McGill Agricultural Robotics Squad: Cotton Rover for 2023 ASABE Student Robotics Challenge

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Abstract

This report presents the design and development of the Cotton Rover (CR), an autonomous robotic system specifically designed for the automation of cotton harvesting. The CR integrates several subsystems including a navigation system, cotton detection and mapping system, harvesting mechanism, and delivery system. The navigation system leverages mecanum wheels for unrestricted movement, LIDAR for boundary detection, and other sensors for precise positioning and orientation. Cotton detection is achieved through an computer vision based low-processing approach including color threshold and shape detection techniques. The harvesting mechanism employs a dual-roller assembly for efficient cotton boll collection, and the delivery system uses a storage unit equipped with computer fans for cotton ejection. Individual performance tests conducted on each subsystem demonstrated promising results, underlining the potential of the fully integrated CR system. Once fully assembled, the Cotton Rover will be evaluated comprehensively to assess its performance in real-world cotton farming scenarios. The development of the CR illustrates the potential of robotics in the agriculture industry and contributes to advancements in automated precision agriculture technology.

1. Introduction

The increase adoption of precision agriculture practices is often driven by the use of autonomous machines. Agricultural robotics has the potential to improve farming practices, increase yield, and may play a significant role in reducing the environmental impact of agriculture [2, 3, 11]. With the goal of cultivating innovation and stimulating progress for future developments, the ASABE Student Robotics Challenge has presented the following challenge: the development of an autonomous robot for cotton harvesting. This technical paper reports the design, implementation, testing, and performance of an autonomous cotton harvesting robot developed by our team, the McGill Agricultural Robotics Squad (MARS).

This year's competition task encompasses the design of a robot that can proficiently navigate a defined 8' x 8' playing field. The robot must be capable of identifying and harvesting cotton from a total of 54 cotton plants, each bearing one to three cotton bolls at heights of 7" to 11" and each boll containing between three and five distinct cotton balls. The task's complexity is further amplified as the robot is expected to not only harvest ripe cotton but also map the locations of the unripe bolls for future harvesting. Additionally, the harvested cotton must be transported and delivered to a designated corner of the field.

Addressing the various challenges presented by this task requires a fusion of several fields of robotics, including but not limited to, robot navigation, computer vision, and mechatronics. The primary focus of this report, hence, is our approach to address these challenges by designing an integrated solution, employing both hardware and software strategies in an optimized manner. The resulting robot developed by our is, the Cotton Rover(CR), which embodies our innovative approach to solving this problem.

The structure of this paper is as follows, section 2 briefly discusses the relevant background and previous work to cotton harvesting and robotics. In section 3 we detail the design methodology for CR and the subsystems of the robot are explained, including the mobile platform, the cotton detection and harvesting mechanism, the mapping and navigation system, and the cotton ball storage and delivery system. The performance testing and evaluation of our design is presented in section 5. Finally, we conclude by summarizing our findings, drawing key insights, and discussing potential avenues for future development.

This report, aims to contribute to the broader discussion on agricultural robotics and precision agriculture and aims to provide practical insights to help guide future developments in this rapidly evolving field.

2. Background

Cotton plays a significant role in the textile industry and the global economy. The labor-intensive nature of cotton harvesting has led to increased interest in the development of robotics and automation technologies to address the challenges associated with this critical agricultural task. Traditional methods of cotton harvesting involve manual labor, which is time-consuming, physically demanding, and often prone to inefficiencies. Mechanized solutions, such as cotton pickers, have improved productivity but can cause damage to the cotton plants, reducing yields and increasing the risk of disease transmission. The need for precise, efficient, and gentle harvesting techniques has driven the exploration of robotics in cotton harvesting [1, 5]. Recent developments in detection and harvesting techniques have been explored with aim of alleviate the labor burden, improve efficiency, minimize plant damage, and optimize the overall cotton production cycle. these development include a combination of computer vision, machine learning, and mechanical manipulation methods.

Harvesting mechanism for cotton robots include solutions that propose the incorporation end-effectors for harvesting cotton. Various end-effectors including grippers as well as serrated belt systems are explored in Gharakhani et al.'s paper [6]. Another Method includes the use of pneumatic suction for picking cotton bolls [12]. While these solutions allow for minimally invasive methods, harvesting time significantly increase as these actions are performed on the individual plant level.

Significant progress have also been made in the development of efficient cotton detection systems. Computer vision techniques, such as image processing and machine learning algorithms, have been applied to accurately detect and classify cotton bolls. These systems leverage high-resolution cameras and sophisticated algorithms to analyze visual data and identify the location, size, and maturity of cotton bolls. By effectively distinguishing between ripe and unripe cotton, these detection systems enable selective harvesting and optimize the efficiency of the harvesting process. One such approach has been proposed and developed by Sun et al. in which a vision platform is used for 3D photogrammetric mapping of cotton bolls *in situ* based on point cloud segmentation and clustering [10].

In addition to harvesting mechanisms and cotton detection, navigation systems plays a critical role in recent advancements in cotton harvesting robotics. Navigating through a cotton field presents challenges such as uneven terrain, varying plant heights, and potential obstructions. To overcome these obstacles, advanced navigation systems utilize a combination of sensors, including GPS, LiDAR, and IMUs, to precisely localize the robot and enable autonomous path planning. Machine learning algorithms and mapping techniques are often employed to enhance the navigation system's ability to identify optimal paths, avoid obstacles, and adapt to changing field conditions. Efficient and reliable navigation systems are crucial for maximizing the coverage of the cotton field and ensuring accurate and timely harvesting operations.

2.1. Objective

The goal of this project is to design, build, and test an autonomous cotton-harvesting robot that is not only effective in a competitive setting but also has potential uses for real-world agricultural application. Thus the objectives of the CR are as follows:

Navigation and Mapping Develop an efficient navigation system that can traverse the complex environment of a cotton field. The system should be able to adjust its course based on its understanding of the field and detect boundaries and proper distances that facilitate the smooth harvest of the the cotton bolls in an efficient manner.

Cotton Boll Detection and Differentiation Incorporate a computer vision system capable of accurately detecting cotton bolls and differentiating between ripe and unripe ones under various lighting and weather conditions. This would involve fine-tuning detection algorithms to handle the complexities and variability inherent in real-world field conditions. This system should perform mapping of the bolls for havest tracking.

Gentle and Precise Harvesting Design a harvesting mechanism that can pick cotton gently to avoid damaging the cotton bolls or the plants, while maintaining a reasonable harvesting speed. This will involve an innovative end-effector design that is effective, precise and time efficient.

Efficiency and Power Management Optimize the robot's operations for energy efficiency, allowing it to operate for extended periods without the need for frequent recharging. This may include strategies for effective power management, such as task prioritization and efficient route planning.

Cost-effectiveness and Scalability Ensure that the robot design uses cost-effective materials and components without compromising on its performance and durability. The design should also consider scalability for potential mass production and real-world agricultural deployment.

Robustness and Reliability The robot should be able to operate reliably under various field conditions and be robust enough to handle the physical challenges of a working cotton field, such as uneven terrain, various weather conditions, and the presence of pests or diseases.

Through achieving these objectives, we aim to create a cotton-harvesting robot that not only performs well in the competition but also takes a step forward in addressing the real-world challenges of automated cotton harvesting.

3. Robot Design and Methodology

In this section, we provide an in-depth overview of the design principles and development methods employed during the conception of the Cotton Rover. Leveraging advancements in robotics, computer vision, and mechatronics, the CR was developed to carry out the tasks set by the student design challenge. The autonomous robot, designed by our team, presents an optimized solution to the complex set of requirements stipulated by the competition. The following subsections details the design and implementation of CR's subsystems, including its navigation capabilities, cotton detection and mapping protocols, harvesting mechanisms, and delivery systems. Through this analysis, we aim to demonstrate the cohesive coordination between hardware and software components that facilitates efficient, autonomous cotton harvesting.

3.1. Robot Navigation

The navigation subsystem forms the backbone of our Cotton Rover (CR), enabling it to efficiently traverse the competition terrain and engage with cotton plants for harvesting. This system encompasses the robotic platform's mobility mechanism, the boundary detection protocol, the robot's position and orientation identification methods, and finally, the fine-tuning of robot's movement.

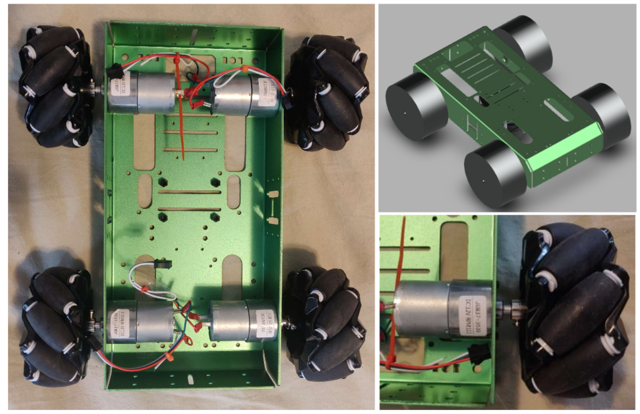

Figure 1. Overview of the robot platform chassis and wheel system. Figure on the left shows the complete robot chassis base with the mecanum wheels and motors attached and coupled with the aluminum frame. The top right figure shows the aluminum frame modeled on CAD software. The bottom right figure shows an individual mecanum wheel coupled to the 12V DC motor.

The robot platform is equipped with mecanum wheels, which allow for omnidirectional movement, significantly increasing the robot's maneuverability on the field. Unlike standard wheels, mecanum wheels have a series of angled rollers around the rim, allowing for diverse movement capabilities. This implies that the CR is not limited to just forward and backward motion, but can also strafe sideways, rotate in place, and even move in any direction without changing its orientation. The advantage of such unrestricted motion is that it permits the CR to navigate through densely planted rows of cotton without causing any inadvertent damage to the plants. The mecanum wheels are controlled individually via generic bidirectional DC motors and fixed onto an aluminium alloy frame. The mecanum wheels used by the CR are 97mm in diameter and are coupled to JGB37-3530 12VDC motors (with no encoders) equipped with a 90:1 worm gear for high torque, resulting in a max speed of 111 RPM. See figure 1 for reference of the robotics platform. This high torque, large wheel system, allow the CR to navigate through the course very quickly, and can sustain obstruction real world field conditions.

To ensure accurate boundary detection and position tracking within the playing field, a Light Detection and Ranging (LiDAR) sensor is integrated into the system. LiDAR is capable of accurately measuring the distances between the sensor and the field boundaries by illuminating the targets with laser light and measuring the reflected light with a sensor. This data is used to build a detailed map of the field, and in conjunction with a localization algorithm, the CR's precise location within the field can be tracked in real-time. The decision to place the LiDAR sensor underneath the robot chassis was done by the MARS team to mitigate the effects of occlusion from the cotton storage and harvesting system. While occlusion still occurs from the wheels, major line of sight detection that make 360 field of view possible. This combined with other navigation sensors allow the robot to traverse the course.

For the determination of the robot's orientation, a gyroscopic and accelerometer sensor is deployed. The gyroscope measures the robot's rotational velocity around each axis, while the accelerometer measures linear acceleration. By fusing the data from both these sensors, a technique often referred to as sensor fusion, the CR is able to maintain a stable and accurate orientation even when the robot is subject to disturbances such as uneven terrain or sudden changes in direction or speed. This is especially significant as the wheel motors do not contain encoders, thus feedback motion control is done via the gyroscopic sensor.

Lastly, for fine-tuning the robot's movements, especially when it is in close proximity to the cotton plants, ultrasonic sensors are utilized. These sensors measure distance by emitting sound waves and recording the time taken for the sound to bounce back, similar to the principle of an echo. They provide an effective and reliable method for maintaining an optimal distance from the cotton plants and ensuring that the robot can approach the plants for harvesting without causing any physical damage.

3.2. Cotton Detection and Mapping

The challenge of cotton harvesting requires the accurate detection and differentiation of ripe and unripe cotton bolls. This not only facilitates the harvesting process but also assists in mapping the locations of unripe bolls for future harvest cycles. The CR utilizes a computer vision based approach to accomplish this objective. This subsystem is specifically designed to work within the processing constraints of a Jetson Nano platform. The primary imaging hardware of the CR is a standard webcam or a Raspberry Pi Camera Module. Despite the relatively lower resolution compared to high-end imaging devices, these cameras have been chosen for their lightweight properties, cost-effectiveness, and their ability to provide sufficient image quality and consistent image stream for the detection process.

The initial detection process uses color-based image segmentation to distinguish between cotton bolls and the background. Due to the visual difference between ripe and unripe bolls, color thresholding serves as a highly effective and computationally light method to segment and identify cotton bolls from the image. The color spectrum and thresholds are selected and fine-tuned to ensure maximum accuracy in diverse lighting conditions. Subsequent classification of the detected bolls as ripe or unripe is performed using a Support Vector Machine (SVM). SVMs are highly efficient and versatile machine learning models, making them ideal for this task, particularly considering the limited computational resources of the Jetson Nano. The SVM is trained on a dataset of cotton boll images which is composed of a combination of images collected from online dataset [7], images collected on field and images obtained online using image scraping script. We are able to quickly classify each detected boll based on the extracted color and shape features. See figure 2 for the color thresholding and classification performed on a single image frame.

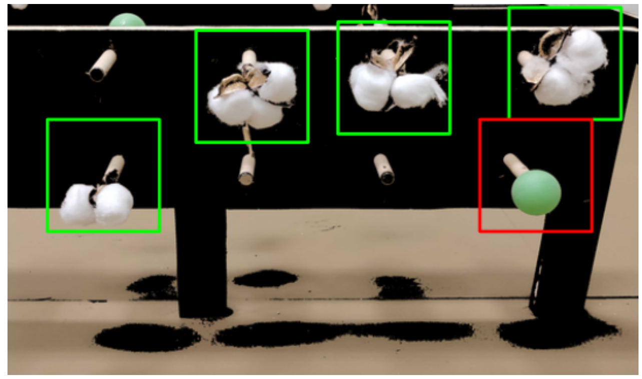

Figure 2. Sample frame from the Cotton Rover computer vision system. Color thresholding results in the black background of the playing field wall, while the classification tasks provides green bounding box on cotton plants and red bounding box on the ping pong ball of the foreground

Following detection and classification, the location of each cotton boll, along with its ripeness status, is recorded in an internal data structure, providing an ongoing account of the cotton bolls encountered during the field traversal. In compliance with the competition requirements, the CR also generates a map marking the positions of the unripe bolls. This map is compiled as a .CSV file with a "1" indicating an unripe boll and "0" representing ripe or absent bolls. The CSV file is written to a USB drive in the appropriate format. The inclusion of this mapping functionality allows the CR to meet the challenge of not only detecting but also effectively communicating the locations of unripe bolls. By combining a standard camera with a streamlined and optimized image processing pipeline, the CR effectively addresses the challenges of cotton boll detection and mapping under the hardware and computational constraints.

3.3. Harvesting Mechanism

The harvesting process relies primarily on a dual-roller system, which has been designed to efficiently separate cotton bolls from their husks. The two rollers, characterized by their serrated surface, provide sufficient traction to enable secure handling of cotton bolls. The mechanical coupling between the rollers via a gear assembly ensures synchronized rotation, providing a consistent grip on the cotton bolls during the harvesting process. The roller gear system is 3D printed using PLA plastic, to ensure affordable manufacturing and serviceability. See Figure 3 for CAD drawings of the assembles dual-roller system.

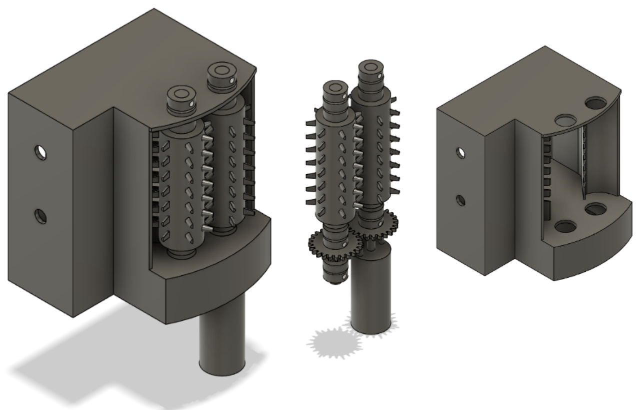

Figure 3. CAD models of the dual-roller harvesting system

The dual-roller mechanism operates through a single DC motor. The utilization of one motor reduces power consumption and allows for a simplified mechanical setup. This decision enhances the overall reliability of the system and facilitates synchronized operation between the two rollers. To accommodate the natural variation in cotton plant sizes, the dual-roller system is attached to a tilt-adjustable end-effector. This end-effector is capable of altering the position of the rollers to target cotton bolls positioned at heights between 7" and 11" using a tilt based servo system. This allows for simple and fast height adjustments, which is a common problem in precision multi Degree of Freedom (DOF) end-effectors. Such an adjustment feature improves the flexibility and adaptability of the Cotton Rover to diverse field conditions.

3.4. Delivery System

The CR is equipped with a unique system to manage the storage and ultimate delivery of the harvested cotton at a designated corner of the field. This system is designed to be simple, efficient, and reliable, thus facilitating the smooth execution of the competition task. The delivery system is composed of two main components: a storage unit and a cotton expulsion mechanism.

The storage unit is the initial repository for the harvested cotton bolls, which are funneled into the unit through a chute connected to the harvesting mechanism. The storage unit is crafted from lightweight yet sturdy ABS plastic to maintain overall mobility while ensuring the safe containment of the cotton bolls.

Once the cotton harvesting process is completed, or the storage unit reaches its capacity, the robot triggers the cotton expulsion mechanism to deliver the collected cotton bolls. This mechanism comprises a servo-controlled flap and a pair of DC computer fans. The servo motor, upon activation, opens the flap located at the bottom of the storage unit, allowing the cotton to escape the vessel. A pair of DC computer fans is then activated to generate a sufficient airflow that expels the cotton from the storage unit onto the designated corner of the field. These fans are selected for their strong airflow, energy efficiency, and compactness, making them an ideal choice for this task.

The delivery system of the Cotton Rover completes the automated cotton harvesting cycle in the context of the competition.

4. Robot Interface

This section of the report delves into the various aspects of the Cotton Rover's interface design, which encapsulates the interaction between the physical robot, its control hardware, software communication and decision-making units, as well as the essential power management system that ensures the robot's sustainable operation. The components that make up the Cotton Rover's interface system have been carefully chosen based on their cost-effectiveness, performance, and compatibility, aiming to deliver a robot that is not only capable but also practical for real-world applications. A detailed list of these components, along with their respective manufacturer's suggested retail prices (MSRP), is provided in Table 1 in the Appendix (6). The following subsections detail the power management strategy, the hardware control interface, and the software communication and decision interface of the Cotton Rover.

4.1. Power Management

Power delivery is an important aspect of a robot's operations and affects the time, performance, and overall efficiency. The power source of the Cotton Rover is based on lithium-ion (Li-ion) batteries due to their high energy density, long life cycle, and lower self-discharge rate compared to other battery types such as lithium-polymer (LiPo) batteries, typically used in standard robotics application. Li-ion batteries also have the advantage of no requirement for periodic discharge to ensure long life, providing better usability for long-term applications.

The CR uses six Li-ion batteries with a 3S2P configuration, meaning three batteries are connected in series (3S) and two sets of these series batteries are connected in parallel (2P). Each individual battery is rated at 3.7V and can deliver 3000mAh of current. In this configuration, the total voltage supplied is 11.1V (3.7V3), and the total current capacity is 6000mAh (3000mAh2), providing the robot with a robust power source for longer operation times. The batteries are configured with modular design consideration. The CR may be powered using only one of the battery packs containing 3 Li-on batteries at half capacity, in the case that a pack needs to be replaced or set aside to charge. See figure 4 for reference to a battery pack used for the CR.

Figure 4. Power supply of the Cotton Rover, consisting of 2 parallel packs of 3 series 3.7V Li-ion batteries. Battery packs can be disconnected and reconnected using the 2 pin connectors.

Given the different power requirements of the robot's components, a step-down converter is incorporated into the design to adjust the voltage supply. The motors require a supply of 12V, and the controller components operate at 5V. The step-down converter effectively reduces the 11.1V output from the battery configuration to a 5V supply for the controller components, allowing all components to be powered by the same power source without risk of damage or inefficiency. the power is further distributed by controllers and motor drivers described further in section 4.2.

The motor driver used in our design incorporates a standby (STBY) mode. This feature provides the capability to deactivate power consumption to the motors when they are not in use. In other words, when the robot is idle, the motor driver switches to STBY mode, effectively reducing the power consumption and thus extending the operational time of the robot.

4.2. Hardware Control Interface

In order to meet the diverse set of tasks that the CR must perform, a layered, hardware interface design was adopted. The system is structured around two Raspberry Pi Pico microcontrollers [4], each dedicated to a distinct set of functions.

The first microcontroller manages the control of the mecanum wheel system. Utilizing two TB6612FNG dual motor drivers, it administers the navigation commands to the robot's motors. This setup provides the required flexibility to control the speed and direction of each wheel independently, allowing the robot to perform intricate maneuvers.Please see Figure The controller board made for the CR navigation control.

The second microcontroller oversees the operation of various sensors and the harvester control mechanism. This allows for efficient data processing and immediate response to sensor feedback, enhancing the overall control precision of the Cotton Rover.

Both microcontrollers interface with a Jetson Nano [8] via serial communication, which serves as the primary processing unit. The Jetson Nano is responsible for the high-level decision making and orchestrates the tasks performed by the two Raspberry Pi Pico controllers. These controllers were custom-developed for the CR by the MARS team. We decided to make our design open source, contributing to the broader community and encouraging further advancements in agricultural robotics. The details of the wiring and integration of the controllers are elaborated in the wiring diagram shown in Figure 6 in the Appendix (6).

4.3. Software Communication and Decision Interface

The Cotton Rover implements the Robot Operating System (ROS) [9] as the primary communication protocol between its various subsystems. ROS uses a publish-subscribe communication model which allows different nodes in the

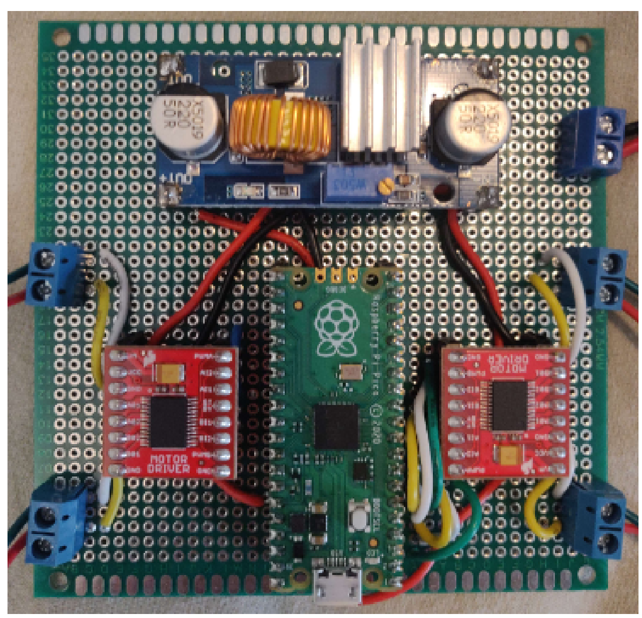

Figure 5. 1 of 2 controllers made for the control of the locomotion motors.

system to share information efficiently. Each node can publish messages to topics or subscribe to topics to receive messages. This message passing mechanism provides a clean and efficient way to connect each of the different subsystems, enabling a high degree of modularization in the system's software architecture.

In the context of the CR, ROS enables high-level command execution between the low-level device control, sensor data aggregation, and complex intercommunication between subsystems. The high level workflow of the system is as follows:

1. The Jetson Nano, running the ROS Master, initiates the navigation system, which commences by gathering data from the LIDAR and ultrasonic sensors to facilitate autonomous navigation.

2. As the Cotton Rover navigates the field, the computer vision system continuously processes data from the onboard camera. When a cotton boll is detected, the location and status (ripe or unripe) are published to their respective ROS topics.

3. Concurrently, the mapping operation subscribes to the cotton boll detection and location topics. This information, in conjunction with the ongoing sensor data, is used to update the map of the playing field. Map data is periodically published to a ROS topic for possible system-wide consumption.

4. The harvesting mechanism controller subscribes to the boll detection topics. Upon confirmation of a ripe cotton boll, the controller activates the roller/grinder and storage subsystem to harvest the boll. Upon successful collection, an event message is published.

5. The navigation controller subscribes to the boll detection and map data topics. Using this data, it calculates navigation commands, which are then published to control the robot's movement across the field.

6. The power management system monitors activity related topics, controlling power usage as necessary. It may publish messages to initiate power-saving measures or resume normal operation based on the robot's status and power levels.

7. After the Cotton Rover completes the harvesting process, the delivery system receives a command to release the harvested cotton bolls. A message is then published, signifying successful delivery.

8. Finally, all map data, alongside other activity logs, are consolidated and written to a CSV file on the provided USB drive for post-operation analysis and scoring.

This design provides an efficient, modular, and scalable system that supports real-time operation of complex tasks such as those required by the Cotton Rover. By decoupling system components and standardizing their communication, ROS allows for efficient debugging, easy system upgrades, and robust operation.

5. Performance Testing

At the time of writing this report, the comprehensive assembly of the Cotton Rover (CR) is yet to be finalized. However, testing of the individual subsystems have been conducted. These tests functionality and efficiency of each subsystem, offering insights into the prospective performance of the fully integrated system. The following sections present the outcomes of these preliminary tests.

Navigation System The navigation system, equipped with mecanum wheels, lidar, and other auxiliary sensors, was tested in a simulated playing field environment. The test results showed that the robot was capable of unrestricted movement and precise navigation within an error margin of $\pm$ 8 cm.

Cotton Detection and Mapping The image processing system's performance was evaluated using a collection of cotton boll images under various conditions. The combination of color threshold and shape detection techniques achieved a cotton boll detection accuracy of 62% and a boll ripeness classification accuracy of 85%.

Harvesting Mechanism The efficacy of the harvesting mechanism was examined through individual testing. The serrated roller/grinder assembly was tested on a range of cotton bolls with different number of bolls. It was able to harvest the cotton bolls in all cases, demonstrating an operational efficiency.

Delivery System The delivery system, comprising of a storage unit, a servo motor, and DC fans, was tested in isolation. The system was able to eject the cotton bolls, demonstrating the efficacy of the delivery system in rapidly discharging harvested cotton.

The results of these individual tests present a promising outlook for the performance of the fully assembled Cotton Rover. Once fully integrated, comprehensive system tests and field trials will be conducted to optimize and validate the robot's performance.

6. Conclusion

This report details the design and development of the Cotton Rover, a specialized robot with the primary objective of automating cotton harvesting tasks. The CR is a comprehensive integration of multiple subsystems, each with a distinctive role in the harvesting process. The subsystems include a sophisticated navigation system, an efficient cotton detection and mapping mechanism, a robust harvesting mechanism, and a unique delivery system. The CR design addresses the challenges inherent in the cotton harvesting process. The robot leverages a unique combination of mechatronics and sensor fusion to accomplish the tasks set by competition. Performance tests conducted on the individual subsystems showed promising results, indicating that the Cotton Rover, once fully assembled and integrated, has the potential to be an effective cotton harvesting robot. Upon finalization, the Cotton Rover will undergo comprehensive testing to evaluate its overall performance and efficiency. This project showcases the significant potential of robotics in agriculture through a simulated environment and serves as a starting point toward real world application.

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Appendix

Table 1. Component List for the Cotton Rover

Control Unit	Type	MSRP (USD)
Jetson Nano Developer Kit	Processor	129
Raspberry Pi Pico x2	Controller	8
Dual TB6612FNG x2	Motor Driver	27.9
HC-SR04P x4	Ultrasonic Sensor	18
MPU-6050	3 axis Gyro with 3 axis Accelerometer	10.85
JGB37-3530-12V111 x4	Motors	70.8
97mm Mecanum wheels (set of 4)	Wheels	39.26
FR0115M	Servo motor	27.93
Raspberry Pi Camera Module v3	Camera	25
29DM9V	DC motor for dual-roller	2.14
Total	-	**358.88**

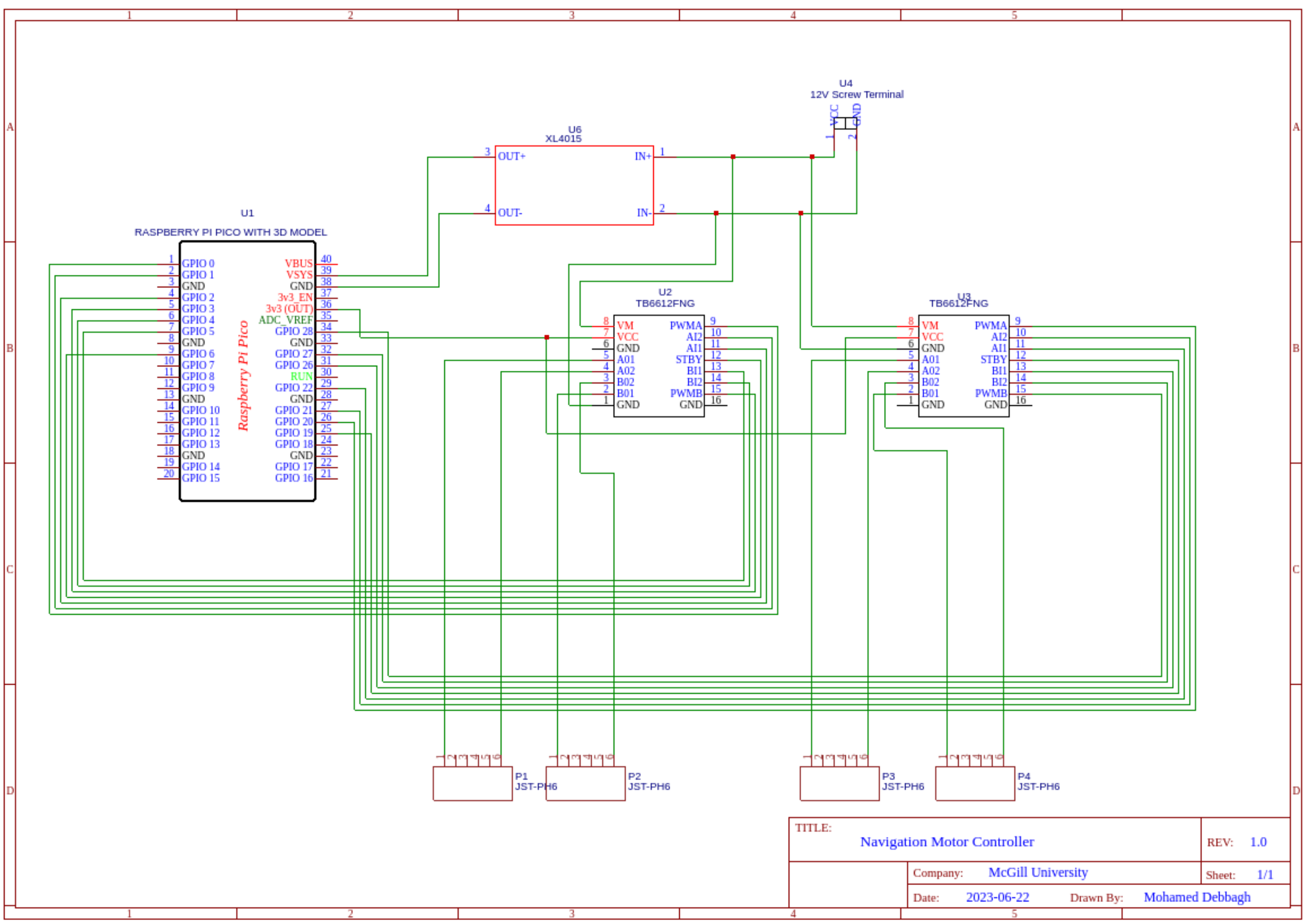

Figure 6. Wire diagram of the Navigation Motor Controller