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Article

Development of Robotics Learning Modules based on IoT and ESP32

A Rofi'i[1], N Afianah [2]*, S Kautsar[3], A W Pratama[4], A W Winardi[5], F E Purnomo[6], S L Putri[7], D. A. Tyagita[8], M I Nari[9], F L Afriansyah[10]

[1] Engineering Departement, Politeknik Negeri Jember; rofii@polije.ac.id
[2] Engineering Departement, Politeknik Negeri Jember; nuzula.afianah@polije.ac.id
[3] Engineering Departement, Politeknik Negeri Jember; syamsiar_kautsar@polije.ac.id
[4] Engineering Departement, Politeknik Negeri Jember; aditya_wa@polijje.ac.id
[5] Engineering Departement, Politeknik Negeri Jember; a_atmajaya@polije.ac.id
[6] Engineering Departement, Politeknik Negeri Jember; fendik_eko@polije.ac.id
[7] Engineering Departement, Politeknik Negeri Jember; salsabila.liandra@polije.ac.id
[8] Engineering Departement, Politeknik Negeri Jember; dickyadi@polije.ac.id
[9] Engineering Departement, Politeknik Negeri Jember, m.irwan.nari@polije.ac.id
[10] Information Technology Departement, Politeknik Negeri Jember; faisal.lutfi@polije.ac.id

***Correspondence:** nuzula.afianah@polije.ac.id

Abstract: This study aims to develop a transporter robot as a learning tool for elementary and secondary school students to introduce them to robotics. The robot features a differential drive system and a lifting arm akin to a forklift system. The robot is controlled using an ESP32 microcontroller and connected to an Android application through a Firebase cloud database. Utilizing an IoT platform, the training can be conducted online, allowing students to control the robot remotely while it remains at the training location. The transporter robot is designed to provide an interactive and hands-on learning experience in robotics, enabling students to grasp fundamental concepts in robotics, programming, and control systems. The differential drive system offers excellent maneuverability, while the lifting arm allows the robot to perform tasks such as lifting and moving objects, adding functional aspects to the learning process. Test results indicate that the robot performs well under online control, with fast and accurate responses to commands from the Android application. The use of Firebase ensures stable and real-time communication between the robot and the application. This implementation not only enhances the accessibility of robotics training but also enables the development of students' STEM skills in a more flexible and affordable manner. The study concludes that an ESP32-based transporter robot with online control via an Android application and Firebase cloud database can be an effective and innovative learning tool. This tool aims to enhance students' STEM skills -especially in programming, control systems, and mechanical design- through interactive, real-world applications.

Keywords: mobile-robot, IoT, ESP32

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1. Introduction

In an era increasingly driven by technology and innovation, skills in Science, Technology, Engineering, and Mathematics (STEM) have become essential for the younger generation. Early childhood education in robotics is an effective approach to introducing and developing STEM skills among students[1]. This introduction not only helps students understand fundamental concepts in technology and robotics but also hones problem-solving skills, creativity, critical thinking, and teamwork. As the demand for a technologically proficient workforce grows, introducing robotics at a young age lays a solid foundation for students to excel in related fields in the future[2].

To enhance students' interest and skills in STEM, we have designed an educational robot equipped with a differential drive system[3]. This robot is not merely a simple

demonstration tool but an interactive platform that allows students to engage directly in the learning process. A key feature of this robot is a forklift-like arm capable of lifting and moving objects. This feature provides students with practical experience in controlling the robot and manipulating objects, enabling them to understand the basic principles of robotics, such as mechanics, control, and human-machine interaction.

The robot utilizes an ESP32 controller, offering broad connectivity capabilities, including remote control via an Android application connected to the internet[4]. The integration with Firebase[5] allows for remote control of the robot, providing flexibility in the learning process, especially in situations where face-to-face learning is not possible. This feature is particularly relevant amidst the global pandemic, which has accelerated the adoption of remote learning and digital technologies in education. Additionally, the robot can be controlled via Bluetooth, offering a simpler and more direct control option for offline learning. This capability ensures that the robot can be used in various learning contexts, whether in the classroom or at home.

The learning arena we designed consists of a grid path with a 20 cm gap between lines. This design not only provides a clear structure for the robot's movement but also challenges students to plan and implement effective navigation strategies. The task for students is to move objects randomly from one end of the grid to the other, simulating real-world scenarios where robots are used to transport goods in industrial or logistics environments[6], [7]. This activity encourages students to think logically and strategically and understand the importance of precision and coordination in robot control.

While various robotics platforms have been introduced in educational contexts, the combination of ESP32, Firebase real-time database, and differential drive mechanics offers a novel, affordable, and internet-based approach to STEM learning. These technologies are rarely integrated simultaneously in educational tools, especially those aimed at primary and secondary school levels [8]. This study distinguishes itself by combining cloud-connected control with hands-on physical robot tasks in a structured learning arena. By allowing students to remotely operate real hardware over the internet while developing logic through grid-based navigation challenges, the system provides an engaging and accessible learning experience that supports the development of core STEM competencies.

2. Methods

The A differential drive system is one of the most commonly used methods for moving mobile robots. This system consists of two wheels mounted on the right and left sides of the robot, each driven by its own motor. By adjusting the rotational speed of the two wheels, the robot can move forward, backward, or turn in a simple and efficient manner. In a differential drive system, the direction of the robot is changed by varying the relative speed between the left and right wheels. For instance, to move straight, both wheels rotate at the same speed. To turn, the speed of one wheel is increased while the other wheel is slowed down or rotated in the opposite direction. If one wheel moves forward and the other moves backward at the same speed, the robot will rotate in place.

The main advantages of the differential drive system[6] are its simplicity and its ability to perform sharp maneuvers in confined spaces. This system also allows for precise and responsive control, making it ideal for various applications, from household cleaning robots to automated vehicles in factories and warehouses. However, the system also has some limitations. One of them is the inability to move sideways without executing a turning maneuver, which distinguishes it from omnidirectional drive systems. Additionally, this system requires a good control algorithm, such as a PID (Proportional-Integral-Derivative) controller[9], to ensure stability and movement accuracy, especially when performing tasks that require high precision. By understanding the basic principles and characteristics of the differential drive system, robot developers can design and implement effective and efficient mobile robots for various industrial and educational purposes.

Figure 1 shows the control system architecture for a robot using a differential drive system controlled via a mobile application. In this system, the mobile application serves as the main interface for the user, allowing them to issue control commands intuitively. The commands given by the user through the app are then relayed to Firebase, a cloud platform that acts as an intermediary between the mobile application and the microcontroller used in the robot. Firebase functions as a real-time data storage and transmission medium, enabling smooth and responsive communication between the mobile device and the robot, even from a distance.

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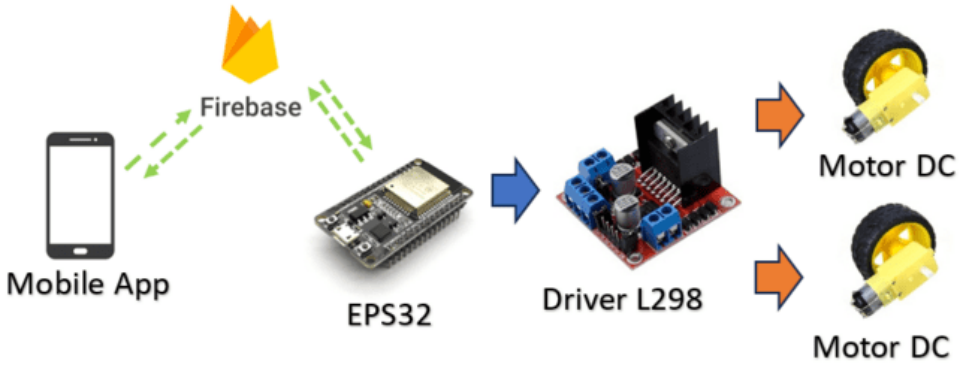


Figure 1. Block Diagrams System

Subsequently, the ESP32 microcontroller, which is connected to Firebase, receives the processed control data. The ESP32 is equipped with Wi-Fi connectivity, allowing the robot to connect to the internet and receive commands from Firebase. Upon receiving these commands, the ESP32 processes the data and forwards it to the L298 motor driver. The L298 driver module is responsible for controlling the DC motors based on the signals received from the ESP32. This module can independently control two DC motors, each connected to the right and left wheels of the robot. By adjusting the PWM (Pulse Width Modulation) signals sent to the motor driver, the ESP32 can precisely regulate the speed and direction of each motor.

The DC motors controlled by the L298 driver then move the robot's wheels. By adjusting the relative speed between the right and left wheels, this differential drive system allows the robot to move forward, backward, or turn efficiently and easily[10]. For instance, to move straight, both wheels are driven at the same speed, while for turning, the speed of one wheel is adjusted. This capability enables the robot to perform various maneuvers, including rotating in place by moving one wheel forward and the other backward. This system not only provides ease of remote control through internet connectivity but also offers flexibility in various environments. By leveraging Firebase as a communication medium, users can control the robot from a distant location, making it ideal for educational demonstrations, robotics experiments, or practical applications like home or industrial automation. Thus, this architecture offers a comprehensive and innovative solution for robot control, integrating mobile technology, cloud computing, and motor control into a single cohesive system[11].

A differential drive system is one of the most commonly used methods for driving mobile robots. This system consists of two main wheels mounted on the right and left sides of the robot, each driven by a separate motor, as seen in figure 2. Unlike conventional vehicles that use steering wheels to turn, the differential drive system controls the robot's direction by varying the relative speed between the two wheels. The working principle of this system is as follows: if both wheels rotate at the same speed and in the same direction, the robot will move straight forward or backward. To change direction or turn, the system adjusts the speed of one of the wheels. For instance, to turn right, the left wheel spins faster than the right wheel. Conversely, to turn left, the right wheel spins faster than the left wheel. If one wheel moves forward while the other moves backward at the same

speed, the robot will rotate in place, allowing for a 360-degree turn without moving forward or backward. The linear velocity V and the angular velocity ω of the robot can be expressed in terms of the left wheel speed ωL and the right wheel speed ωR. The position (x,y) (x,y) and orientation θ θ of the robot at any time t t can be updated using the differential equations (1).

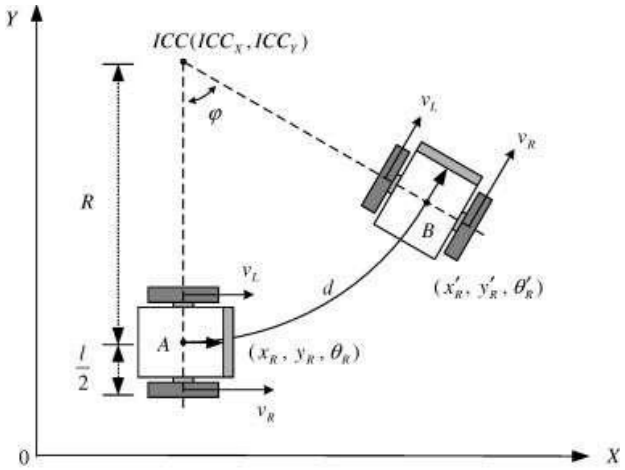


Figure 2. Mobile-robot differential drive system

$$V = \frac{R}{2}(\omega_R + \omega_L) \quad (1)$$

$$\omega = \frac{R}{L}(\omega_R - \omega_L) \quad (2)$$

$$\dot{x} = V\cos(\theta) \quad (3)$$

$$\dot{y} = V\sin(\theta) \quad (4)$$

$$\dot{\theta} = \omega \quad (5)$$

The primary advantage of the differential drive system is its simplicity. This system does not require a complex steering mechanism, and the controller can easily manage the robot by adjusting the motor speeds. Additionally, it is highly versatile and can be used in various applications, ranging from simple educational robots to more complex autonomous vehicles. However, there are some limitations to consider. One of the main drawbacks is that robots with a differential drive system cannot move sideways or laterally. The movement of the robot is limited to turning or moving forward/backward, unlike omnidirectional drive systems that allow movement in all directions. Furthermore, to achieve smooth and stable control, a good control algorithm, such as a PID (Proportional-Integral-Derivative) controller, is needed, especially when the robot has to follow a specific path or navigate complex environments. Overall, the differential drive system is an efficient and effective choice for various types of mobile robots, allowing for precise control with a relatively simple design. This system continues to be a popular choice in robotics design due to its ease of use and sufficient maneuverability in diverse environments.

The flowchart as shown in figure 3, outlines the control flow for moving a mobile robot using an ESP32 via a mobile application with Firebase integration. The process starts with the user inputting commands through the mobile app. These commands are then sent to the Firebase cloud service, which acts as an intermediary to store and transmit data. The ESP32 microcontroller retrieves the command from Firebase and processes it, sending the appropriate signals to the L298 motor driver. The L298 driver then controls the DC motors to execute the movement commands, enabling the robot to move accordingly. The system

was deployed in a real laboratory environment, with students remotely accessing and controlling the robot in real-time. The physical robot remained in a monitored lab setting, while students interacted with it via mobile devices, simulating industrial automation scenarios. To ensure reproducibility and clarify the communication flow between the mobile application, Firebase, and the ESP32 microcontroller, a simplified pseudocode is provided. The pseudocode outlines the essential steps executed by the system to interpret user commands and convert them into robot movements in real time.

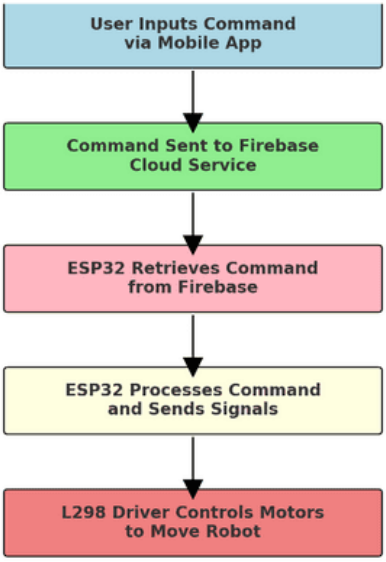


Figure 3. Flowchart system

Pseudocode: Firebase to ESP32 Data Handling

```
1. Mobile App: Send command → Firebase (Database path: /robotControl)
2. Firebase Cloud: Stores latest command value
3. ESP32:
  loop:
    connect to WiFi
    access Firebase
    read command from /robotControl
    if new command:
       parse command
       control motors (via L298) accordingly
    delay(100ms)
```

3. Results and Discussion

The robot was built using a smart robot car body measuring 15cm x 20cm, with a yellow gearbox wheel drive. The wheel diameter is 4cm. For the forklift lifting arm, an MG90 servo was used. The robot's power supply is a 1000mAh power bank. Figure 4 shows a photo of the IoT-based educational mobile robot. Figure 5 shows the mobile application for internet-based control. The application was developed using App Inventor. After the construction and assembly process, several testing stages were carried out.

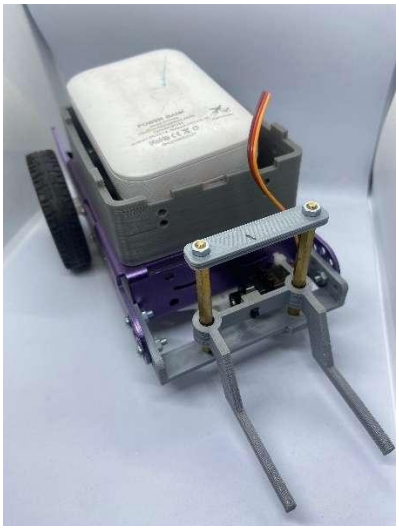


Figure 4. Educational Mobile-robot Hardware

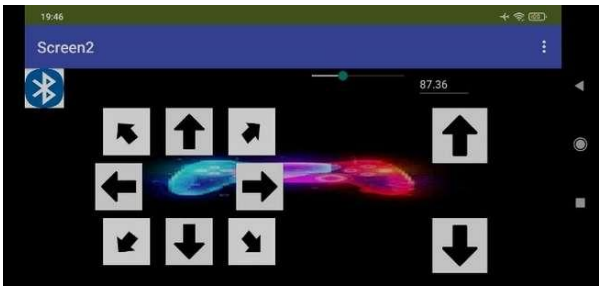


Figure 5. Educational Mobile-robot Mobile-App

3.1 Connectivity and Response Testing of ESP32

At this stage, testing focuses on the connectivity and response of the ESP32-based robot control system via the Firebase platform. The testing begins by ensuring that the ESP32 can consistently connect to Firebase, checking the stability of the connection under various network conditions. Additionally, response speed is evaluated by measuring the time taken from when a command is sent through the mobile app until the robot responds. This test is crucial to ensure that the system can react to user commands quickly and without significant delay, which is critical for real-time robot control.

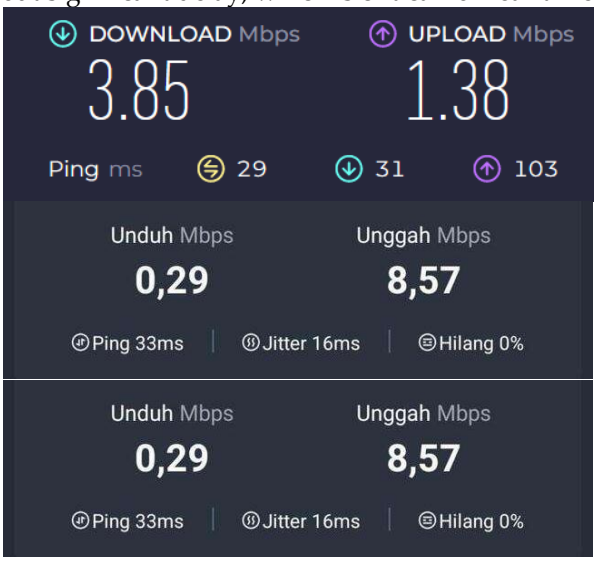


Figure 6. Speed test result for ESP32 connection

Table 1. Speedtest result

No	Blynk	ESP32 Response	Uptime (mS)
1	On	On	90
2	Off	Off	124
3	On	On	242
4	Off	Off	98
5	On	On	92
		Average Uptime	129,2

3.2 Basic Functionality Testing of the Robot

This testing involves evaluating the robot's ability to perform basic functions such as moving forward, backward, turning, and rotating in place. Each function is tested individually to ensure that the robot can execute commands accurately according to the inputs provided via the mobile application. The tests are conducted by sending commands to move forward or backward and observing whether the robot moves according to the instructions. Additionally, the robot's ability to turn left and right and rotate in place is tested, paying attention to the agility and precision in responding to these commands. The stop function is also tested to ensure that the robot can halt immediately when a stop command is given. Table 2 is an on-line robot control test.

Table 2. Speedtest result

No	Set Point (mL)	Result	Respons (mS)	Error (%)
1	Up	Success	200	0
2	Down	Success	300	0
3	Left	Success	200	0
4	Right	Success	200	0
5	Arm Up	Success	300	0
6	Arm Down	Success	400	0

3.3 System Reliability Testing

System reliability testing aims to ensure the stability and consistency of the robot's performance over extended operation. This includes load testing, where the robot is subjected to a series of sequential or simultaneous commands to test the system under intensive conditions. Furthermore, durability testing is conducted by operating the robot for extended periods to identify potential issues such as overheating or performance degradation. The security of the connection is also tested to ensure that data transmitted via Firebase is protected from unauthorized access. The results of these tests provide insights into the system's readiness for real-world applications, ensuring that the robot can operate reliably and safely under various conditions. Figure 7 is a robot trajectory simulation based on several speed references provided. The trajectory simulation illustrates how varying speed references affect the robot's ability to follow commands with precision. It mimics real-time student control input and system robustness under different signal delay conditions, reflecting both the learning curve of students and the system’s resilience.

To assess learning outcomes, a small trial was conducted with a group of school students. 90% of students reported high engagement and satisfaction during the robot control activity via the mobile app. Compared to similar educational robots such as mBot and Arduino-based kits, this system stands out due to its online control capability using Firebase, which is more scalable for remote learning. The use of differential drive also allows students to experience industrial-style maneuvering, which is often absent in simple wheeled robot kits.

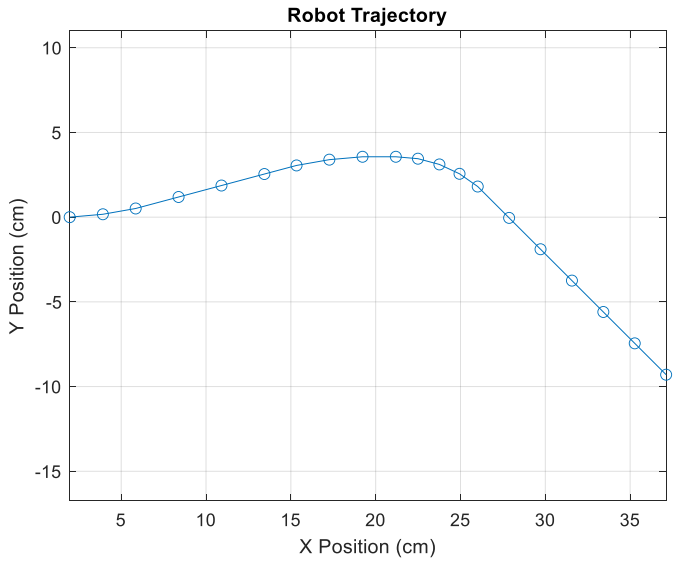


Figure 7. Trajectory robot

4. Conclusions

This study successfully designed and tested an educational mobile robot equipped with a differential drive system and a forklift-like arm, controlled remotely via an Android application and Firebase cloud database. The robot demonstrated high functionality and reliability during tests, proving to be an effective learning tool for elementary and secondary school students. The integration of IoT technology allows for remote interaction, expanding the learning environment beyond physical classrooms. The ability to control the robot both online and offline offers flexibility in various educational settings, making it suitable for remote learning scenarios, such as during a pandemic.

The use of Firebase for real-time control ensures seamless communication between the robot and the control application, providing students with a practical understanding of cloud-based control systems. Additionally, the implementation of a grid-based learning arena encourages strategic thinking and problem-solving, further enhancing the educational experience. The differential drive system, combined with an intuitive mobile application, delivers an accessible and interactive approach to robotics education, effectively building foundational STEM skills in students.

Preliminary results from small-scale implementation showed improved student understanding and enthusiasm for robotics. Future iterations should incorporate broader testing, more complex tasks, and integration with classroom learning goals. Moving forward, further developments could include expanding the robot's capabilities to accommodate more complex tasks, implementing AI-based path planning for autonomous navigation, improving its user interface, and exploring additional control methods to enhance the learning experience.

Supplementary Materials: -

Author Contributions: "Conceptualization, 1st. and 2nd; methodology, 3rd; software, 4th; validation, 3rd and 6th; formal analysis, 5th; investigation, 4th; resources, 7th; data curation, 8th; writing—original draft preparation, 3rd; writing—review and editing, 4th; visualization, 7th; supervision, 5th; project administration, 2nd; funding acquisition, 1st"

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