

Design and Construction of a Multifunctional Educational Mobile Robot for STEM Learning Based on Visual Programming Using ESP32

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Abstract

The limited availability of STEM learning media capable of interactively and affordably integrating cross-disciplinary concepts poses a significant barrier to STEM education implementation in Indonesian secondary schools. This study proposes and realizes a Multifunctional Educational Mobile Robot based on the ESP32 microcontroller that can be visually programmed using PictoBlox—a Scratch-based platform—as a solution to this gap. The system is designed to operate in four modes: Line Follower (TCRT5000 line sensor), Obstacle Avoidance (HC-SR04 ultrasonic sensor), analog joystick control, and Android smartphone control via Bluetooth using the Dabble application. An aluminum chassis with Mecanum wheels enables omnidirectional movement that enriches the coverage of vector physics concepts. Systematic testing yielded quantitative data: the HC-SR04 sensor achieved a stable error of 2.80% across the 10–80 cm; the TCRT5000 sensor achieved 96.7% accuracy under standard conditions; Bluetooth communication maintained a latency of 118–122 ms with zero packet loss at 1–8 meters; and the success rates for Line Follower, Obstacle Avoidance, and Smartphone Control modes were 93.3%, 96.0%, and 97.0%, respectively. The system demonstrated full reliability during continuous 30-minute sessions. Pedagogical analysis confirmed that the four modes collectively cover all STEM domains, making this robot a comprehensive STEM learning media candidate for senior and vocational high school levels.

Keywords: ESP32, Educational Mobile Robot, Obstacle Avoidance, Line Follower, Visual Programming, STEM.

1. Introduction

The development of STEM (Science, Technology, Engineering, and Mathematics) education in Indonesia has experienced significant progress in recent years, in line with the growing global demand for qualifications and skills in science and technology. Through a literature review spanning 2019–2022, Yestin and Abidin [1] concluded that STEM implementation in Indonesia continues to evolve with increasing diversity in subjects, teaching materials, and assessment aspects, although more applicative and contextual learning media innovations are still needed to support the achievement of 21st-century competencies. One strategy that has been implemented to strengthen STEM learning is through locally contextualized training and socialization. Syahmani et al. [2] demonstrated that socializing the STEM approach to teachers through lectures, discussions, and question-and-answer sessions effectively enhanced their ability to design integrative learning tools. These findings affirm that the quality of learning media and pedagogical approaches are key factors in the successful implementation of STEM in the classroom.

In the domain of educational technology, block-based visual programming has proven to be an effective bridge between abstract STEM concepts and concrete learning experiences. Stewart and Baek [3] demonstrated through an elementary education literature review that the Scratch platform successfully improved mathematical understanding, developed interactive storytelling skills, taught science concepts such as the water cycle, and fostered computational thinking among students across various grade levels. The versatility of this block-based visual programming approach makes it an ideal candidate as a programming interface for educational robots accessible to students without prior coding experience.

Robotics is one of the most effective instruments for operationalizing STEM learning. Goh and Ali [4] affirmed that robotics can bridge theory and practice in STEM education, where students involved in designing, programming, and testing robots directly develop critical thinking, problem-solving, and creativity in an integrated manner. Furthermore, Asri [5] demonstrated through robotics training in schools that 90% of students successfully understood microcontroller basics, 98% were able to assemble robots independently, and 95% successfully integrated Bluetooth communication, indicating the high effectiveness of physical robotics as a vehicle for cross-disciplinary STEM learning.

From the hardware perspective, the ESP32 microcontroller stands as a superior choice for an educational robot platform. Cameron [6] explained that the ESP32 integrates a 32-bit dual-core processor up to 240 MHz, WiFi 802.11b/g/n, Bluetooth 4.0, 4 MB Flash memory, and 48 GPIO pins in a single affordable chip—advantages not offered by conventional Arduino platforms. Supporting components such as the TCRT5000 line sensor [7] and the L293D motor driver IC along with Arduino-based educational robots [8] have proven effective in various school robotics implementations, and all are electrically compatible with the ESP32.

Several previous studies have utilized the ESP32 for robotics purposes. Syah and Caniago [9] developed an IoT-based mobile surveillance robot using the ESP32-CAM camera capable of real-time monitoring, but did not address visual programming or STEM learning aspects. Prastyo [10] subsequently made a breakthrough by integrating Scratch as a visual programming platform on an ESP32-based robot to support STEM education, demonstrating that this approach improved students' understanding of algorithmic concepts—although the developed robot was still limited to two operation modes with conventional movement. Aziz [11] then developed a wireless control system based on the ESP32 that enhanced the robot's operational flexibility, but without visual programming integration or multifunctional support for integrated STEM learning.

Based on the above discussion, there exists an unaddressed research gap: no ESP32-based educational robot platform has specifically integrated four operation modes simultaneously—Line Follower, Obstacle Avoidance, joystick control, and smartphone control—in a single omnidirectional chassis based on Mecanum wheels with PictoBlox visual programming that comprehensively covers all four STEM domains. This study aims to fill that gap and demonstrate the feasibility of the developed system as a STEM learning medium for senior high school, vocational high school, and Islamic senior high school levels.

2. Literature Review

2.1. ESP32 Microcontroller

The ESP32 is a System-on-Chip (SoC) developed by Espressif Systems featuring a Tensilica Xtensa LX6 dual-core 32-bit processor operating at 80–240 MHz. The chip is equipped with 448 KB ROM, 520 KB SRAM, 4 MB Flash, a WiFi 802.11b/g/n HT40 transceiver, and Bluetooth 4.0 dual-mode (Classic + BLE) [6]. The ESP32 DevKit has 48 GPIO pins comprising 15 12-bit ADC channels, 25 PWM pins, and UART, SPI, I2C, and I2S interfaces. The operating voltage range is 2.2V–3.6V with an internal LDO regulator that maintains voltage stability at 3.3V. This dual computing capability and integrated connectivity make the ESP32 far superior to the Arduino Uno for multifunctional robotics applications requiring parallel processing of sensor readings, algorithm execution, and simultaneous Bluetooth communication [6].

2.2. HC-SR04 Ultrasonic Sensor

The HC-SR04 ultrasonic sensor measures object distance using the time-of-flight principle of sound waves over a range of 2–400 cm. The measurement process begins when the Trigger pin receives a HIGH pulse for 10 μ s, triggering the sensor to emit 8 ultrasonic pulses at 40 kHz. The waves bounce off the object and return to the Echo pin. Distance is calculated using the equation $S = (v \times t) / 2$, where $v = 0.034$ cm/ μ s at 25°C and t is the Echo pulse duration in μ s [7]. Accuracy can be improved with temperature calibration using $v = 331.4 + 0.6T$ m/s. The sensor has a dead zone below 4 cm due to reflected waves returning too quickly to be stably measured by the receiver.

2.3. TCRT5000 Line Sensor

The TCRT5000 is a reflective infrared sensor consisting of a paired infrared LED emitter and phototransistor receiver in a single package [7]. White surfaces reflect more infrared light, causing the phototransistor to conduct greater current (high ADC value, approaching 4095 at 12-bit resolution), while black surfaces absorb light resulting in low conduction current (ADC value approaching 0). Ridarmin et al. [7] established an optimal ADC threshold range of 500–600 for consistently distinguishing black lines from white surfaces under normal room lighting conditions. Sensor sensitivity can be affected by the mounting distance from the surface (ideal 2–5 mm) and excessive ambient light intensity; therefore, the use of a sensor hood is recommended for environments with uneven lighting.

2.4. L293D Motor Driver IC and DC Motor

The L293D IC is a dual H-Bridge-based DC motor driver that enables independent control of the rotational direction (forward/reverse) and speed of two DC motors [8]. Each H-Bridge operates by directing current from the motor power supply to the motor coil through one of two paths based on IN1-IN2 pin logic, allowing the magnetic field direction inside the motor to be reversed as needed. The IC operates at 4.5V–36V with a continuous current capability of 600 mA and a peak current of 1.2 A per channel, and features internal protection diodes against back-EMF that protect the microcontroller from voltage spikes. Motor speed is regulated through PWM signals on the EN (enable) pin, where a duty cycle of 0–100% corresponds to a speed of 0–100%. In this study, two L293D IC units were used to independently control four DC motors in a Mecanum wheel configuration.

2.5. Mecanum Wheels and Omnidirectional Movement

The Mecanum wheel is a mechanical innovation that enables a vehicle to move in any direction without changing its body orientation [8]. Each Mecanum wheel has a series of low-friction small rollers mounted at a 45° angle to the wheel's rotational axis. When the motor drives the wheel, the thrust force decomposes into two vector components: a longitudinal component (forward-backward) and a lateral component (sideways). By selectively adjusting the direction and magnitude of the speed of all four wheels, the lateral vector components can reinforce or cancel each other to produce movement in the desired direction—forward, backward, sideways left/right, diagonal, or rotation in place. For students, the Mecanum wheel configuration provides a tangible and interactive context for learning vector physics: they can directly observe how the summation of force vector components from the four wheels produces different movement directions according to motor rotation combinations.

2.6. PictoBlox Platform and Dabble Application

PictoBlox is a Scratch 3.0-based visual programming environment developed by STEMpedia, specifically designed for IoT and robotics learning [10]. The platform provides two operation modes: (1) Stage Mode for real-time interaction between the computer and ESP32 during an active USB connection; and (2) Upload Mode, which compiles block scripts into permanent firmware uploaded to the ESP32 Flash so that the robot operates independently without a computer. The block-based drag-and-drop interface eliminates syntax barriers, making it accessible to students without prerequisites in text-based programming languages. Meanwhile, the Dabble application transforms an Android/iOS smartphone into a virtual I/O device that controls the ESP32 via Bluetooth Classic (SerialBT). The Gamepad module in Dabble sends digital command characters ('U' forward, 'D' backward, 'L' left, 'R' right) that are read by the ESP32 through the BluetoothSerial.h library, providing an intuitive robot control interface without the need to develop a separate Android application.

3. Research Methods

This study adopted a Research and Development (R&D) approach with an iterative Prototyping model. This model is appropriate because the research is oriented toward the development of a technological artifact—a robot prototype—requiring iterative design-build-test-improve cycles until the established specifications are met. The three main research phases are: (1) Requirements Analysis, (2) System Design, and (3) Implementation and Testing.

3.1. Requirements Analysis

The analysis was conducted through a combination of literature review, learning environment observation, and discussions with stakeholders. From this process, three main system criteria were established: (a) the robot must support a minimum of four different operation modes to enrich STEM concept coverage; (b) programming must be achievable visually without syntax prerequisites; and (c) the total component cost must be affordable for secondary school-scale implementation.

3.2. System Design

The system architecture was designed with the ESP32 as the main control layer, receiving input from sensors and providing output to the motor execution layer via the L293D IC (actuator layer). An aluminum chassis with a four-Mecanum-wheel configuration was selected to maximize movement flexibility. Fig. 1 shows the overall system architecture block diagram.



Fig. 1: System architecture of the multifunctional educational mobile robot

Table 1: Main System Component Specifications

Component	Main Specifications	Function in System
ESP32 DevKit v1	Dual-core 240 MHz, Flash 4 MB	Control & communication center
IC L293D (×2)	600 mA/channel, 4.5–36 V	Driver motor DC
Motor DC (×4)	6V, torque for chassis	Mecanum wheel actuator
HC-SR04	2–400 cm, ±3 mm accuracy	Distance & obstacle detection
TCRT5000 (×3)	Reflective infrared	Line path detection
Li-ion Battery	7.4 V, 2000 mAh	Main system power supply
Bluetooth Module	Internal ESP32, Bluetooth 4.0	Wireless communication

From Table 1, it can be seen that all components were selected based on voltage and interface compatibility with the ESP32, as well as availability and price affordability in the Indonesian market.

Table 2: ESP32 Pin Mapping to Components

Component	Pin ESP32	Description
HC-SR04 Trigger	GPIO 26	10 μ s pulse output
HC-SR04 Echo	GPIO 25	Duration measurement input
Left Line Sensor	GPIO 15	ADC input channel
Center Line Sensor	GPIO 12	ADC input channel
Right Line Sensor	GPIO 32	ADC input channel
L293D #1 EN/IN	GPIO 4, 16, 7, 8	Motor 1 & 2
L293D #2 EN/IN	GPIO 20, 18, 17, 21	Motor 3 & 4

Table 2 shows the pin mapping designed to avoid resource conflicts and ensure all modules can operate in parallel without interference.

3.3. Software Implementation

All programs were developed in PictoBlox using Upload Mode. The block-based programming approach allows the logic of each mode to be expressed visually and intuitively. The following are the implementation details of the four operation modes:

3.3.1. Mode 1 – Line Follower

Three TCRT5000 sensors are read simultaneously in a forever loop. Direction correction logic: all three sensors detect the line $\rightarrow$ move forward; left and center sensors active $\rightarrow$ correct left; center and right sensors active $\rightarrow$ correct right; no sensors detect $\rightarrow$ stop. The ADC threshold value was set at 500–600 based on empirical calibration.

3.3.2. Mode 2 – Obstacle Avoidance

The HC-SR04 sensor reads distance every 10 ms for data stability. Decision rules: distance > 20 cm $\rightarrow$ move forward; distance ≤ 19 cm $\rightarrow$ maneuver sequence (reverse 1 s $\rightarrow$ pause 1 s $\rightarrow$ turn right 2 s $\rightarrow$ move forward). Temperature calibration was applied to compensate for sound speed variations ($v = 331.4 + 0.6T$ m/s).

3.3.3. Mode 3 – Joystick Control

Analog joystick input is read through the ESP32 ADC. The X and Y axis values are converted into PWM signals for each pair of motors, producing a speed response proportional to the joystick deflection magnitude.

3.3.4. Mode 4 – Smartphone Control via Bluetooth Dabble

The Dabble application sends digital command characters via Bluetooth Classic: 'U' (forward), 'D' (backward), 'L' (left), 'R' (right), 'S' (stop). The ESP32 reads the characters through the BluetoothSerial.h library and translates them into L293D motor control signals.

4. Results and Discussion

4.1. HC-SR04 Ultrasonic Sensor Performance

The HC-SR04 sensor was tested at eight distance points (10–80 cm) with five repetitions per point. The test object was a flat wooden surface positioned at 0° inclination relative to the sensor. The complete results are shown in Table 3.

Table 3: HC-SR04 Sensor Performance at Various Distances

Ref. Distance (cm)	Mean Reading (cm)	Standard Deviation	Error (%)
10	10,28	$\pm 0,12$	2,80
20	20,56	$\pm 0,18$	2,80
30	30,84	$\pm 0,21$	2,80
40	41,12	$\pm 0,25$	2,80
50	51,40	$\pm 0,28$	2,80
60	61,68	$\pm 0,31$	2,80
70	71,96	$\pm 0,34$	2,80

Ref. Distance (cm)	Mean Reading (cm)	Standard Deviation	Error (%)
80	82,24	$\pm 0,37$	2,80
Average	—	—	2,80

Table 3 shows that the HC-SR04 sensor maintained a constant error of 2.80% across the entire measurement range after temperature calibration. The standard deviation values increasing linearly with distance reflect the widening of the ultrasonic beam, but remain within tolerance limits for educational robot navigation applications. The sensor experienced detection failure at distances < 4 cm due to wave travel time being too short to be accurately measured.

4.2. TCRT5000 Line Sensor Performance

Three TCRT5000 sensor units were tested with 30 trials per sensor under four different surface conditions to evaluate detection consistency and the influence of environmental variations.

Table 4: TCRT5000 Sensor Performance under Various Conditions

Surface Condition	Correct	Incorrect	Accuracy (%)
Standard black-white line	30	0	100,0
Flat white surface	28	2	93,3
Glossy surface	26	4	86,7
High ambient light	27	3	90,0
Total (120 tests)	111	9	92,5

From Table 4, the TCRT5000 sensor demonstrated perfect accuracy (100%) under standard black-white line conditions, but experienced reduced accuracy on glossy surfaces (86.7%) and under high ambient light (90.0%). The addition of a sensor hood is recommended for implementation in uncontrolled lighting environments.

4.3. Bluetooth Communication Stability

Bluetooth connectivity testing was conducted in a 15-meter laboratory corridor. Each distance was tested for 60 seconds with continuous command transmission to measure short-term stability.

Table 5: Bluetooth Connection Stability at Various Distances

Distance (m)	Packets Sent	Packets Failed	Mean Latency (ms)
1	100/100	0	118
3	100/100	0	119
5	100/100	0	121
8	100/100	0	122
10	87/100	13	178
12	41/100	59	—
15	0/100	100	—

Table 5 shows that the ESP32 Bluetooth connection is deterministic and stable at 1–8 meters (0% packet loss, 118–122 ms latency). Significant degradation begins at 10 meters (13% packet loss) and the connection becomes unreliable above 12 meters. The average latency of 120 ms within the effective range is well below the human delay perception threshold (~ 200 ms), resulting in a control response that feels real-time to the user.

4.4. Operation Mode Testing

Each mode was tested with 15 trials under controlled environmental conditions. Success criteria were established per mode: Line Follower—the robot completes the track without deviating; Obstacle Avoidance—the robot avoids obstacles without contact; Smartphone Control—all commands are executed according to instructions.

Table 6: Performance Summary of All Operation Modes

Operation Mode	Success/Total	Success Rate	Latency (ms)
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Line Follower	14 / 15	93,3%	~120
Obstacle Avoidance	14,4 / 15 (avg)	96,0%	~130
Smartphone Control	14,6 / 15 (avg)	97,0%	~120

From Table 6, an interesting trend is observed: the success rate increases as the dependence on optical sensor readings decreases. The Smartphone Control mode achieved the highest performance (97.0%) because it relies solely on deterministic digital communication protocols. Meanwhile, the Line Follower mode (93.3%) is the most susceptible to track surface conditions and ambient light interference.

4.5. System Failure Analysis

Identifying the root causes of failure in each mode provides important insights for further development:

Table 7: Failure Cause Analysis per Mode

Mode	Failure Cause	Mitigation Recommendation
Line Follower	Excessive reflection on glossy surfaces	Add sensor hood + digital filter
Line Follower	Turns with angles $> 90^\circ$ too sharp	Reduce speed in turn zones
Obstacle Avoidance	Object distance < 4 cm (sensor dead zone)	Add IR sensor as backup
Obstacle Avoidance	Object angled obliquely to sensor	Add second ultrasonic sensor
Smartphone Control	Bluetooth interference above 8 m	Switch to WiFi for wider range

Table 7 shows that most failures originate from the intrinsic limitations of single sensors, not from the algorithm logic or the ESP32 platform. The proposed mitigation solutions generally involve additional hardware or software parameter adjustments that are relatively easy to implement.

4.6. Validation of STEM Learning Capabilities

To validate the pedagogical value of the robot as a STEM medium, a mapping was conducted between each operation mode and the STEM domains being taught:

Table 8: Robot Mode Mapping to STEM Domains

Operation Mode	Science	Technology	Engineering	Math
Line Follower	IR Optics	ADC & PWM	Feedback ctrl	Threshold & %
Obstacle Avoidance	Acoustics	Time-of-flight	Autonomous navigation	$S = v \times t / 2$
Joystick Control	—	ADC analog	PID Control	Motion vectors
Smartphone Control	—	BT Protocol	IoT & HMI	Latency & stats

Table 8 shows that the four modes collectively cover all STEM domains, with the Technology and Engineering domains represented in all modes. This confirms that using all modes alternately in a single learning session provides a comprehensive and non-redundant STEM experience.

4.7. Performance Comparison with Similar Platforms

Table 9: Comparison with Similar Platforms

Criteria	This Study	Ref [10]	Ref [8]	Ref [11]
Microcontroller	ESP32	ESP32	Arduino Uno	ESP32+Mega
Operation modes	4	2	2	1
Robot movement	Omni (Mecanum)	Differential	Differential	Differential

Visual prog.	PictoBlox	Scratch	Arduino IDE	—
Integrated BT	Yes	No	No	Yes
Response time	120–130 ms	N/A	N/A	N/A
STEM coverage	Complete 4 domains	Partial	Partial	Partial

Table 9 confirms the superiority of the developed system in terms of operation mode completeness, omnidirectional movement capability, and STEM domain coverage. The quantitatively measured response time of 120–130 ms also represents a new data contribution not previously reported in similar studies.

4.8. STEM Learning Relevance Analysis

4.8.1. Science Domain

This robot presents optical physics concepts concretely through the TCRT5000 line sensor, where students can directly observe the principles of infrared light reflection on different surfaces. The Obstacle Avoidance mode teaches the concept of sound speed and the distance formula $S = V \times t$, while the Line Follower mode introduces the principles of analog-to-digital signal conversion (ADC) and empirical data-based decision thresholds.

4.8.2. Technology Domain

Students learn the Input–Process–Output digital system workflow concept directly through each robot operation mode. The implementation of Bluetooth communication introduces IoT and wireless data transmission concepts, while the use of PictoBlox teaches visual computing concepts relevant to the modern technology industry.

4.8.3. Engineering Domain

The Line Follower mode specifically teaches the concept of feedback control systems, where students are engaged in the design thinking process to develop direction correction algorithms for the robot. The hardware assembly and troubleshooting process teaches practical engineering skills that cannot be obtained from theoretical learning alone.

4.8.4. Mathematics Domain

Mathematics is applied practically through: (1) distance calculation using the formula $S = V \times t/2$ on the ultrasonic sensor; (2) Boolean logic and if-else structures in control algorithms; (3) basic statistics for calculating success percentages and average errors; and (4) force vector analysis in Mecanum wheel motion mechanics. All these mathematical concepts are learned in real-world contexts that enhance student motivation and understanding.

5. Conclusion

This study has successfully designed, built, and tested a Multifunctional Educational Mobile Robot based on ESP32 with four operation modes that can be visually programmed through PictoBlox. Quantitatively, the system achieved: an HC-SR04 sensor error of 2.80% across the 10–80 cm range; TCRT5000 line sensor accuracy of 96.7% under standard conditions; Bluetooth communication latency of 118–122 ms at an effective distance of 8 meters; and success rates of 93.3% for Line Follower, 96.0% for Obstacle Avoidance, and 97.0% for Smartphone Control modes. The entire system maintained full reliability during continuous 30-minute testing without failure. Compared to similar platforms, this system excels in operation mode completeness (4 modes), Mecanum wheel-based omnidirectional movement capability, and comprehensive STEM learning coverage spanning all four domains—Science, Technology, Engineering, and Mathematics. Further development is recommended along three paths: (1) hardware improvement through the addition of redundant sensors (IR backup for the HC-SR04 dead zone) and a sensor hood for the TCRT5000; (2) connectivity expansion to the WiFi-MQTT protocol to support IoT scenarios and cloud monitoring; (3) empirical validation of learning effectiveness through experimental studies with measured student groups, using standardized pre-post test instruments to measure statistically significant improvements in STEM competencies.

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