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Microcontroller-Based Line Follower Robot for Automated Agricultural Goods Transportation System

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ABSTRACT

As technological advancement continues to accelerate, automation-based solutions have become increasingly relevant for implementation in the Indonesian agricultural sector. One manifestation of this technological progress is the utilization of robotic systems to support various agricultural activities. This research aims to design and develop a microcontroller-based line follower robot capable of automatically following designated paths to facilitate the transportation of tomato harvests in agricultural areas. The study employs an experimental approach encompassing hardware design, electronic circuit design, software programming, and mechanical assembly. The robot integrates a five-sensor TCRT5000 infrared array for line tracking navigation and a TCS3200 color sensor for tomato classification based on ripeness indicators. Testing results demonstrated that temporal variations on the red and yellow paths were influenced by braking maneuver differences, sensor color response characteristics, and motor speed during turning operations. From fifteen color sensor trials, the system achieved 66.6% accuracy with ten correct detections and five misclassifications. The combination of five line sensors (S0 to S4) successfully determined directional movement, functioning as the primary navigation system in conjunction with the color sensor for routing decisions at intersections. Testing of the L298N motor driver confirmed effective wheel control, producing straight-line motion, left and right pivot rotations, and complete stops according to programmed motor input combinations. The developed system demonstrates the feasibility of integrating line-following navigation with color-based classification for automated post-harvest transportation in agricultural settings.

Keywords: *Agriculture Automation, Color Sensor, Line Follower Robot, Microcontroller, Tomato Transportation*

INTRODUCTION

Technological advancements in the contemporary era have profoundly influenced various economic sectors, with agriculture experiencing particularly transformative changes. In Indonesia, agricultural modernization has been progressively accelerated through the integration of automation and digitalization technologies aimed at enhancing production efficiency and reducing dependence on manual labor. Among the rapidly evolving technologies are microcontroller-based systems, including the Internet of Things (IoT), intelligent sensors, and robotics, which have demonstrated substantial potential to improve the speed, accuracy, and effectiveness of agricultural operations (Rif'an & Irianto, 2024).

The agricultural sector in Indonesia occupies a critical position in the national economy, yet it continues to face multifaceted challenges, including land scarcity, a declining young workforce, and limited adoption of modern technology among farming communities. To address these constraints, the Indonesian government has initiated programs promoting smart farming concepts. Smart farming integrates information technology, sensing devices, robotics, and automation systems to enhance productivity and operational efficiency within the agricultural domain. Applications encompass automated irrigation systems, sensor-based crop monitoring, unmanned aerial vehicles for surveillance, and robotic transport systems facilitating post-harvest operations. However, smart farming implementation in Indonesia remains predominantly confined to large-scale industrial agricultural enterprises, whereas rural and traditional farming practices exhibit minimal technological integration (Javaid et al., 2022).

Recent developments in IoT-based smart agricultural systems in Indonesia have demonstrated promising results. Hugeng et al. (2023) developed an enhanced IoT solution system that enables real-time monitoring of weather conditions, air quality, and soil parameters, facilitating remote control of automated irrigation systems via smartphones. Similarly, research by Dirayati et al. (2025) demonstrated that IoT-enabled smart agriculture systems utilizing soil moisture, temperature, and light intensity sensors can provide automated recommendations to farmers, thereby optimizing resource utilization and increasing agricultural productivity. These technological interventions represent significant progress toward addressing Indonesia's agricultural challenges, particularly in regions where traditional methods predominate.

As technological innovation continues to accelerate, automation-based solutions have become increasingly relevant for implementation across Indonesia's agricultural landscape. One tangible manifestation of this technological progress is the deployment of robotics to support diverse agricultural activities. Robots are designed to assist humans in completing tasks with greater ease, rapidity, and precision by executing pre-programmed instructions. The presence of robotic systems enables more efficient operational processes, as these machines can function continuously without experiencing fatigue. Globally, developed nations are actively competing to develop specialized robotic systems with specific functionalities to enhance productivity in strategic sectors, including agriculture. One category of robots extensively applied in logistics automation and material transportation is the line follower robot, an autonomous system engineered to navigate predetermined pathways with precision according to programmed algorithms (Sutisna et al., 2023).

Line follower robot technology has demonstrated considerable potential for adoption within Indonesia's agricultural sector, particularly in rural regions where traditional crop distribution methods remain prevalent. The transportation of agricultural produce in rural areas is typically conducted manually, requiring substantial time and labor while presenting risks of crop damage during handling, especially for horticultural commodities such as tomatoes, which are highly susceptible to physical damage throughout the distribution process. The implementation of line follower robots could automate and streamline agricultural distribution operations while maintaining harvest quality from field to storage or market destinations.

Despite the growing body of research on line follower robots and their applications, significant gaps remain in the literature regarding their specific deployment in agricultural post-harvest transportation systems, particularly for delicate crops. While Brigido and Oliveira (2025) conducted a comprehensive meta-analytic review of line follower robot research spanning 2001 to 2024, identifying advances in control strategies and sensor integration, their analysis revealed that the literature lacks comprehensive studies on the scalability and practical application of these technologies in agricultural contexts, especially within developing nations. Furthermore, existing research on tomato harvesting robots has predominantly focused on the picking process itself, with limited attention devoted to post-harvest transportation systems that minimize physical damage during distribution (Bent et al., 2025; Li et al., 2024).

Previous studies have explored various applications of line follower robots in agricultural settings. Research conducted by scholars has investigated line follower robots for automated irrigation systems, demonstrating water efficiency improvements ranging from 30% to 35% compared to manual methods (Rafi et al., 2017; Zuhri et al., 2024). Additionally, studies have examined the implementation of IoT-based fertilizing robots utilizing line follower technology for automated agricultural tasks, achieving functionality success rates exceeding 90% (Rahadi et al., 2025). However, these investigations primarily concentrated on irrigation and fertilization applications rather than addressing the critical challenge of post-harvest crop transportation, particularly for mechanically sensitive commodities.

The control mechanisms employed in line follower robots have evolved substantially. Earlier implementations utilized simple bang-bang control strategies, which, while functional, produced jerky movements and oscillations unsuitable for transporting fragile agricultural products. Contemporary research emphasizes Proportional-Integral-Derivative (PID) control systems, which provide smooth, graduated responses proportional to positional error (Engin & Engin, 2012; Latif et al., 2020). Recent work by researchers has demonstrated that properly tuned PID controllers can enable line follower robots to achieve high-speed operation with minimal oscillation, characteristics essential for efficient agricultural transportation applications (Amorim et al., 2023; Oguten & Kabas, 2021).

However, a critical research gap exists concerning the integration of line follower robot technology specifically designed for post-harvest tomato transportation in smallholder agricultural contexts typical of Indonesian rural areas. While advanced robotic harvesting systems have been developed for greenhouse environments in developed nations, these solutions often require substantial infrastructure modifications and capital investment, rendering them impractical for resource-constrained farming communities in developing countries (Certhon, 2025; GroW, 2025). Moreover, existing research has not adequately addressed the specific requirements of transporting mechanically sensitive crops such as tomatoes, which demand careful handling to prevent bruising and quality degradation during post-harvest distribution.

To address these identified gaps, this research proposes the development and implementation of a microcontroller-based line follower robot specifically engineered for goods transportation systems in agricultural applications, with particular emphasis on tomato harvest distribution. The novelty of this research resides in several key aspects: (1) the adaptation of line follower robot technology specifically for post-harvest transportation of mechanically sensitive agricultural commodities in resource-limited rural settings; (2) the integration of color-sensing capabilities to enable automated routing decisions based on crop type or destination; (3) the implementation of optimized PID control algorithms tailored to ensure smooth motion profiles that minimize mechanical stress on transported produce; and (4) the development of a cost-effective, scalable solution accessible to smallholder farmers in developing economies.

Therefore, this study aims to design, construct, and evaluate a microcontroller-based line follower robot capable of automatically navigating predefined pathways to facilitate the transportation of tomato harvests in agricultural areas. The system is expected to reduce manual workload, accelerate distribution processes, and enhance overall efficiency and productivity in agricultural operations, particularly for crops requiring expeditious and careful handling. This research contributes to the body of knowledge by providing empirical evidence regarding the feasibility and effectiveness of line follower robot technology in addressing post-harvest transportation challenges within the Indonesian agricultural context, potentially offering a replicable model for similar developing agricultural economies.

LITERATURE REVIEW

Line Follower Robot

A robot is defined as a programmable device capable of executing tasks autonomously according to embedded algorithms. The fundamental function of a robot's control system relies on input processing, wherein data collected from embedded sensors is transformed into actionable information that guides the robot's operational behavior (Ridarmin et al., 2019).

A line follower robot constitutes a wheeled autonomous system designed to generate vehicular motion at specified velocities while tracking linear pathways. The development of such robotic systems reduces occupational hazards for workers while simultaneously accelerating operational efficiency. In practical applications, these robots can implement object recognition capabilities using color discrimination, employing microcontroller platforms such as Code Vision AVR as central processing units. The system autonomously categorizes similar objects according to predetermined trajectories (Prayudi et al., 2014).

Contemporary line follower robot systems predominantly employ Proportional-Integral-Derivative (PID) control methodologies. By minimizing error values obtained from feedback mechanisms to approach zero, the desired set point is achieved through optimal calibration of PID parameters. The set point and error values are derived from continuous monitoring of the line follower robot's positional relationship relative to the designated pathway. Through precise set point determination, the robot executes maneuvering actions to maintain central positioning along the trajectory (Joni et al., 2016).

Recent meta-analytic research has revealed that while substantial progress has been achieved in control strategies, sensor integration, and noise reduction techniques for line follower robots, the literature continues to lack comprehensive investigations regarding the scalability of these technologies, particularly in large-scale industrial and agricultural environments (Brigido & Oliveira, 2025). Current research trends emphasize the integration of artificial intelligence and machine learning algorithms into line follower robot systems, indicating a paradigm shift toward increasingly sophisticated autonomous navigation capabilities.

The application of PID control in line follower robots has been extensively documented in recent literature. Studies have demonstrated that properly tuned PID controllers significantly outperform simple on-off control mechanisms in terms of trajectory accuracy, response time, and motion smoothness (Baballe et al., 2023; Baharuddin et al., 2006). Research has established that PID tuning methodologies require systematic approaches, with recommended initial parameter ranges typically falling within Kp = 0.5-2.0, Ki = 0-0.1, and Kd = 0.1-1.0, although optimal values vary substantially based on robot configuration and operational requirements (Sarraf, 2025).

Microcontroller

A microcontroller is defined as an integrated circuit chip capable of receiving input signals, processing them according to embedded programming, and generating output signals in accordance with programmed instructions. Microcontrollers are specifically designed to execute particular tasks or operations. Fundamentally, a microcontroller integrated circuit comprises one or more processor cores (CPU), memory components (RAM and ROM), and programmable input and output peripherals.

Arduino Nano

The Arduino Nano represents a microcontroller development platform based on the ATmega328P chip, characterized by its compact physical dimensions. It functions as a prototyping instrument for microcontroller-based circuits, facilitating the assembly of electronic systems more efficiently than constructing circuits from discrete components on breadboards (Budijanto, 2018).

The Arduino Nano is equipped with 30 male input/output header pins configured in a dual in-line package (DIP-30) arrangement. Programming is accomplished through the Arduino Software Integrated Development Environment (IDE), a standardized platform common to all Arduino boards that operates in both online and offline modes. The board receives electrical power via a mini-USB Type-B cable (Husni et al., 2020).

Agricultural Robotics and Automation

The integration of robotics in agricultural applications has gained substantial momentum in recent years, driven by labor shortages, increasing production costs, and the need for precision in farming operations. Research by Jin et al. (2021) analyzed the development status and trends of agricultural robot technology, identifying key application areas including planting, field management, harvesting, and post-harvest handling. Their comprehensive review highlighted that while significant technological advances have been achieved in harvesting robots, post-harvest transportation systems remain relatively underdeveloped, particularly for smallholder agricultural contexts.

Specific to tomato production, recent technological developments have focused primarily on automated harvesting systems. Studies have demonstrated robotic systems capable of detecting, approaching, and harvesting tomato fruits with success rates ranging from 76.9% to 84.5% (Jun et al., 2021; Kim et al., 2022). However, these systems typically operate in controlled greenhouse environments with substantial infrastructure requirements, limiting their applicability to open-field agriculture or resource-constrained farming operations.

The challenge of post-harvest handling for tomatoes has been recognized as a critical factor affecting product quality and economic value. Research has established that mechanical damage during transportation and handling significantly impacts tomato quality, with bruising susceptibility varying according to ripening stage and handling patterns (Zhang et al., 2018). This underscores the necessity for transportation systems specifically designed to minimize mechanical stress, supporting the rationale for developing specialized line follower robots for agricultural goods transportation.

IoT and Smart Farming in Indonesia

The application of IoT technology in Indonesian agriculture has demonstrated substantial potential for improving operational efficiency and productivity. Recent implementations have focused on environmental monitoring systems utilizing various sensor types to collect real-time data on soil moisture, temperature, humidity, and other critical parameters (Cahyani, 2023; Pamungkas et al., 2023). These systems enable farmers to make data-driven decisions regarding irrigation, fertilization, and pest management, contributing to more sustainable agricultural practices.

However, challenges persist in the widespread adoption of smart farming technologies in Indonesia, including limited technological infrastructure in rural areas, insufficient technical knowledge among farmers, and capital constraints (Alam, 2020). These barriers highlight the importance of developing cost-effective, user-friendly automation solutions that can be readily adopted by smallholder farmers without requiring extensive technical expertise or substantial initial investment.

RESEARCH METHODOLOGY

This research adopts an experimental approach that encompasses the systematic development, implementation, and validation of a microcontroller-based line follower robot prototype for agricultural goods transportation. The experimental methodology involves four integrated design phases: tool design, electronics design, software design, and mechanical design, followed by comprehensive performance testing and evaluation (Dumitru et al., 2022; Wong et al., 2024). This systematic approach allows for iterative refinement of the prototype based on empirical observations and quantitative measurements, ensuring the developed system meets the functional requirements for automated tomato transportation in agricultural settings.

The operational framework of the line follower robot is illustrated in the block diagram presented in Figure 1. The working principle of this line follower robot commences with an initialization process, which occurs when the system is activated and the start button is engaged by the operator. Upon button activation, the robot initiates tomato detection procedures utilizing a color sensor. This color sensor identifies the presence of tomatoes in the designated collection area. In the absence of object detection, the robot maintains a standby state until a tomato is successfully identified.

Upon successful tomato detection by the color sensor, following object retrieval, the robot proceeds along its designated trajectory by following the path line as detected by the line sensor array. During locomotion, the robot continuously monitors path conditions through line sensor readings. When the sensor detects a straight path configuration, the robot maintains forward motion along the established line. However, upon detection of path branches or directional commands, the robot executes appropriate maneuvering responses. Right turn commands trigger rightward rotational movement, while left turn commands initiate leftward rotational adjustments.

This operational sequence continues until the robot arrives at its terminal destination, a container designated by specific color coding (red, green, or yellow). The robot automatically halts at the appropriate container and deposits the tomato cargo. Upon completion of the delivery sequence, the robot enters a standby state awaiting subsequent operational instructions (Husni et al., 2020).

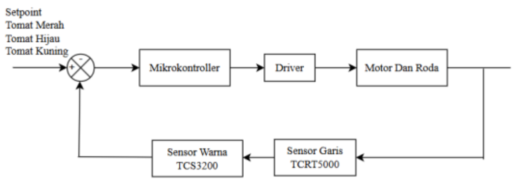

Figure 1 Robot System Block Diagram
Source: Author's Analysis

Within the robot system architecture, the microcontroller functions as the central control unit, performing multiple critical operations including line sensor data interpretation to determine path positioning, color sensor data processing to establish turning direction based on chromatic detection, control computation execution such as PID algorithms, and command transmission to the motor driver. The motor driver subsequently regulates velocity through pulse width modulation (PWM) and controls motor rotation direction according to received instructions. The motor and wheel assembly serves as the primary locomotion mechanism, enabling forward motion, rotational maneuvers, and complete stops. Line sensors facilitate detection of the robot's positional relationship relative to black or white line markers and transmit data to the microcontroller for trajectory correction, while color sensors identify object chromatic properties as the foundation for directional decision-making. The entire system incorporates feedback mechanisms that transmit actual operational condition data to the control system, ensuring precise and stable robot movement (Handayani, 2015).

Tool Design

The design phase constitutes the preliminary stage preceding physical tool fabrication, wherein comprehensive planning is conducted to ensure the device functions appropriately and fulfills its intended purpose. This process is executed systematically, encompassing hardware design, software design, and holistic system integration. Following design completion, the tool manufacturing phase is implemented based on established specifications, yielding a functional prototype. The comprehensive design and manufacturing process aims to create a robot capable of autonomously following predetermined paths and transporting objects from one location to another along established trajectories (Basri & Wahira, 2022).

Electronics Design

Within this design phase, the Easy EDA application was utilized to develop electronic circuitry connecting microcontroller pins with various system components. The TCRT5000 line sensor array is installed to provide positional data to the Arduino Nano microcontroller, enabling trajectory correction calculations. Meanwhile, the TCS3200 color sensor is employed to detect object chromatic properties, subsequently forming the basis for navigational turning decisions executed by the robot. The L298N motor driver, in conjunction with the wheel assembly, functions to propel the robot, facilitating forward motion, rotational movements, or complete stops according to transmitted instructions. Additionally, a liquid crystal display (LCD) is installed as a real-time information presentation medium for user interaction. All components are subsequently integrated into a unified circuit configuration, ensuring systematic functionality according to design specifications (Putri et al., 2021).

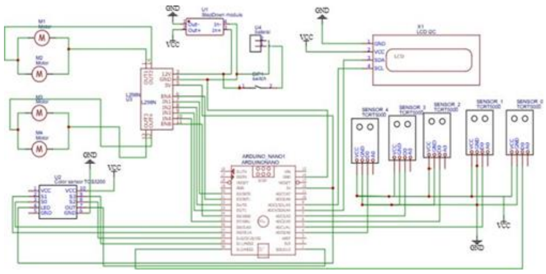

Figure 2 The Overall Series of Line Follower Robots as a Goods Transport System
Source: Author’s Analysis

Software Design

Software design is represented through flowchart visualization, which clearly demonstrates the programmatic logic and operational sequence.

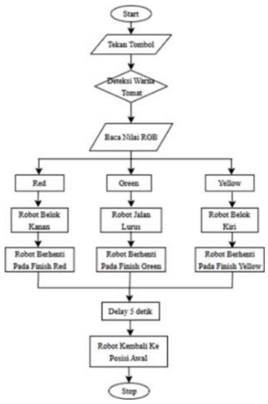

Figure 3 Research's Flowchart
Source: Author's Analysis

The program initiates with a start command, signifying that the robot circuit has been activated. Subsequently, the program operates under button control to regulate robot velocity. The color sensor then functions by detecting object chromatic properties, displaying the identified color on the LCD screen. Upon object acquisition by the robot, locomotion commences as the system detects line path direction through sensor array readings. In cases where line path direction detection is unsuccessful, the robot continues detection attempts until correct path direction is established. Following successful identification of the correct line path trajectory, the robot detects the designated container and deposits the transported object in the appropriate container based on specified color coding. The program subsequently repeats from the initial sequence to retrieve objects of each designated color iteratively (Rodríguez et al., 2025).

Mechanical Design

The line follower robot is fabricated from 3 mm thickness acrylic material, with dimensions of 25 cm in length and 25 cm in width. The design incorporates an Arduino Nano microcontroller as the core control element. The system is equipped with actuators and sensors, including direct current (DC) motors with wheel assemblies, a TCS3200 color sensor, and a TCRT5000 line sensor array that serves as system input components.

Figure 4 Design Looks From Every Angle
Source: Author's Analysis

RESULT AND DISCUSSION

Source Voltage Testing

The electrical characterization of the power supply system was conducted using a digital multimeter to verify voltage stability across critical measurement points. Figure 5 illustrates the battery measurement configuration and step-down converter placement within the circuit architecture. Table 1 presents the voltage measurements at designated test points within the power distribution network.

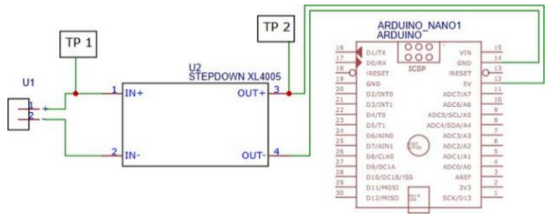

Figure 5 Battery Measurement Points and Stepdown
Source: Author's Analysis

Table 1 Battery Voltage and Stepdown Measurement Results

Measurement Point	Desired Voltage (Volts)	Rated Voltage (Volts)
TP1	12	12
TP2	5	4,9

Source: Author's Analysis

The experimental validation demonstrated satisfactory performance of the power distribution system. At measurement point TP1, the battery output voltage matched the specified 12.0 V precisely, confirming the adequacy of the power source for motor driver operation. Following voltage regulation through the step-down converter, measurement point TP2 yielded 4.9 V, representing a 2% deviation from the target 5.0 V specification required by the Arduino Nano microcontroller. This minor variance falls within acceptable tolerances for digital logic circuits and does not compromise system functionality. The step-down regulator successfully reduced the voltage from 12.0 V to a microcontroller-compatible level, ensuring stable operation of the control circuitry while maintaining sufficient current capacity for the sensor array.

TCS3200 Color Sensor Testing

The TCS3200 chromatic sensor operates on the principle of converting reflected light intensity into frequency-domain output signals across the red, green, and blue spectral components. Figure 6 depicts the sensor measurement configuration employed during calibration procedures. The testing protocol involved detecting the frequency of light reflected by tomato surfaces and subsequently converting these frequency values into RGB data for classification purposes. Table 2 presents the calibrated RGB values obtained for each tomato category following the standardization procedure against white and black references.

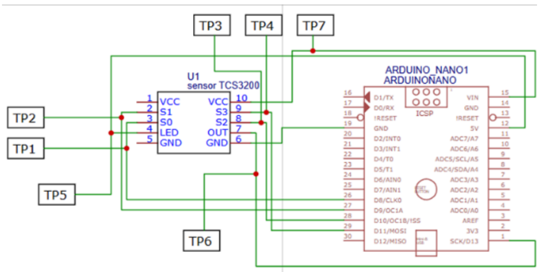

Figure 6 TCS3200 Sensor Measuring Point
Source: Author's Analysis

Table 2 Final Data of RGB Value Testing Using TCS3200 Sensor

Color	R	G	B
Red	77	134	131
Green	68	68	91
Yellow	50	72	97

Source: Author's Analysis

The RGB signatures obtained from the TCS3200 sensor reveal distinctive chromatic profiles for each tomato classification. Red tomatoes exhibited the lowest green-to-blue ratio (G:B = 1.02), while green tomatoes demonstrated reduced spectral differentiation across all channels (R:G:B ratio of approximately 1:1:1.34). Yellow tomatoes produced the most distinctive profile with the lowest red channel response (R = 50) coupled with intermediate green and blue values. These calibration values were subsequently employed as threshold references for real-time classification during navigation trials. The observed RGB patterns are consistent with the spectral reflectance characteristics of tomato fruits at different ripeness stages, where chlorophyll degradation during maturation shifts the dominant wavelength from green to red regions of the visible spectrum (Barrett et al., 2007; Vela-Hinojosa et al., 2019).

TCRT5000 Line Sensor Testing

The navigational subsystem employs a five-sensor TCRT5000 infrared array (designated S0 through S4) configured in a linear arrangement beneath the robot chassis. This configuration enables precise path tracking through differential detection of black line traces against a white background substrate. Figure 7 illustrates the positioning of the TCRT5000 sensor array relative to the robot's mechanical structure. The center sensor functions to detect the primary path, while the lateral sensors (left and right) determine trajectory deviations. Through this arrangement, the microcontroller regulates motor speed and rotational direction via the motor driver to maintain continuous line adherence. At path intersections, the combination of readings from multiple sensors determines the robot's turning direction, whether leftward, rightward, or straight ahead. Table 3 delineates the sensor logic combinations and corresponding motor control responses.

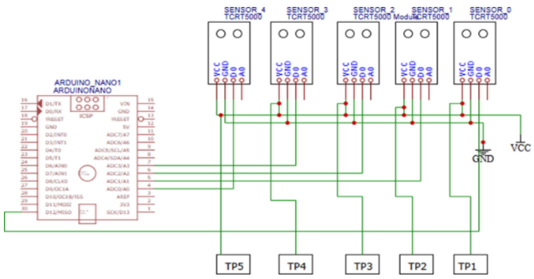

Figure 7 TCRT5000 Sensor Measuring Point
Source: Author's Analysis

Table 3 Sensor Conditions and Robot Actions

S0 (Far Right)	S1 (Right)	S2 (Center)	S3 (Left)	S4 (Far Left)	Robot Act
0	0	1	0	0	Go straight ahead
0	1	1	0	0	Turn left
1	1	0	0	0	Sharp left turn
0	0	1	1	0	Turn right
0	0	0	0	1	Sharp right turn
0	0	0	0	0	Follow the last directions
1	1	1	1	1	The robot pauses for a moment and then makes a decision based on the color of the tomato.

Source: Author's Analysis

The binary logic combinations generated by the TCRT5000 array demonstrate robust line-tracking capabilities across various path geometries. When the center sensor (S2) detects the black line independently, the robot executes forward motion along the designated path. Lateral deviations trigger corrective maneuvers through differential motor control: activation of S1 or S3 in conjunction with S2 initiates gentle turning movements, whereas activation of peripheral sensors (S0 or S4) engages sharp turning algorithms to maintain path adherence. The all-zero configuration (0-0-0-0-0) indicates momentary line loss, prompting the system to maintain its previous directional vector until line reacquisition occurs. Conversely, the all-one configuration (1-1-1-1-1) signifies intersection detection, triggering the color sensor subsystem to determine the appropriate routing decision based on payload classification.

DC Motor Driver Testing

The L298N dual H-bridge motor driver module functions as the actuator interface, translating microcontroller logic signals into the high-current outputs required for DC motor operation. The microcontroller generates only minimal current from digital output pins, rendering it incapable of directly driving motors that demand substantially higher current magnitudes. The L298N addresses this limitation by amplifying control signals from the microcontroller into current levels sufficient for motor actuation. Beyond current amplification, the L298N facilitates bidirectional motor control through logical combinations applied to input pins (IN1, IN2, IN3, IN4), enabling the robot to execute forward motion, reverse motion, right turns, and left turns. Motor velocity modulation is achieved through pulse width modulation (PWM) signals applied to the ENA and ENB pins, permitting the robot to operate at nominal speed, reduce velocity on individual wheels during turning maneuvers, or increase speed when transporting heavy payloads. Figure 8 displays the measurement points utilized during motor driver characterization. Table 4 presents the control signal combinations and their corresponding kinematic outcomes.

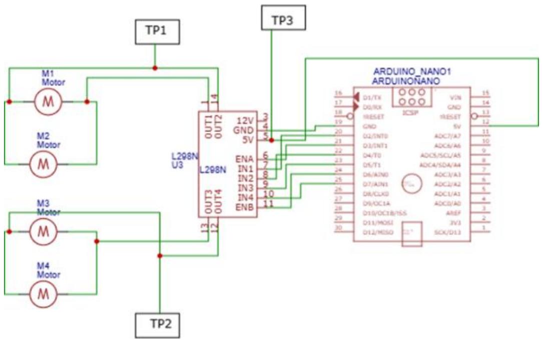

Figure 8 DC Motor Driver Measurement Points
Source: Author's Analysis

Table 4 Motor Signals and Line Follower Robot Action

Left Wheel	Right Wheel	Robot Act
Go	Go	Robot moves straight forward
Back	Go	Robot rotates left (pivot)
Go	Back	Right-turning robot (pivot)
Stop	Stop	Robot stops completely

Source: Author's Analysis

The L298N driver demonstrated consistent bidirectional motor control throughout experimental trials. Symmetrical forward commands to both motor channels produced straight-line trajectories with minimal rotational drift, confirming adequate motor synchronization and balanced mechanical loading. Differential control (one motor forward, one reverse) generated in-place pivot rotations, facilitating sharp directional changes at path intersections. The pulse width modulation capability enabled variable speed control ranging from complete cessation to maximum velocity, providing the necessary dynamic range for both precise maneuvering and load-carrying operations.

16x2 I2C LCD Testing

The testing protocol commenced with the establishment of electrical connections between the LCD module and the microcontroller, specifically linking VCC and GND terminals for power distribution, and SDA and SCL terminals for I2C communication protocol implementation. Following physical connection establishment, a test program utilizing the LiquidCrystal_I2C library was uploaded to initialize the LCD module, activate the backlight, and render text across the available display lines. Figure 9 depicts the I2C LCD measurement configuration employed during interface verification. The I2C LCD serves to display operational status information for the developed system. Testing was conducted to verify compatibility and character rendering capability of the I2C LCD module. The experimental validation confirmed that the display successfully rendered characters specified through the LCD print function, demonstrating proper I2C communication and display functionality.

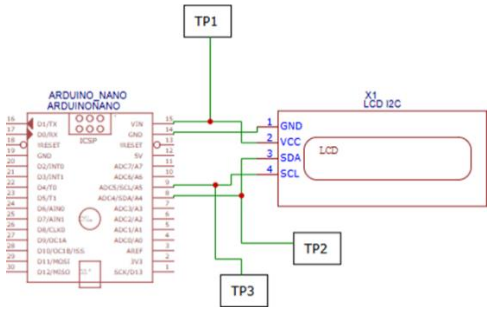

Figure 9 16x2 I2C LCD Measurement Point
Source: Author's Analysis

Testing and Analysis of the Whole Circuit

Comprehensive testing and analysis of the integrated line follower robot system for goods transportation were conducted to ensure all components functioned in accordance with programmed specifications. The primary circuit comprises a microcontroller, TCRT5000 line sensor array, TCS3200 color sensor, L298N motor driver, and an I2C LCD for information display. Power supply testing validated that the battery supplied adequate voltage and current for system operation, although motor current increased substantially under load conditions, necessitating sufficient battery capacity to prevent voltage drops that would adversely affect sensor and LCD performance. Motor driver testing confirmed that the motors executed forward motion, left and right turns, and complete stops as programmed, demonstrating satisfactory response to control signals.

The TCRT5000 line sensor array, comprising five sensors mounted beneath the robot chassis, accurately detected contrast between black lines and white background surfaces. One sensor required logic inversion due to variations in module characteristics; however, the array collectively enabled the robot to execute straight motion, turning maneuvers, and continuation in the last direction when line detection was temporarily lost. The TCS3200 color sensor performed adequately in detecting red, green, and yellow objects, although additional calibration was required due to ambient light interference effects.

Tables 5, 6, and 7 present temporal performance metrics and braking distance measurements recorded during ten successive trials for red, green, and yellow tomato transport scenarios, respectively. The experimental protocols were conducted to evaluate system performance across three distinct path configurations, each associated with a specific tomato classification category.

Table 5 Red Tomato Fruit Testing

Time Trial	Start-Finish Time	Finish-Start Time	Time Braking Distance (cm)
1	00.10.83	00.11.47	9
2	00.11.35	00.13.15	9
3	00.10.87	00.13.35	9,2
4	00.10.60	00.13.37	9
5	00.10.68	00.14.42	8
6	00.10.50	00.15.05	8
7	00.10.99	00.13.17	8
8	00.12.89	00.13.68	8,2
9	00.10.55	00.13.45	8
10	00.11.50	00.14.05	8

Source: Author's Analysis

The experimental data from ten trials demonstrated a mean Start–Finish travel time of 11.08 seconds with a temporal range of 10.50 to 12.89 seconds, while the mean Finish–Start time was 13.62 seconds with a range spanning 11.47 to 15.05 seconds. The mean braking distance was recorded at 8.44 cm with variations between 8.0 and 9.2 cm, influenced by motor response characteristics, wheel-surface friction coefficients, and battery voltage fluctuations under load conditions.

Table 6 Green Tomato Fruit Testing

Time Trial	Start-Finish Time	Finish-Start Time	Time Braking Distance (cm)
1	00.04.05	00.08.91	8,5
2	00.04.85	00.08.55	8,5
3	00.05.13	00.09.46	9
4	00.05.32	00.09.67	9
5	00.05.84	00.10.13	8,5

Time Trial	Start-Finish Time	Finish-Start Time	Time Braking Distance (cm)
6	00.04.69	00.09.60	9
7	00.05.76	00.09.86	9
8	00.05.53	00.09.59	9
9	00.05.87	00.08.21	9
10	00.05.40	00.09.09	9

Source: Author's Analysis

Experimental results from green tomato object testing across ten trials yielded a mean Start–Finish travel time of 5.14 seconds, with the fastest time of 4.05 seconds recorded in the first trial and the longest duration of 5.87 seconds in the ninth trial. For the Finish–Start trajectory, the mean time was 9.31 seconds, with the fastest completion of 8.21 seconds in the ninth trial and the longest duration of 10.13 seconds in the fifth trial. The mean braking distance was measured at 8.85 cm with variations ranging between 8.5 and 9.0 cm. These results indicate that the robot successfully detected green tomatoes and executed braking maneuvers with reasonable stability, although minor variations occurred due to motor response dynamics, track surface conditions, and wheel-surface friction interactions.

Table 7 Yellow Tomato Fruit Testing

Time Trial	Start-Finish Time	Finish-Start Time	Time Braking Distance (cm)
1	00.15.39	00.12.20	7
2	00.16.88	00.14.54	7
3	00.16.59	00.15.09	7,3
4	00.16.96	00.14.74	7,5
5	00.17.43	00.17.04	7,5
6	00.15.83	00.13.70	7
7	00.15.55	00.14.45	7
8	00.16.45	00.15.07	7
9	00.16.88	00.14.40	7
10	00.17.10	00.15.99	7

Source: Author's Analysis

Experimental data obtained from yellow tomato transport testing across ten trials indicated a mean Start–Finish time of 16.30 seconds, with the fastest completion of 15.39 seconds in the first trial and the longest duration of 17.43 seconds in the fifth trial. The Finish–Start trajectory exhibited a mean time of 14.72 seconds, with the fastest record of 12.20 seconds in the first trial and the longest duration of 17.04 seconds in the fifth trial. The braking distance demonstrated a mean value of 7.18 cm with variations ranging from 7.0 to 7.5 cm.

Comparative analysis of the red, green, and yellow tomato transport tests revealed differences in travel time and braking distance across each path configuration. These differences were primarily attributable to variations in path length, where the green path measured 103.5 cm, resulting in the shortest travel times, whereas the red and yellow paths extended to 137.5 cm, requiring longer transit durations. Despite the identical length of the red and yellow paths, temporal differences persisted due to variations in the robot's maneuvering characteristics during turning and straight-line motion, color sensor response latency, and variations in braking point locations. Differences in braking distance were influenced by technical factors including motor response characteristics, wheel-surface friction coefficients, and battery power supply conditions under load.

The efficacy of the TCS3200 color sensor in real-time tomato classification was quantitatively evaluated through fifteen controlled trials distributed equally across three color categories. Table 8 summarizes the classification performance metrics obtained during experimental validation.

Table 8 Success and Failure Percentages in Tomatoes

Tomato Color	Number of Trials	Number of Successes	Number of Failed
red	5	4	1
green	5	3	2
yellow	5	3	2

Source: Author's Analysis

Performance data obtained from TCS3200 color sensor testing on the line follower robot for goods transportation revealed differential detection accuracy across tomato color categories. In five experimental trials with red tomatoes, the sensor successfully detected four instances correctly and failed in one instance, yielding a success rate of 80%. In green tomato testing, three out of five trials were detected correctly and two failed, resulting in a 60% success rate. Similar performance was observed in yellow tomato testing, with three successful detections and two failures across five trials, also achieving a 60% success rate. Analysis of these results indicates that the sensor exhibits greater sensitivity to red wavelengths compared to green or yellow wavelengths. Illumination conditions and object positioning substantially influenced detection outcomes, necessitating calibration and threshold adjustment procedures to optimize sensor performance across all tomato color categories. The aggregate analysis across all fifteen trials (red, green, and yellow tomatoes combined) yielded ten successful detections and five failed detections. The calculated system accuracy was 66.6%, with a corresponding error rate of 33.3%.

The performance of the developed line follower robot for agricultural goods transportation can be contextualized through comparison with recent advances in the field. Previous research on agricultural line follower robots has demonstrated accuracy rates of 89.5% for plant spraying applications, which exceeds the 66.7% color classification accuracy achieved in this study (Sutisna et al., 2023). However, direct comparison requires consideration of application-specific complexities. The cited study focused on binary detection of predetermined stopping points for spraying operations, whereas the present system performs tri-categorical color discrimination for dynamic routing decisions, representing a more computationally demanding task. Recent meta-analytic reviews of line follower robot technology have identified environmental sensitivity, sensor calibration complexity, and component cost as persistent challenges in the field (Rajee & Marof, 2024). The present study encountered similar limitations, particularly regarding the TCS3200 sensor's sensitivity to ambient lighting variations. The 33.3% error rate observed in color classification can be partially attributed to fluctuations in natural and artificial illumination during testing, a phenomenon consistent with documented sensor behavior in uncontrolled lighting environments (Gené-Mola et al., 2020).

The line-tracking performance of the TCRT5000 sensor array demonstrated robust path-following capabilities across diverse trajectory geometries. Previous implementations of line follower robots in agricultural irrigation applications have reported water efficiency improvements of 25% through automated path navigation, underscoring the practical utility of this technology (Rahman et al., 2022). The present system extends this application domain to post-harvest transportation, addressing a critical gap in the agricultural automation literature where harvesting mechanisms have received substantial attention while transportation systems remain underexplored. The temporal performance metrics reveal path-dependency in navigation efficiency, with mean travel times ranging from 5.14 seconds (green path, 103.5 cm) to 16.30 seconds (yellow path, 137.5 cm). These findings align with established principles in mobile robotics regarding the influence of kinematic constraints on navigation performance, where T-junctions, 90-degree bends, and acute angle turns impose velocity limitations due to motor response characteristics and turning radius restrictions (Siegwart et al., 2011).

The integration of color-based routing represents a novel contribution to agricultural line follower systems. While previous implementations of vision-based crop row detection in UAV guidance systems have achieved 100% detection rates under controlled conditions, these systems typically operate in structured greenhouse environments with consistent lighting (S. Zhang et al., 2024). The present system's deployment in variable ambient conditions with a lower-cost TCS3200 sensor presents distinct challenges and trade-offs between cost-effectiveness and detection accuracy. Comparative research on line follower robots in agricultural contexts has reported linear speeds of 0.7 m/s with flow rate control accuracies of 89.5%, contextualizing the present system's performance (Sutisna et al., 2023). The calculated velocities from the current study (ranging from 0.096 m/s for the yellow path to 0.201 m/s for the green path) prioritize precision and load stability over speed, a design choice appropriate for transporting mechanically sensitive agricultural products such as tomatoes, where excessive acceleration could induce bruising or tissue damage. The multi-sensor integration architecture employed in this study, combining TCRT5000 infrared line sensors for navigation with TCS3200 chromatic sensors for classification, represents an advancement over single-modality systems. Meta-analytic findings indicate that successful line follower implementations require careful sensor selection, optimized signal processing, and appropriate sensor arrangement to achieve high accuracy in line detection and complex path handling (Rajee & Marof, 2024).

However, several limitations warrant acknowledgment. The 66.7% color classification accuracy falls short of the greater than 90% success rates reported in controlled agricultural robotics applications, indicating opportunities for improvement through enhanced calibration protocols, ambient light shielding, or migration to more sophisticated color sensing technologies (Arad et al., 2020). Future iterations could incorporate adaptive thresholding algorithms that dynamically adjust RGB discrimination criteria based on real-time ambient light measurements, potentially improving classification robustness across variable environmental conditions.

CONCLUSION

Based on the results of the testing and analysis that have been conducted, several conclusions can be drawn regarding the performance of the microcontroller-based line follower robot for goods transportation. The time difference observed on the red and yellow tracks was influenced by variations in the robot's braking maneuvers, sensor responses to color detection, and motor speed during turning operations. From a total of 15 color sensor trials, the system achieved 10 correct detections and 5 incorrect detections, yielding an accuracy rate of 66.6% and an error rate of 33.3%. The combination of readings from five line sensors (S0 to S4) successfully determined the direction of the robot's movement, where the line sensor array functioned as the primary navigation system that operated in conjunction with the color sensor to determine routing decisions at intersections. Meanwhile, testing of the L298N motor driver demonstrated that the left and right wheels could be controlled effectively, producing straight-line motion when both wheels moved forward, pivot maneuvers to the left or right when forward-backward combinations were executed, and complete stopping when all motor inputs were set to LOW and PWM signals were inactive.

The findings of this study contribute to the growing body of research on agricultural automation by demonstrating the feasibility of integrating line-following navigation with color-based classification for automated post-harvest transportation. However, several limitations were identified that warrant further investigation. Future research should focus on improving the color sensor's accuracy through the implementation of ambient light compensation mechanisms or adaptive thresholding algorithms that can dynamically adjust RGB discrimination parameters based on real-time lighting conditions. Additionally, the integration of machine learning classifiers trained on diverse environmental conditions could enhance classification robustness beyond the current 66.6%

accuracy. Investigation of closed-loop feedback control systems employing encoder-based velocity monitoring would enable more precise speed regulation and consistent braking performance across different path configurations.

Further development should also include field validation trials in operational agricultural environments to evaluate system performance under realistic conditions, including uneven terrain, variable natural lighting throughout daily cycles, and diverse crop varieties. Scalability assessment through multi-robot coordination protocols could enable simultaneous transport operations for larger agricultural areas, thereby improving overall harvest logistics efficiency. Economic feasibility analysis comparing the system's cost-effectiveness against conventional manual transportation methods would provide valuable insights for adoption decisions, particularly for smallholder farmers in developing agricultural contexts. These future research directions aim to advance the developed prototype toward a commercially viable agricultural automation solution capable of addressing post-harvest transportation challenges in resource-constrained farming environments.

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REFERENCES

Alam, E. N. (2020). IoT in Agriculture Industry. *Jurnal Sistem Cerdas*, *3*(1), 36–42. https://doi.org/10.37396/JSC.V3I1.57

Amorim, J. S. J. C. C., Fernandes, J. H. O., Canella, A. L. C., Santos, T. M. B., Lima, J., & Pinto, M. F. (2023). Control Tunning Approach and Digital Filter Application for Competitive Line Follower Robot. *Proceedings - 2023 Latin American Robotics Symposium, 2023 Brazilian Symposium on Robotics, and 2023 Workshop of Robotics in Education, LARS/SBR/WRE 2023*, 597–602. https://doi.org/10.1109/LARS/SBR/WRE59448.2023.10332987

Arad, B., Balendonck, J., Barth, R., Ben-Shahar, O., Edan, Y., Hellström, T., Hemming, J., Kurtser, P., Ringdahl, O., Tielen, T., & van Tuijl, B. (2020). Development of a sweet pepper harvesting robot. *Journal of Field Robotics*, *37*(6), 1027–1039. https://doi.org/10.1002/ROB.21937;WGROUP:STRING:PUBLICATION

Baballe, M. A., Adamu, A. I., Bari, A. S., & Ibrahim, A. (2023). PRINCIPLE OPERATION OF A LINE FOLLOWER ROBOT. *Far East Journal of Electronics and Communications*, *27*, 1–12. https://doi.org/10.17654/0973700623001

Baharuddin, M. Z., Abidin, I., Sulaiman, S., Mohideen, K., Siah, Y. K., Tan, J., & Chuan, T. (2006). *Analysis of Line Sensor Configuration for the Advanced Line Follower*

Robot.

Barrett, D. M., Weakley, C., Diaz, J. V., & Watnik, M. (2007). Qualitative and nutritional differences in processing tomatoes grown under commercial organic and conventional production systems. *Journal of Food Science*, *72*(9). https://doi.org/10.1111/J.1750-3841.2007.00500.X

Basri, M., & Wahira, I. (2022). Robot Line Follower Pemindah Barang Berdasarkan Warna Berbasis Mikrokontroler. *Jurnal Mosfet*, *2*(2), 11–15. https://doi.org/10.31850/jmosfet.v2i2.1973

Bent, L. van den, Coleman, T., & Babuška, R. (2025). Robotic Grasping of Harvested Tomato Trusses Using Vision and Online Learning. *Proceedings - IEEE International Conference on Robotics and Automation*, 13947–13953. https://doi.org/10.1109/ICRA57147.2024.10610089

Brigido, W. J. H., & Oliveira, J. M. P. de. (2025). The line follower robot: a meta-analytic approach. *PeerJ Computer Science*, *11*. https://doi.org/10.7717/PEERJ-CS.2744/SUPP-2

Budijanto, A. (2018). PENGATURAN KECEPATAN MOTOR DC PADA ROBOT LINE FOLLOWER MENGGUNAKAN PULSE WIDTH MODULATION (PWM). *Seminar Nasional Sistem Informasi (SENASIF)*, *2*, 1162–1169. https://jurnalfti.unmer.ac.id/index.php/senasif/article/view/178

Cahyani, M. P. (2023). *IOT DALAM SMART FARMING 4.0 UNTUK UPAYA TINGKATKAN EFESIENSI AGRIBISNIS*. https://www.researchgate.net/publication/369378549_IOT_DALAM_SMART_FARMING_40_UNTUK_UPAYA_TINGKATKAN_EFESIENSI_AGRIBISNIS

Certhon. (2025). *Artemy. Harvesting cherry tomatoes autonomously*. Certhon. https://certhon.com/robot-harvesting/

Dirayati, F., Sari, R. A., & Purnomo, R. F. (2025). Perancangan dan Implementasi Sistem Smart Agriculture Berbasis Internet of Things untuk Meningkatkan Produktivitas Pertanian. *Jurnal Media Informatika*, *6*(2), 863–872. https://doi.org/10.55338/JUMIN.V6I2.4982

Dumitru, N., Ciurezu-Gherghe, L., Copiluși, C., Geonea, I., & Dumitru, S. (2022). Theoretical and experimental study methods for a robotic system with deformable elements used in minimally invasive surgery. *Mechanism and Machine Theory*, *167*. https://doi.org/10.1016/J.MECHMACHTHEORY.2021.104459

Engin, M., & Engin, D. (2012). Path planning of line follower robot. *EDERC 2012 - Proceedings of the 5th European DSP in Education and Research Conference*, 1–5. https://doi.org/10.1109/EDERC.2012.6532213

Gené-Mola, J., Llorens, J., Rosell-Polo, J. R., Gregorio, E., Arnó, J., Solanelles, F., Martínez-Casasnovas, J. A., & Escolà, A. (2020). Assessing the Performance of RGB-D Sensors for 3D Fruit Crop Canopy Characterization under Different Operating and Lighting Conditions. *Sensors*, *20*(24). https://doi.org/10.3390/S20247072

GroW. (2025). *GRoW Tomato Harvesting Robot | For picking, collecting and boxing your tomatoes*. GroW. https://grow.ridder.com/

Handayani, T. P. (2015). *RANCANG BANGUN SISTEM KEAMANAN PINTU RUMAHMENGGUNAKAN SWITCH MAGNETIK DENGAN MONITORING WEBBOOTSTRAP BERBASIS RASPBERRY PI*. Politeknik Negeri Sriwijaya.

Hugeng, H., Trisnawarman, D., Irving, A., & Huntarso, Y. (2023). Enhanced IoT Solution System for Smart Agriculture in Indonesia. *Green Intelligent Systems and Applications*, *3*(2), 111–125. https://doi.org/10.53623/GISA.V3I2.325

Husni, N. L., Rasyad, S., Putra, M. S., Hasan, Y., & Rasyid, J. Al. (2020). PENGAPLIKASIAN SENSOR WARNA PADA NAVIGASI LINE TRACKING ROBOT SAMPAH BERBASIS MIKROKONTROLER. *Jurnal Ampere*, *4*(2), 297–306. https://doi.org/10.31851/ampere.v4i2.3450

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enhancing smart farming through the applications of Agriculture 4.0 technologies. *International Journal of Intelligent Networks*, *3*, 150–164. https://doi.org/10.1016/j.ijin.2022.09.004

Jin, Y., Liu, J., Xu, Z., Yuan, S., Li, P., & Wang, J. (2021). Development status and trend of agricultural robot technology. *International Journal of Agricultural and Biological Engineering*, *14*(4), 1–19. https://doi.org/10.25165/IJABE.V14I4.6821

Joni, K., Ulum, M., & Abidin, Z. (2016). Robot Line Follower Berbasis Kendali Proportional-Integral-Derivative (PID) Untuk Lintasan Dengan Sudut Ekstrim. *JURNAL INFOTEL - Informatika Telekomunikasi Elektronika*, *8*(2), 138. https://doi.org/10.20895/infotel.v8i2.129

Jun, J., Kim, J., Seol, J., Kim, J., & Son, H. Il. (2021). Towards an Efficient Tomato Harvesting Robot: 3D Perception, Manipulation, and End-Effector. *IEEE Access*, *9*, 17631–17640. https://doi.org/10.1109/ACCESS.2021.3052240

Kim, J. Y., Pyo, H. R., Jang, I., Kang, J., Ju, B. K., & Ko, K. E. (2022). Tomato harvesting robotic system based on Deep-ToMaToS: Deep learning network using transformation loss for 6D pose estimation of maturity classified tomatoes with side-stem. *Computers and Electronics in Agriculture*, *201*. https://doi.org/10.1016/J.COMPAG.2022.107300

Latif, A., Widodo, H. A., Rahim, R., & Kunal, K. (2020). Implementation of Line Follower Robot based Microcontroller ATMega32A. *Journal of Robotics and Control (JRC)*, *1*(3), 70–74. https://doi.org/10.18196/JRC.1316

Li, X., Ma, N., Han, Y., Yang, S., & Zheng, S. (2024). AHPPEBot: Autonomous Robot for Tomato Harvesting based on Phenotyping and Pose Estimation. *Proceedings - IEEE International Conference on Robotics and Automation*, 18150–18156. https://doi.org/10.1109/ICRA57147.2024.10610454

Oguten, S., & Kabas, B. (2021). *PID Controller Optimization for Low-cost Line Follower Robots*. https://doi.org/10.13140/RG.2.2.22102.98886

Pamungkas, M. A., Wijayanti, A. T., Harjanti, A. M., Fahriani, A., Berliana, D., Sari, K., Putri, D. S., Fitriawan, H. R., Rahman, M. A., Kamila, S., Aryasatya, N. R., Darojat, I., Putri, S. T., Margita, T. N., Indriani, W., Hudan, Y. N., & Handoyo, G. C. (2023). PEMBERDAYAAN MASYARAKAT MELALUI PENGIMPLEMENTASIAN SMART FARMING GUNA MENINGKATKAN EFISIENSI BUDIDAYA PADI KONVERSI ORGANIK DI DESA GLAGAHWANGI, KABUPATEN KLATEN. *Community Development Journal : Jurnal Pengabdian Masyarakat*, *4*(4), 8496–8503. https://doi.org/10.31004/CDJ.V4I4.19695

Prayudi, M. A., Sianturi, E. haryanto, Rahmad, I. F., & Ummi, K. (2014). Perancangan Robot Line Follower Pemisah Benda Berdasarkan Warna Berbasis Mikrokontroler ATMega16. *Creative Information Technology Journal*, *1*(3), 183–193. https://ojs.amikom.ac.id/index.php/citec/article/view/345

Putri, R. A., Kholis, N., & Baskoro, F. (2021). Automatic Packaging Conveyor Tracking System Based on Arduino Uno Using Photodiodes and SRF04 Ultrasonic Sensors. *INAJEEE Indonesian Journal of Electrical and Eletronics Engineering*, *4*(2), 38–43. https://doi.org/10.26740/inajeee.v4n2.p38-43

Rafi, R. H., Das, S., Ahmed, N., Hossain, I., & Reza, S. M. T. (2017). Design & implementation of a line following robot for irrigation based application. *19th International Conference on Computer and Information Technology, ICCIT 2016*, 480–483. https://doi.org/10.1109/ICCITECHN.2016.7860245

Rahadi, R. H., Khair, H., & Syari, M. A. (2025). Design and Build a Robot for Fertilizer Irrigation in Agricultural Land Using IoT. *Journal of Artificial Intelligence and Engineering Applications (JAIEA)*, *5*(1), 1190–1195. https://doi.org/10.59934/JAIEA.V5I1.1582

Rahman, A., Raheem, R., & Sharmilan, T. (2022). Design a Smart Mini Robot for Indoor Plant Watering System. *International Journal of Sciences: Basic and Applied*

Research (IJSBAR), *61*(1), 1–9. https://gssrr.org/JournalOfBasicAndApplied/article/view/13588

Rajee, A., & Marof, M. R. I. (2024). *Project Report on Line Follower Robot: A System Design Using Microcontroller*. https://www.researchgate.net/publication/385796819_Project_Report_on_Line_Follower_Robot_A_System_Design_Using_Microcontroller

Ridarmin, R., Fauzansyah, F., Elisawati, E., & Prasetyo, E. (2019). PROTOTYPE ROBOT LINE FOLLOWER ARDUINO UNO MENGGUNAKAN 4 SENSOR TCRT5000. *I N F O R M A T I K A*, *11*(2), 17. https://doi.org/10.36723/juri.v11i2.183

Rif'an, M., & Irianto, K. D. (2024). Precision Agriculture System with IoT: An Approach to Increase Production and Efficiency. *International Journal Software Engineering and Computer Science (IJSECS)*, *4*(3), 1305–1316. https://doi.org/10.35870/ijsecs.v4i3.3259

Rodríguez, L. G., Castro-Santos, L., & Galdo, M. I. L. (2025). Techno-Economic Analysis of the Implementation of the IEC 62034:2012 Standard—Automatic Test Systems for Battery-Powered Emergency Escape Lighting—In a 52.8-Meter Multipurpose Vessel. *Eng*, *6*(6), 110. https://doi.org/10.3390/eng6060110

Sarraf, G. (2025, August 20). *PID Tuning for Line Follower Robot: Complete How-To Guide – ThinkRobotics.com*. ThinkRobotics. https://thinkrobotics.com/blogs/learn/pid-tuning-for-line-follower-robot-complete-how-to-guide

Siegwart, R., Scaramuzza, D., & Nourbakhsh, I. R. (2011). *Introduction to autonomous mobile robots, second edition* . The MIT Press.

Sutisna, S. P., Siregar, T. H., & Ahmad, A. R. (2023). Design and Function Evaluation of Line Follower Plant Sprayer Robot. *Journal of Applied Science and Advanced Engineering*, *1*(1), 1–4. https://doi.org/10.59097/JASAE.V1I1.7

Vela-Hinojosa, C., Escalona-Buendía, H. B., Mendoza-Espinoza, J. A., Villa-Hernández, J. M., Lobato-Ortíz, R., Rodríguez-Pérez, J. E., & Pérez-Flores, L. J. (2019). Antioxidant Balance and Regulation in Tomato Genotypes of Different Color. *Journal of the American Society for Horticultural Science*, *144*(1), 45–54. https://doi.org/10.21273/JASHS04525-18

Wong, K. Y., Pu, S. C., & Wong, C. C. (2024). A Robotics Experimental Design Method Based on PDCA: A Case Study of Wall-Following Robots. *Sensors*, *24*(6). https://doi.org/10.3390/S24061869

Zhang, B., Zhou, J., Meng, Y., Zhang, N., Gu, B., Yan, Z., & Idris, S. I. (2018). Comparative study of mechanical damage caused by a two-finger tomato gripper with different robotic grasping patterns for harvesting robots. *Biosystems Engineering*, *171*, 245–257. https://doi.org/10.1016/J.BIOSYSTEMSENG.2018.05.003

Zhang, S., Liu, Y., Xiong, K., Tian, Y., Du, Y., Zhu, Z., Du, M., & Zhai, Z. (2024). A review of vision-based crop row detection method: Focusing on field ground autonomous navigation operations. *Computers and Electronics in Agriculture*, *222*. https://doi.org/10.1016/J.COMPAG.2024.109086

Zuhri, M., Irzaman, I., Setiawan, A., Satrio, M. A., Ramdhani, H. N., Iqbal, M., & Baihaki, R. A. (2024). Design and Implementation of Line Follower Robot for Automatic Watering of Orchid Plants. *INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND ANALYSIS*, *07*(11). https://doi.org/10.47191/IJMRA/V7-I11-04