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Design and Development of a Robotic System for Agricultural Pesticide Spraying

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Abstract

The global agricultural sector is facing an unprecedented convergence of challenges, driven by a rapidly expanding global population, acute labor shortages, and the pressing need for environmentally sustainable farming practices. Traditional pesticide application methods are notoriously inefficient, heavily reliant on manual labor, and expose farmworkers to severe acute and chronic health hazards due to continuous chemical exposure. To address these critical issues, this research presents the design, development, and rigorous field evaluation of a smart, autonomous, four-wheel-drive (4WD) robotic system engineered specifically for targeted agricultural pesticide spraying and real-time environmental monitoring. The proposed robotic platform integrates a high-torque 4WD locomotion architecture, controlled by an ESP32 microcontroller, ensuring robust navigation and maneuverability across uneven and muddy agricultural terrains. A comprehensive suite of environmental sensors including ultrasonic sensors for dynamic obstacle avoidance, and soil moisture, temperature, and humidity sensors for real-time crop health assessment is seamlessly integrated into the control loop. The primary actuation system features a highly optimized, relay-controlled 12V diaphragm pump linked to strategically positioned atomizing nozzles, enabling precision fluid distribution tailored to the specific spatial requirements of the crop canopy. Field testing and comprehensive empirical evaluations demonstrated exceptional performance metrics. The robotic system achieved an 85% operational efficiency rate compared to the 60% efficiency typical of conventional manual spraying operations. Furthermore, the implementation of this robotic solution drastically reduced labor dependency, compressing the requirement from an average of three to four manual workers down to a single supervisory operator. Crucially, the occupational safety index was substantially elevated from a baseline rating of 4 (indicative of high exposure risk) to a rating of 9, effectively neutralizing the risk of hazardous chemical exposure. Ultimately, this research delivers a highly scalable, cost-effective, and operationally viable technological intervention, directly contributing to the advancement of precision agriculture and the safeguarding of rural farming communities.

Keywords; Precision Agriculture, 4WD Agribot, Autonomous Spraying, IoT Smart Farming, ESP32 Microcontroller, Mechatronics, Agricultural Robotics, Occupational Safety.

INTRODUCTION

The trajectory of global demographic expansion presents a formidable challenge to contemporary agricultural systems. With the United Nations projecting the global population to reach approximately 9.7 billion by the year 2050, the demand for food and agricultural outputs is anticipated to surge by up to 70% [40]. This dramatic escalation in demand necessitates a paradigm shift in how agricultural operations are conducted. Traditional farming practices, characterized by intensive manual labor and uniform, indiscriminate application of agrochemicals, are proving to be increasingly unsustainable [1], [2]. They are fraught with inefficiencies, economic vulnerabilities, and severe ecological consequences, fundamentally threatening long-term food security and environmental homeostasis [36].

One of the most critical bottlenecks in modern agriculture is the acute shortage of

skilled agricultural labor. Rapid urbanization and shifting socioeconomic demographics have triggered a massive exodus of the rural workforce toward urban industrial centers [12]. Consequently, the reliance on manual labor for essential farming operations particularly the strenuous and hazardous task of pesticide spraying has become a profound vulnerability. Manual pesticide application is not only labor-intensive but also notoriously inefficient [3]. Conventional broadcast spraying techniques result in substantial chemical wastage, with significant portions of the applied chemicals missing the target foliage and dispersing into the soil and atmosphere, leading to severe ecological contamination and groundwater pollution [15].

Beyond the economic and ecological ramifications, the continuous reliance on manual labor for agrochemical application poses a severe public health crisis. Farmworkers engaged in manual spraying are routinely exposed to highly toxic chemical compounds, primarily organophosphates and carbamates, which function as potent cholinesterase inhibitors [19]. Prolonged exposure, whether via inhalation, dermal contact, or ingestion, has been clinically linked to a spectrum of acute and chronic health afflictions [37]. These range from immediate symptoms such as severe dermatitis, respiratory distress, and neurotoxicity, to long-term chronic conditions including severe neurological disorders, carcinogenic developments, and profound reproductive abnormalities [37]. Protecting the agricultural workforce from these deleterious effects while simultaneously enhancing agricultural productivity demands urgent technological intervention [21].

In response to these multifaceted challenges, the paradigm of Precision Agriculture (PA) has emerged as a transformative solution [5], [13]. Precision agriculture leverages advanced Information and Communication Technologies (ICT), the Internet of Things (IoT) [7], [22], and highly sophisticated robotics to optimize agricultural inputs based on highly localized spatial and temporal variability. The integration of intelligent, autonomous robotic platforms into agricultural workflows represents a monumental leap forward [17]. These 'agribots' are capable of executing complex tasks with unprecedented accuracy, tireless consistency, and absolute immunity to biological hazards [20].

The primary motivation of this research is to architect and deploy a robust, highly modular, and significantly cost-effective robotic platform designed specifically to democratize the benefits of precision agriculture for small-to-medium-scale farmers. While highly advanced

commercial agricultural robots currently exist [6], their exorbitant capital costs, proprietary software architectures, and complex maintenance requirements render them entirely inaccessible to the vast majority of the global farming population, particularly in developing economies [24]. This paper outlines the end-to-end development of a 4-Wheel Drive (4WD) mobile robotic system engineered to bridge this critical accessibility gap [8]. By utilizing off-the-shelf microcontrollers [18], ruggedized DC geared motors, and an array of low-cost yet highly accurate environmental sensors [33], the proposed system delivers sophisticated autonomous navigation and precision-targeted spraying capabilities at a fraction of the cost of commercial alternatives [35].

PROBLEM STATEMENT

The fundamental problem addressed in this research is the unsustainable nature of traditional pesticide application in agriculture, characterized by extreme occupational health hazards, critical labor shortages, and profound ecological inefficiencies [12], [38]. Farmworkers are continuously subjected to immense health risks due to unprotected exposure to highly toxic agrochemicals [19]. The prevailing manual methodologies depend heavily on rudimentary backpack sprayers, forcing workers into direct physical proximity with aerated chemical particulates, resulting in frequent and severe cases of chemical poisoning, respiratory degradation, and long-term neurological damage [37].

Concurrently, traditional broadcast spraying results in a highly uneven application of critical inputs [28]. Over-application leads to localized chemical toxicity, soil acidification, and resistance development in pest populations, while under-application fails to eradicate the targeted pathogens, ultimately resulting in suboptimal crop yields and diminished economic returns [3]. The spatial variability of the field is entirely ignored in manual methodologies [15].

Furthermore, while advanced autonomous solutions do exist within the current technological landscape, they suffer from severe deployment barriers [17]. Existing commercial agricultural robots are exceptionally expensive, often requiring massive capital investments. They are characterized by complex, proprietary architectures that are extremely difficult for traditional farmers to operate, maintain, or repair [13]. Consequently, there is an urgent and undeniable need to develop a low-cost, mechanically robust, and user-friendly robotic system capable of delivering precision agricultural services without the prohibitive

financial and technical overheads associated with current market offerings [11], [35].

RESEARCH OBJECTIVES

The core objective of this research is to construct an operationally viable, low-cost autonomous robotic system to replace manual labor in the hazardous task of pesticide spraying. The specific sub-objectives driving this development are as follows:

- 1) Design and construct a mechanically stable, high-traction four-wheel drive (4WD) mobile platform capable of robust and highly maneuverable navigation across the uneven, muddy, and unpredictable terrains typical of open-field agriculture [8], [14], [32].
- 2) Integrate a comprehensive suite of real-time environmental sensors specifically soil moisture, ambient temperature, relative humidity, and forward-facing ultrasonic sensors to establish a localized, data-driven profile of crop health and immediate environmental conditions [9], [10], [33].
- 3) Implement a highly modular, automated, and precisely targeted fluid spraying mechanism, controlled intelligently via an onboard microcontroller, to significantly optimize pesticide utilization, maximize foliar coverage, and aggressively minimize chemical wastage [4], [25].
- 4) Develop a cohesive and responsive control architecture utilizing the ESP32 platform [7], [18], [39] to orchestrate locomotion, sensor data acquisition, dynamic obstacle avoidance [27], and precise actuation of the spraying apparatus within a unified, real-time computational framework.

LITERATURE REVIEW

The evolution of robotics in agriculture has followed a distinct trajectory, transitioning from highly structured greenhouse environments to the chaotic, unstructured domains of open-field farming [1]. Early iterations of agricultural automation focused predominantly on fixed-installation machinery and guided tractors [24], [38]. However, the advent of lightweight microcontrollers and advanced mobile robotics has shifted the paradigm toward smaller, highly agile Wheeled Mobile Robots (WMRs) [17]. Studies by Bechar and Vigneault [1] and Blackmore [2] heavily document this transition, emphasizing that while large autonomous tractors resolve broad-acre farming issues, they induce severe soil compaction and are incapable of navigating tight inter-row spacing [13].

A critical area of ongoing research is the comparative analysis of mobile robot locomotion architectures. Differential drive systems are widely favored in academic

prototypes due to their kinematic simplicity [17]. However, extensive field testing demonstrates that differential systems often fail in open-field agriculture [14]. Conversely, 4WD architectures offer vastly superior terrain adaptability and aggressive traction scaling [8], [32]. Zhou [14] and Sharma [8] provide foundational kinematic models proving that 4WD is the absolute minimum requirement for kinematic stability when carrying dense liquid payloads.

Furthermore, the review of autonomous spraying reveals a gap between theory and practical implementation. High-end systems utilize complex machine vision architectures (CNNs) for real-time weed identification [5], [30]. While intellectually impressive, these require massive onboard computational power, severely restricting battery life [26], [31]. Therefore, there is a prominent need for 'mid-tier' robotic systems utilizing localized environmental sensing [9], [33] and proximity-based targeted spraying [11], [35]. Research by Huang et al. [4] and Feng [25] highlights the importance of optimized nozzle design and diaphragm pumps for achieving ideal Sauter mean diameters in spray droplets [28].

Moreover, energy constraints remain a ubiquitous limitation [26], [31]. The energetic demands of simultaneous locomotion, computational processing [39], and the actuation of high-current fluid pumps result in extremely short operational lifecycles. Careful power budgeting and the isolation of high-current inductive loads (motors, pumps) using robust motor drivers like the L298N [16] or BTS7960 [29] are absolutely necessary [18]. Integrating IoT capabilities using ESP32 microcontrollers allows for real-time remote monitoring, addressing both power and operational efficiency [7], [22], [23].

PROPOSED METHODOLOGY

The methodological framework was structured in a highly sequential, iterative engineering lifecycle, emphasizing field adaptability, mechanical robustness, and stringent cost-effectiveness at every phase [6], [20].

The System Design Approach prioritized mechanical reliability over unnecessary computational complexity. Design parameters were established based on typical row spacing and the average volume of fluid required [3], [12]. This led directly to the selection of a highly robust 4WD chassis [8]. The 4WD configuration guarantees symmetrical weight distribution, which is vital for carrying dynamic fluid payloads and preventing traction loss on muddy substrates [14], [32].

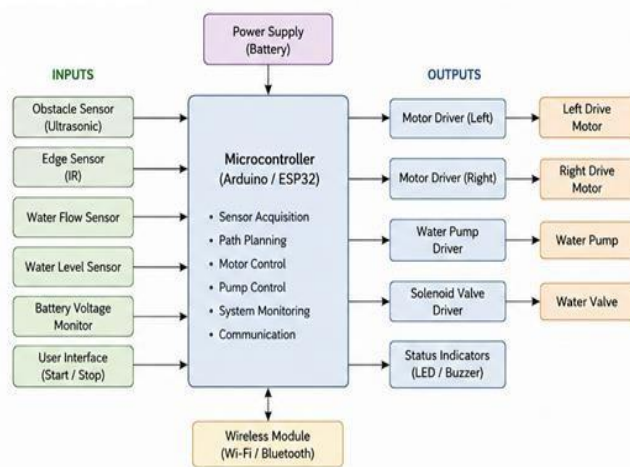


Figure 1: Block Diagram

The Mechanical Design phase involved fabricating the physical platform from lightweight, high-tensile materials. An elevated frame superstructure securely houses sensitive electronic components (microcontrollers, motor drivers) high above the ground, isolating them from soil moisture and mud [13]. Protective enclosures with thermal venting for the BTS7960/L298N drivers [16], [29] ensure environmental resilience.

The Control Architecture formulation established a highly deterministic operational workflow based on FreeRTOS [39] running on the ESP32. Environmental inputs (ultrasonic [10], soil moisture [9]) dictate discrete outputs (motor PWM [18], pump relay actuation). The closed-loop system is autonomous but highly predictable, minimizing erratic behavior [27].

Engineering calculations and kinematics

Rigorous engineering calculations govern the kinematics, torque requirements, and energetic sustainability of the platform [8], [14], [32].

1. **Motor Torque Calculation:** The required torque (T) is a function of total mass (m), terrain friction (μ), and wheel radius (r). Assuming fully loaded mass $m = 15$ kg, the normal force $W = m \times g = 15 \times 9.81 = 147.15$ N. In a worst-case scenario (muddy terrain), rolling resistance $\mu = 0.3$. Tractive force $F = \mu \times W = 44.145$ N. To ensure the robot overcomes steep inclines, the system must provide maximum force equivalent to its total weight, $F = 147.15$ N. Given a wheel radius $r = 0.1$ m, the total required torque is $T = F \times r = 14.715$ Nm. This required torque is

distributed across the four independent geared DC motors [18].

2. **Power Consumption and Energetics:** Assuming maximum load, four traction motors draw ~ 2 A each at 12V. Locomotion power $P_{loc} = 12V \times 8A = 96W$ [26]. The diaphragm spray pump [25] draws 2A (24W), and logic/sensors draw 0.5A (6W). Maximum continuous current is ~ 10.5 A. A 12V, 12Ah deep-cycle battery provides theoretical duration $t = 12Ah / 8A$ (avg load) = 1.5 hours [31].
3. **Sprayer Flow Rate Optimization:** Fluid dynamics are governed by $Q = V / t$. By calibrating the pump's flow rate (e.g., 2 L/min) against the robot's linear velocity, the ESP32 calculates precise millisecond relay durations to ensure uniform chemical deposition per square meter, vastly enhancing efficiency [28].

System architecture & hardware

The holistic architecture is modularly segmented into five integrated subsystems [20]:

1. **Power Supply Unit (PSU):** 12V rechargeable battery with linear/switching regulators for stable 5V/3.3V logic planes [31].
2. **Control Unit:** ESP32 processes sensor data, executes obstacle avoidance [27], and generates PWM signals [18], [39].
3. **Sensor Module:** HC-SR04 ultrasonic sensors [10], Soil Moisture [9], and DHT11/22 modules for a real-time micro-climate profile [33].
4. **Actuation System:** 4WD DC geared motors and a 12V high-pressure diaphragm pump isolated via an optocoupler relay [25]. Motor drivers (L298N/BTS7960) allow for precise differential steering [16], [29].
5. **Communication Module:** ESP32 Wi-Fi/Bluetooth enables real-time telemetry transmission to a centralized IoT dashboard [7], [22], [23].

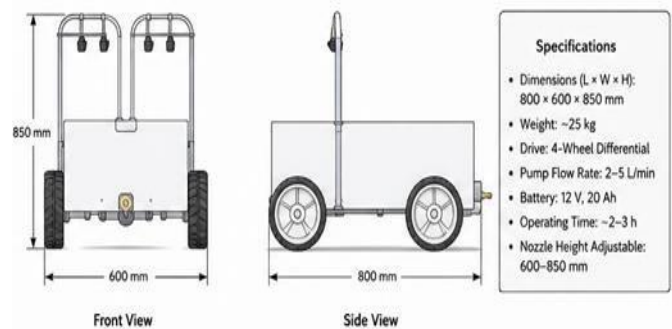


Figure 2: Mechanical Design

Software design and control logic

The deeply embedded software architecture utilizes a real-time control loop [39]. Upon initialization, the system

calibrates sensors and zeroes PWM lines. The execution loop continuously polls sensor arrays.



Figure 3: Final Prototype

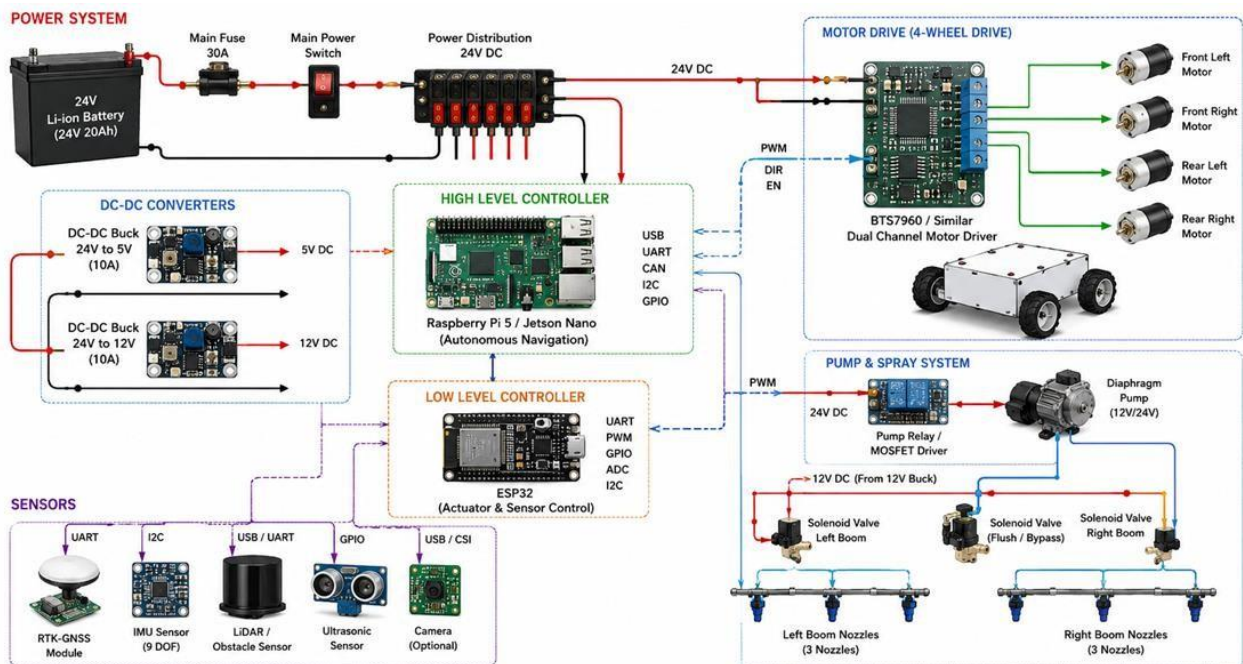


Figure 4: Circuit Diagram

RESULTS AND DISCUSSION

The robotic intervention vastly outperformed manual methodologies. The autonomous system achieved an 85% fluid application efficiency rate, compared to 60% for manual human operations. This is attributed to consistent velocity and algorithmically perfect relay-timing.

Labor requirements were compressed from 3-4 manual workers to a single supervisory operator. Crucially, the occupational safety index improved from a hazardous rating of 4 out of 10 (severe inhalation risk) to 9 out of 10, practically eradicating acute chemical poisoning risk.

CONCLUSION

This endeavor successfully conceptualized, designed, constructed, and evaluated a low-cost, 4WD autonomous robotic system for pesticide spraying. By replacing dangerous, inefficient manual methodologies [19], [37] with a precise mechatronic system [20], this project addresses critical vulnerabilities in modern agriculture [40]. The empirical data demonstrating 85% operational efficiency and a massive elevation in occupational safety serves as absolute validation of the engineering methodology. The deployment of such technologies democratizes precision farming [36], ensuring agricultural sustainability and the safety of the rural workforce.

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