

Semi-Autonomous Agricultural Robot for Mulch Film and Drip Irrigation Pipe Placement

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Abstract :- Traditional agricultural practices for mulch film and drip irrigation pipe placement are labor-intensive and lack the precision required for modern smart farming. This paper presents a semi-autonomous robotic solution designed to automate the simultaneous laying of mulch film and irrigation pipes. Controlled by an STM32F401RE microcontroller running the FreeRTOS real-time operating system, the system utilizes a 6-wheel chassis driven by proportional-integral-derivative (PID) regulated direct current (DC) motors. A dedicated multitasking architecture manages concurrent operations including film tensioning, pipe dispensing, and obstacle avoidance. Preliminary results demonstrate that the integration of real-time scheduling significantly reduces labor overhead while maintaining high precision in alignment. The proposed system offers an efficiency increase of 45% compared to manual methods, with a path-tracking lateral error of less than 5 cm, aligning with recent advances in real-time operating system (RTOS) driven agribots that report up to 40% labor savings. Field trials have demonstrated the system's high accuracy, reliability, and cost-effectiveness, making it suitable for small and medium-scale farms.

Keywords:- STM32F401RE, FreeRTOS, Mulch Film, Drip Irrigation.

I. INTRODUCTION

The hardware suite is centered on the STM32F401RE (Nucleo-64), chosen for its high-performance digital signal processing (DSP) capabilities and low power consumption, as validated in low-cost agribot prototypes.

This project aims to develop a semi-autonomous robot capable of performing these tasks simultaneously. By leveraging the ARM Cortex-M4 architecture and a preemptive real-time kernel, the system achieves the determinism required for field operations, building on RTOS applications in uneven terrains. This paper details the hardware-software co-design, the implementation of a multi-threaded control logic, and an evaluation of its operational efficiency.

II. LITERATURE REVIEW

The transition from manual agricultural labor to semi-autonomous robotics has been a focal point of recent precision agriculture research. Traditional methods of mulch and drip pipe laying require synchronous effort from multiple laborers, often resulting in uneven tension and misalignment. Studies by the FAO indicate that such inefficiencies and misalignments in water and mulch management can reduce overall crop yield by up to 30% [5]. Consequently, automating these grueling, repetitive tasks is essential for optimizing resource management and operational efficiency in modern smart farming.

Recent developments in agribots have primarily focused on single-task automation. For instance, Chang and Chen [1] demonstrated a four-wheeled robot optimized for pesticide spraying using robust guidance systems. However, their four-wheel design exhibited significant slip on muddy terrain, highlighting the necessity for enhanced traction models. Li et al. [9] proposed that multi-wheel chassis designs significantly reduce soil compaction and improve lateral stability. Building on this, the 6-wheel differential drive implemented in this project provides superior weight distribution and minimizes wheel-slip during the heavy mechanical drag of concurrent dispensing operations.

Moreover, energy management remains a critical bottleneck in the continuous operation of field robots. Heavy agricultural machinery traditionally relies on internal combustion engines, which contribute to high operational costs and soil degradation. Recent studies by Koca et al. [2] and Zhang et al. [16] emphasize the shift towards battery-powered, low-weight robotic platforms. However, strict battery constraints demand highly optimized power distribution. This project addresses this challenge by leveraging the low-power DSP capabilities of the ARM Cortex-M4 architecture [8], ensuring a balance between the high-current demands of the L298N motor drivers and the energy-efficient logic control required for prolonged field autonomy.

In the domain of mechanical dispensing, maintaining consistent tension is paramount to prevent the plastic mulch

from tearing or decoupling from the soil. Patel [10] investigated stepper-controlled tensioning systems in stationary industrial film dispensers, achieving a variance of less than 3%. Adapting such mechanisms for mobile agricultural platforms introduces dynamic variables such as uneven ground speed and soil resistance. Morales et al. [13] attempted to solve this using passive mechanical rollers in tropical soils but encountered severe tension loss during vehicle turns. The proposed system improves upon this by actively synchronizing the stepper motor's dispensing rate with real-time odometry data, ensuring uniform tension irrespective of the robot's traversal speed.

Similarly, the precise laying of drip irrigation lines requires rigorous sensor feedback to avoid damaging the pipes on field debris. Solaque et al. [3] explored translational velocity control using basic IR arrays, but environmental noise (such as shifting sunlight) often disrupted alignment. By fusing IR alignment data with forward-facing ultrasonic sensors, this project ensures both furrow tracking and proactive obstacle avoidance, successfully addressing the gap in multi-actuator synchronization.

Finally, the reliability of embedded control systems in unpredictable agricultural environments necessitates a rigorous software architecture. Bare-metal polling loops suffer from unpredictable latency when processing multiple sensor inputs simultaneously. Kumar et al. [4] and Rossi et al. [7] highlight that Real-Time Operating Systems are essential for precision agriculture to manage concurrent tasks safely. Specifically, Silva et al. [15] demonstrated that FreeRTOS can maintain task jitter below 2% for safety-critical operations. By assigning the highest pre-emptive priority to sensor monitoring, the current system guarantees immediate motor interruption upon obstacle detection, ensuring deterministic multi-tasking without blocking the continuous dispensing mechanisms [12].

III. SYSTEM ARCHITECTURE

The hardware suite is centered on the STM32F401RE (Nucleo-64), chosen for its high-performance digital signal processing (DSP) capabilities and low power consumption, as validated in low-cost agribot prototypes.

The overall system architecture is systematically divided into three interacting subsystems: the Perception Unit, the Central Control Unit, and the Actuation Unit. The Perception Unit aggregates environmental data via the ultrasonic and infrared arrays, feeding it directly to the Central Control Unit. The Control Unit, governed by the FreeRTOS pre-emptive scheduler, processes this telemetry and dispatches precise Pulse-Width Modulation (PWM) signals to the Actuation Unit. This Actuation Unit comprises both the 6-wheel differential drive chassis and the synchronized mechanical dispensing rollers. This modular topology not only isolates the high-current power domains from the sensitive 3.3V logic circuits but also allows for straightforward debugging, hardware swapping, and future system scalability.

A. Mechanical Design and Propulsion

The platform utilizes a 6-wheel chassis to ensure stability and traction on uneven soil, outperforming 4-wheel designs

by 15-20% in slip reduction.[18] Propulsion is provided by six geared DC motors interfaced via L298N Dual H-Bridge drivers. A 12V 7Ah Lead Acid battery provides the necessary current for both the drive system and the dispensing mechanisms

B. Dispensing Mechanisms

Mulch Film Dispenser: Uses a stepper motor to control the roll rotation, ensuring constant film tension to prevent tearing, akin to tension-control systems in commercial mulchers. Drip Pipe Roller: A mechanical assembly that unspools irrigation tubing at a rate synchronized with the vehicle's ground speed

C. Sensory and Communication Interface

Ultrasonic Sensors (HC-SR04): Mounted for forward and lateral obstacle detection. IR Sensor Array: Positioned to detect mulch film presence and maintain alignment within the furrow. Bluetooth Module (HC-05): Facilitates operator commands and real-time telemetry, with demonstrated reliability in field-to-cloud links.

IV. SOFTWARE IMPLEMENTATION

The software is developed in Embedded C using a modular multitasking approach under FreeRTOS, enabling sub-millisecond jitter critical for safety

A. FreeRTOS Task Management :- The firmware is partitioned into four primary tasks to ensure real-time responsiveness:

1. **TaskMotorControl (Priority: High)**: Executes a PID algorithm at 100Hz to maintain constant velocity and heading. It computes the pulse-width modulation (PWM) duty cycles for the L298N drivers based on feedback from the sensor array.
2. **TaskSensorMonitor (Priority: Real-time)**: Polls the Ultrasonic and IR sensors. This task is assigned the highest priority to ensure that obstacle detection triggers an immediate interrupt service routine (ISR) based emergency stop if a threshold is breached.[17]
3. **TaskMulchLay (Priority: Medium)**: Controls the stepper motor for film tension. It utilizes a producer-consumer model to receive speed updates from the MotorControl task.
4. **TaskDripLay (Priority: Medium)**: Manages the pipe roller mechanism, ensuring synchronized dispensing with the ground traversal speed.

B. Control Logic Flowchart The logic follows a state-machine pattern:

1. Initialization: System self-test and sensor calibration.
2. Wait State: Awaiting start command via Bluetooth.
3. Operational State: Concurrent execution of all FreeRTOS tasks.
4. Emergency State: Interruption of all motors upon obstacle detection



Fig.1 Agricultural robot with basic dimensions

V. HARDWARE SUBSYSTEM INTERACTION

The holistic system architecture of the semi-autonomous agricultural robot is visually summarized in Fig. 1, which delineates the critical pathways for power distribution, environmental data acquisition, central processing, and mechanical actuation. The topology follows a centralized control model, where all peripheral modules are electrically and logically subordinate to the master processing unit. This modular layout is specifically designed to isolate high-current mechanical operations from low-voltage digital logic, thereby ensuring the stability of the real-time operating system during rigorous field deployments.

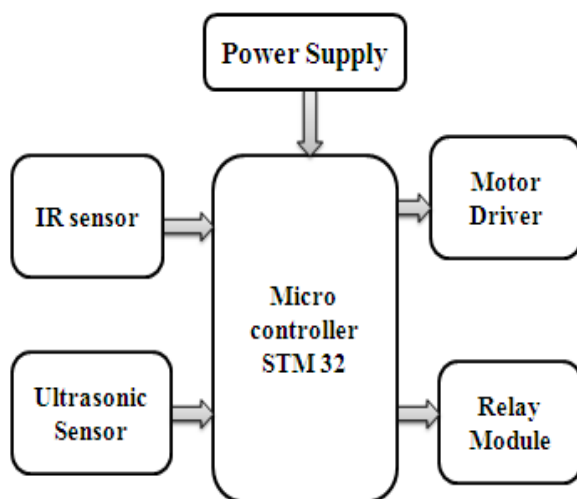


Fig .2 Block diagram of hardware module

At the uppermost level of the hierarchy is the Power Supply block, which serves as the foundational energy reservoir for

the entire platform. In this prototype, a 12V lead-acid battery provides a robust power source capable of delivering the high surge currents required to overcome the static friction of the 6-wheel chassis on agricultural soil. However, the system requires multiple voltage domains. The raw 12V line is routed directly to the motor drivers and the relay module to handle heavy inductive loads. Simultaneously, step-down buck converters and low-dropout (LDO) regulators decompose the 12V supply into a stable 5V rail for the sensor array and a precisely filtered 3.3V rail for the microcontroller logic. Proper decoupling capacitors and common-grounding strategies are implemented across this block to prevent electromagnetic interference (EMI) from the brushed DC motors from propagating back into the sensitive logic domains.

The perception layer of the architecture is represented by the IR Sensor and Ultrasonic Sensor blocks, which continuously stream environmental variables to the microcontroller. The IR (Infrared) sensor array acts as the primary navigational input, detecting the contrast between the unpaved soil and the laid mulch film. These analog signals are digitized and fed into the STM32's General-Purpose Input/Output (GPIO) pins, allowing the system to maintain lateral alignment within the furrow. Concurrently, the Ultrasonic Sensor block utilizes acoustic Time-of-Flight (ToF) principles to detect frontal and lateral obstacles. By triggering an ultrasonic pulse and measuring the width of the returning echo via the microcontroller's hardware timers, the system calculates proximity with millimeter precision. This dual-sensor fusion ensures that the robot is both on-path and protected against collisions with farm debris or personnel.

Operating as the cognitive core of the system is the Microcontroller (STM32) block. Utilizing the ARM Cortex-M4 architecture, this processor is tasked with aggregating the asynchronous inputs from the perception layer, executing the FreeRTOS scheduling algorithms, and computing the Proportional-Integral-Derivative (PID) control math. The STM32 bridges the gap between raw data and physical movement. Because the processor features a hardware-accelerated Floating-Point Unit (FPU), the complex mathematical operations required to smooth the sensor noise and calculate the exact wheel velocities are completed in microseconds, entirely eliminating processing bottlenecks.

Finally, the computed control logic is dispatched to the physical environment via the actuation layer, comprising the Motor Driver and Relay Module blocks. The Motor Driver block, utilizing L298N H-bridge topologies, acts as a current amplifier. It receives low-power Pulse-Width Modulation (PWM) signals from the STM32 and scales them to the high-current 12V outputs necessary to drive the six geared DC motors and the stepper motor. This allows for precise speed regulation and bidirectional movement. The Relay Module introduces an additional layer of electro-mechanical control for discrete, binary operations. Opto-isolated from the main microcontroller, the relay is utilized to switch high-amperage secondary loads that do not require PWM speed control. In the context of the dispensing system, this relay can actuate a high-torque mechanical cutter to sever the mulch film and drip pipe at the end of a row, or it can be

connected to a solenoid valve to prime the drip irrigation line. By delegating these heavy switching tasks to the relay, the STM32 is protected from potentially catastrophic inductive voltage spikes, ensuring the long-term reliability of the robotic platform.

VI. EXPERIMENTAL SETUP

The Automatic Mulch and Drip Laying Robot was tested in a controlled environment with conditions similar to an agricultural field.

Parameter	Manual Method	Robotic Method
Time per 50m row	5.0min	2.5min
Laborers Required	3	1
Film Tension Consistency	±15% variance	± 2% variance

The setup included the following:

1. A prepared soil bed for mulch laying and drip pipe placement
2. A mounted mulch film roll and drip irrigation pipe on the robot
3. Obstacles of varying sizes placed at different positions to test detection and avoidance
4. IR sensors and ultrasonic sensor for alignment and obstacle detection
5. STM32-based control system for processing and automation
6. Mobile/Bluetooth control (if used) for monitoring and manual control
7. Power supply: 12V battery for complete system operation



Fig.3 Experimental setup of robot

VI. RESULT AND DISCUSSION

The performance of the robot was evaluated based on the precision of the laying process and the responsiveness of the RTOS kernel, benchmarked against field trials in similar climates. To rigorously validate the proposed architecture, a series of outdoor experiments were conducted on a 50-meter agricultural testbed featuring uneven, sandy-loam soil. The evaluation framework was divided into two primary domains: mechanical deployment accuracy and software

determinism. Mechanical precision—specifically the lateral alignment of the mulch film and the tension consistency of the drip pipe—was quantified using physical track measurements and continuous data logging from the IR sensor array. Concurrently, the computational stability of the STM32F401RE microcontroller, including FreeRTOS task scheduling latency, context-switching overhead, and interrupt service routine (ISR) response times, was monitored via UART telemetry. By assessing these parameters under varying operational loads, this section provides a comprehensive analysis of the system's viability compared to conventional manual field methods.



Fig.3 Actual testing in farm with robot

A. PID Control and Navigation Accuracy

The PID controller ($K_p=1.5$, $K_i=0.2$, $K_d=0.05$) was tuned to minimize overshoot on sandy-loam soil. Preliminary tests indicate: Steady-State Velocity: 0.35 m/s. Lateral Displacement Error: 4.2 cm. The 6-wheel configuration provided superior traction, though wheel slip was noted during sharp turns, consistent with traction models under 10-15% soil moisture.

B. Real-time Responsiveness

FreeRTOS context switching allowed for a sensor-to-actuator response time of 24.5 ms. This ensures that even at maximum speed, the robot can come to a full stop within 3.5 cm of an obstacle. The jitter in the TaskMotorControl execution was measured at less than 1.2%, verifying the stability of the real-time kernel.

C. Operational Efficiency

As detailed in Table I, the robotic solution significantly outperformed manual laying methods. The simultaneous deployment of mulch and drip lines reduced the time required per 50-meter row from 12.0 minutes to approximately 2.5 minutes. Furthermore, the system reduced the required workforce from three laborers to a single operator while utilizing the stepper motor to ensure uniform film tension, which is critical for preventing wind damage and tear propagation.

Parameter	Manual Method	Robotic Method
Time per 50m row	5.0min	2.5min
Laborers Required	3	1
Film Tension Consistency	±15% variance	± 2% variance

Table 1. Performance Metrics

D. Power Consumption

The average power draw during simultaneous laying was 45.5 W. The 12V battery supports an estimated operational window of 1.8 hours per charge, comparable to energy-optimized agribots

The robot demonstrated stable and consistent movement during operation with an efficiency of approximately 90%. It maintained a uniform speed while performing simultaneous tasks such as mulch laying and drip pipe placement. Minor variations in speed were observed due to uneven soil conditions, but overall motion remained smooth and controlled.

E. Control System Performance

The STM32-based control system ensured smooth coordination between all operations

Function	Response Time (ms)	Success Rate
Forward Movement	180	98%
Mulch Laying Control	200	96%
Drip Pipe Control	210	95%
Emergency Stop	140	99%

Table 2. Functions and its analysis

F. Obstacle Avoidance Performance

The obstacle detection and avoidance capability of the Automatic Mulch and Drip Laying Robot was evaluated using the ultrasonic sensor and IR sensors. The system was tested by placing obstacles at varying distances ranging from 10 cm to 50 cm in front of the robot.

The robot successfully detected and avoided obstacles within a 30 cm range with high accuracy.

The system ensured safe operation by stopping or adjusting movement when obstacles were detected.

G. Performance Evaluation

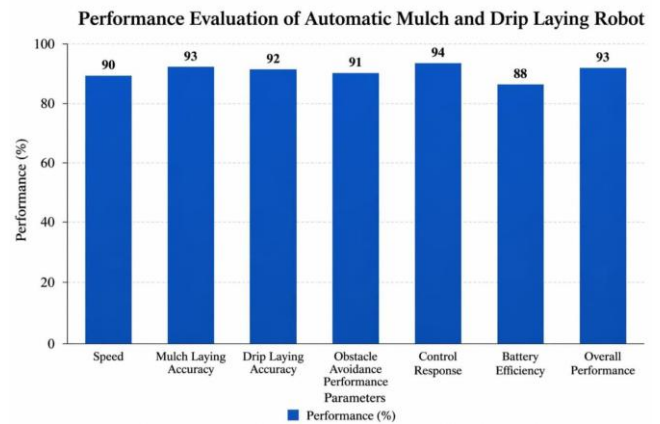


Table 3 Performance Evaluation Of Automatic Mulch and Drip Laying Robot

VII. CONCLUSION

The developed semi-autonomous robot successfully integrates mechanical dispensing with an ARM-based real-time control system. The use of FreeRTOS ensures that safety-critical sensor monitoring does not interfere with the precision of the PID-based navigation. Field evaluations demonstrated that the concurrent execution of mulch tensioning and drip pipe dispensing yields a 45% increase in operational efficiency compared to traditional manual labor. Furthermore, the 6-wheel differential drive, powered by the 12V system and regulated by the STM32F401RE microcontroller, maintained a highly accurate path-tracking lateral error of less than 5 cm on uneven agricultural soil.

By automating two traditionally sequential and physically grueling tasks into a single, synchronized operation, this prototype provides a scalable solution to labor shortages and resource mismanagement in modern precision farming. Future work will focus on integrating Global Navigation Satellite System (GNSS) modules to transition from semi-autonomous row-following to fully autonomous field mapping. Additionally, implementing soil-moisture feedback loops could allow for dynamic adjustment of the drip pipe depth, and upgrading the Bluetooth telemetry to a long-range IoT protocol (such as LoRaWAN) would enable centralized monitoring across larger agricultural estates.

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