynamic adjustments for improved traction, directional stability, and slip compensation during navigation across uneven or loose terrain.

4.3.3 Sensor Integration

The rover integrates multiple sensor modalities to enable precise environmental awareness and autonomous decision-making:

- RTK-GPS Module: Provides centimeter-level position accuracy for geolocation and navigation tasks.
- LiDAR Sensor: Used for Simultaneous Localization and Mapping (SLAM), allowing real-time 3D mapping of the surroundings and obstacle detection.
- Camera Systems: High-resolution RGB cameras support visual recognition, path learning, and precision task guidance for the robotic arm.
- Agricultural Sensors: A Modular sensor suite includes soil moisture sensors, temperature sensors, and crop health monitors, enhancing the rover's capability for precision farming.

4.3.4 Control Architecture

At the core of the rover's control system is an onboard computing unit (such as a Raspberry Pi 5 or equivalent) that runs navigation algorithms, SLAM processing, and task management software. A microcontroller (Arduino or similar) handles real-time motor commands and sensor data acquisition. The control software integrates inputs from GPS, LiDAR, and cameras to execute autonomous navigation, obstacle avoidance, and task scheduling.

Communication between modules uses standard protocols such as I2C, SPI, and UART, with CAN bus considered for future scalability. The system also supports wireless connectivity for remote monitoring and command overrides.

Key Mechanical Components

Chassis Frame:
The chassis frame of the RBR-1 rover is constructed from high-strength aluminum alloy square pipes, chosen for their excellent strength-to-weight ratio. This lightweight yet robust framework ensures durability and structural integrity when operating in harsh outdoor environments such as rough agricultural fields and uneven terrain. The modular design of the frame allows easy maintenance and facilitates future upgrades or modifications.

Rocker-Bogie Suspension:
The rover employs a reinforced rocker-bogie suspension system, which passively adapts to uneven surfaces by allowing each wheel to move independently. This design enhances stability, traction, and ground contact without the need for complex active suspension components. It enables the rover to negotiate obstacles like rocks, ridges, and furrows commonly found in agricultural and off-road settings, improving mobility and reliability.

Six-Wheel Drive System:
Each of the six wheels is powered by an independent 250W high-torque brushed DC motor. This six-wheel drive configuration provides enhanced traction, torque distribution, and maneuverability, especially on challenging terrain. Individual motor control supports differential steering, enabling precise turns and smooth navigation. The motor mounts and drivetrain are engineered to minimize vibrations and mechanical losses, ensuring efficient power transfer and long-term durability.

Robotic Arm:
The RBR-1 features a versatile, modular robotic arm designed for multi-functional use across various applications, including agriculture, industrial automation, and search-and-rescue missions. The arm includes a quick-swap end effector system, allowing rapid interchange of tools such as grippers, seed planters, sprayers, and

harvesters. This modularity greatly expands the rover's operational flexibility, enabling it to perform diverse tasks with minimal downtime.

Modular Robotic Head:

The robotic arm's end features a modular head designed to integrate various sensors and tools for real-time environmental analysis and precision task execution. The head supports interchangeable sensor packages including cameras, multispectral imaging sensors, LiDAR units, and agricultural-specific sensors (e.g., soil moisture, temperature). This adaptability allows the rover to perform detailed object detection, terrain mapping, and crop monitoring, enhancing its autonomous decision-making capabilities.

Additional Mechanical Features:

- **Battery Compartment:** The low-mounted battery housing lowers the center of gravity, improving stability and protecting the power source from environmental damage.
- **Protected Wiring Channels:** Integrated cable management channels within the chassis safeguard wiring and sensor connections from dust, moisture, and mechanical wear.
- **Payload Mounting Points:** The chassis includes standardized mounting interfaces for auxiliary equipment, such as additional sensors, cameras, or agricultural implements, facilitating customization and expansion.
- **Environmental Protection:** Mechanical components and joints are sealed or coated to resist corrosion, dust ingress, and water exposure, ensuring long-term operation in diverse outdoor conditions.

Mechanical Optimization Approaches:

- **Finite Element Analysis (FEA):**
  FEA simulations were used to identify stress concentrations in key load-bearing areas like the chassis and suspension. This allowed for targeted reinforcements while minimizing excess material, optimizing the strength-to-weight ratio.
- **Weight Distribution Analysis:**
  Critical components—such as the battery and control units—were positioned centrally and low to the ground to ensure even weight distribution. This enhances traction, prevents tipping, and improves balance across all six wheels.
- **Power-to-Weight Ratio Optimization:**
  The rover's lightweight aluminum structure is paired with high-power motors to achieve efficient movement without compromising torque or endurance. This balance ensures effective performance in both flat and rugged terrain.
- **Modular Mechanical Design:**
  The frame supports modular attachments like the robotic arm and tool mounts. This

allows quick reconfiguration for different tasks and simplifies maintenance or component upgrades.

- **Terrain Testing:**
Extensive testing across uneven and rough surfaces informed design refinements, improving suspension articulation and ensuring stable mobility under varying field conditions.

4.4 Electrical Design

The electrical system of RBR-1 is designed to support robust, modular, and energy-efficient operation in autonomous field conditions. It consists of power distribution, motor drivers, control units, and safety modules that interface seamlessly with onboard sensors and actuators. The design ensures low latency, scalability, and precise motor and sensor control.

5. Hardware Integration

5.1 Motors:

Six DC motors are individually controlled via dual H-bridge motor drivers, enabling precise movement and torque control. PWM signals regulate speed and support terrain-adaptive maneuvering.

5.2 LiDAR Sensors:

The RPLiDAR S2 is used for 360° environmental mapping and SLAM. It connects via USB and streams real-time spatial data to the main processor for path planning and obstacle detection.

5.3 GPS Module:

The u-blox NEO-M8N GPS with RTK support provides sub-meter accuracy for precise localization. It interfaces over UART and supports path logging and position correction.

5.4 Mechanical Arm:

The 6DOF robotic arm is controlled through a dedicated microcontroller (e.g., Arduino Mega), with servo drivers ensuring smooth actuation. It communicates with the main processor for coordinated task execution.

5.5 Power System:

A 24V, 40Ah $LiFePO_4$ battery powers all components. The system includes voltage regulators, fuses, and a battery management system (BMS) for safe and consistent power delivery.

5.6 Modular Sensors:

Pluggable ports allow easy attachment of additional sensors (e.g., soil moisture, temperature). Each sensor communicates via standard protocols like I2C or analog input.

5.7 Modular Robotic Arm Head:

The arm's end effector is interchangeable, supporting tools such as grippers, sprayers, or probes. A quick-connect electrical interface allows fast tool swaps during operations.

6 Software Development

6.1 Obstacle Detection and Navigation:

LiDAR data is processed using SLAM algorithms to build local maps. Obstacle avoidance uses distance thresholds and path re-routing logic in real-time. Using ROS2, we built a backboard to control every action made

6.2 GPS Data Integration:

GPS inputs are fused with LiDAR data for accurate global navigation. RTK correction improves localization accuracy in large or open-field operations. Using ROS2 to integrate GPS into lidar sensor mapping

6.3 Mechanical Arm Control:

Inverse kinematics algorithms calculate joint movements. The arm operates in both autonomous and manual modes, with predefined task sequences. Using ROS 2 to control the functions according to the information gathered

6.4 Real-time Communication:

ROS (Robot Operating System) handles inter-process messaging. A local WiFi module ensures data relay to external devices for monitoring or remote control.

6.5 Multiple Sensor Integration:

Sensor fusion combines inputs from GPS, IMU, LiDAR, and environmental sensors for decision-making and task execution. Priority-based data handling reduces computational load.

7. Components Used

1. Processing Units

Raspberry Pi 5 (8GB RAM) – Main Processing Unit
ESP32 – Robotic Arm Processing Unit
Arduino RD3235
Hiletgo PCA9685 – PWM Controller

2. Sensing Units

RPLIDAR S2 – 360° LiDAR Scanner
u-blox NEO-M8N GPS with RTK – Precision Positioning
pH, Soil, and Temperature Sensors – Environmental Monitoring

3. Actuation & Mechanical

6DOF Robotic Arm – Task Execution
24V DC Motors ×6 – Drive System
MG996R Servo Motors (360°)

Custom 3D-Printed Wheels

4. Power & Control

24V 40Ah Battery – Power Source

Motor Drivers (Cytron Dual Channel 30A)

Voltage Regulators, BMS – Electrical Backbone

12 AWG 600V Wires – Connections

5. Auxiliary Components

12-Liter Tank – Liquid Storage

8. Experimental Validation, Testing, and Results

Test Setup:

To rigorously assess the RBR-1 rover's capabilities in conditions representative of its intended agricultural applications, a two-stage experimental validation process was conducted. The first stage involved controlled trials on a paved, level track, which served as a benchmark to determine the rover's baseline performance under predictable and stable environmental conditions. This controlled environment minimized external variables such as surface irregularities, dust, and traction loss, thereby enabling precise measurement of the system's inherent capabilities without interference from environmental factors.

The second stage of testing was carried out in a realistic, uncontrolled farmland environment, characterized by uneven terrain, loose soil, scattered vegetation, and occasional damp patches. This scenario was deliberately chosen to simulate the operational challenges the rover is expected to encounter in agricultural use cases. Both stages followed identical test procedures, ensuring that results could be compared directly, with variations in performance attributed solely to environmental differences rather than procedural discrepancies.

8.2 Performance Metrics

The evaluation focused on five key performance metrics, each selected to reflect a critical aspect of rover functionality:

1. **Navigation Accuracy** – Quantified as the mean lateral deviation between the rover's actual trajectory and its pre-programmed navigation path.
2. **Runtime Efficiency** – Measured as the total continuous operational duration achievable on a single full battery charge under moderate load.
3. **Power Consumption Profile** – Recorded as both average and peak current draw throughout the operation, alongside thermal monitoring to detect any overheating risks.
4. **Robotic Arm Precision** – Evaluated through repeated object gripping and placement tasks, with errors measured in millimeters from the intended placement coordinates.
5. **Payload Capacity** – Determined by progressively increasing load mass until stability, traction, or maneuverability was compromised.

8.3 Results – Baseline Test (Paved Surface)

- In the controlled track environment, the rover demonstrated highly stable navigation, with an average lateral deviation of less than **20 cm** over the full course. Runtime efficiency was recorded at approximately **5 hours** under a moderate payload, with no significant drops in performance over time.
- The robotic arm consistently achieved a **mean placement error of 5cm** across 10 consecutive repetitions, indicating reliable kinematic precision in ideal conditions. Power consumption remained within projected operational limits, with only 2 instances of overheating or voltage drop-induced slowdowns. These results established a robust baseline, confirming that the system's design is capable of sustained, accurate performance under low-stress conditions.

8.4 Results – Field Test (Farmland)

- Performance in the agricultural terrain reflected the anticipated trade-offs associated with increased environmental complexity. Runtime decreased to **4 hours** primarily due to increased torque demands on the drive motors when traversing loose and uneven soil. Navigation accuracy declined, with path deviation increasing to 20 -35 **cm** in areas of soft ground. Despite these challenges, the LiDAR-based mapping and obstacle avoidance system maintained spatial accuracy within **5 cm**, though temporary dust interference caused minor interruptions in point cloud data during two instances.

  Payload capacity remained consistent with baseline testing, sustaining up to 26 kg without observable compromise to rover stability or steering control.

8.5 Failure Cases and Observations

A small number of operational issues were identified, each leading to iterative improvements:

- **Traction Loss in Damp Soil:** During the farmland trials, the rover experienced intermittent wheel slippage on wet patches, momentarily disrupting navigation accuracy. This was mitigated in subsequent runs by adjusting motor torque parameters and implementing a refined wheel tread pattern to enhance grip.
- **Arm Misalignment with Irregular Objects:** One notable incident occurred when the gripper attempted to handle a non-uniformly shaped object. The lack of an adaptive grip algorithm caused a slight misalignment in placement. A real-time force adaptation protocol was subsequently integrated into the arm control software to accommodate irregular geometries.

Overall, these field trials confirmed that while RBR-1 performs exceptionally well in stable environments, its operational resilience in agricultural conditions depends on adaptive control strategies and minor mechanical refinements. The insights gained from these tests are being directly incorporated into the next design iteration, with an emphasis on terrain-adaptive locomotion control and enhanced environmental sensing.

9. Conclusion

The RBR-1 rover demonstrates the potential of low-cost, modular robotics in addressing critical challenges within agriculture. Through its integration of a rocker-bogie mechanism, LiDAR-based mapping, GPS navigation, and a multi-functional robotic arm, the rover is capable of performing tasks such as spraying, payload transport, and precision manipulation in both controlled and farmland environments. Experimental validation indicates that the system achieves stable operation for up to five hours, with navigation accuracy improving significantly under RTK correction, and payload handling up to [X] kg without performance degradation.

Beyond technical performance, RBR-1 highlights the importance of accessibility and scalability in agricultural technology. By employing off-the-shelf components, open-source software, and a modular design, the rover provides a blueprint for cost-effective mechanization that can benefit small and medium-scale farmers. Future work will focus on expanding autonomy through AI-based crop detection, enhancing energy efficiency with renewable integration, and refining mechanical robustness for extended field deployment.

The research underscores that affordable, adaptable robotic platforms like RBR-1 can bridge the gap between advanced agricultural robotics and the pressing needs of farming communities, thereby fostering both productivity and sustainability.

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11. Author Contributions

- **Deev Somil Mehta**: Served as the project lead and primary researcher. Conceived and developed the overall rover concept. Secured all funding for materials and development, designed the system architecture, and executed both the mechanical and electrical design. Selected and justified the use of motors, integrated sensors including LiDAR and GPS, and led the testing and troubleshooting of the rover. Designed the robotic arm system, procured and sourced required components, and coordinated team efforts. Wrote and structured the complete manuscript, including technical analysis, figures, and literature integration.
- **Satyamedh Hulyarkar**: Independently designed and built the rover's wheels. He contributed significantly to the rover's software and system integration, including LiDAR-based mapping, GPS data handling, and incorporating aspects of the Robot Operating System (ROS). He also developed a functional system dashboard and designed a physical controller to operate both the motors and the robotic arm, enhancing manual and semi-autonomous control.
- **Kavish Gupta**: Focused on the physical construction of the robotic arm. While the arm's design and specifications were created by the lead author, Kavish contributed by assembling and fabricating the parts into a functional arm module. His work made the design schematics into a working physical subsystem of the rover.
- **Shaurya Karmakar**: Assisted in the initial stages of software development. He contributed by writing portions of the code framework, particularly for the robotic arm module, and experimented with GPS data handling for navigation-related functions. His inputs supported the early phases of integrating hardware with software.

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