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Article

Teleoperation of Mecanum Wheels Robot Actuation Integrated with MQTT as an Interactive STEM Learning Tool

Ardianto Syaifur Rohman [1], Tunjung Genarsih [2*], Sihmaulana Dwianto [3], Nuzula Afianah [4], Salsabila Liandra Putri [5], Ahmad Rofi'i [6], Fendik Eko Purnomo [7], Syamsiar Kautsar [8], Mochamad Irwan Nari [9], Nurul Zainal Fanani [10], Angga Dwinanda[11]

[1] Engineering Departement; Politeknik Negeri Jember; ardianto.sr@polije.ac.id
[2] Engineering Departement; Politeknik Negeri Jember; tunjung.genarsih@polije.ac.id
[3] Engineering Departement; Politeknik Negeri Jember; sihmaulana@polije.ac.id
[4] Engineering Departement; Politeknik Negeri Jember; nuzula.afianah@polije.ac.id
[5] Engineering Departement; Politeknik Negeri Jember; salsabila.liandra@polije.ac.id
[6] Engineering Departement; Politeknik Negeri Jember; rofii@polije.ac.id
[7] Engineering Departement; Politeknik Negeri Jember; fendik_eko@polije.ac.id
[8] Engineering Departement; Politeknik Negeri Jember; syamsiar_kautsar@polije.ac.id
[9] Engineering Departement; Politeknik Negeri Jember; m.irwan.nari@polije.ac.id
[10] Engineering Departement; Politeknik Negeri Jember; zainal_fanani@polije.ac.id
[11] Engineering Departement; Politeknik Negeri Jember; angga.dwinanda@polije.ac.id

* Correspondence: tunjung.genarsih@polije.ac.id

Abstract: This research presents the development of a teleoperation system for a mecanum wheel robot actuation integrated with the MQTT (Message Queuing Telemetry Transport) protocol to be used as an interactive STEM (Science, Technology, Engineering, and Mathematics) learning tool. The system employs four independently actuated mecanum wheels enabling omnidirectional mobility through coordinated wheel control. The teleoperation architecture utilizes a Raspberry Pi 3B+ connected to HiveMQ Cloud broker implementing MQTT protocol for real-time remote actuation via Flutter-based mobile interface. Each wheel actuation is controlled through L298N motor drivers operating at 300Hz PWM (Pulse Width Modulation) frequency, providing precise speed and directional control. Experimental results demonstrate system reliability with an average position deviation of 1.86 cm for forward actuation, 1.93 cm for backward, 2.64 cm for left slide, and 1.71 cm for right slide movements across 140 cm distance. The MQTT integration achieves a command execution latency of 200-400ms, suitable for educational teleoperation applications. The Flutter interface provides intuitive control with real-time visualization of wheel actuation states, enhancing user understanding of mecanum wheel kinematics. This implementation successfully demonstrates the effective use of teleoperation of a mecanum wheel robot actuation as platform for interactive STEM education, providing hands-on experience in robotics actuation, IoT protocols, control systems, and mobile application development.

Keywords: Mecanum wheels robot, Teleoperation, MQTT, STEM, IoT.

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1. Introduction

In the past decade, robotics technology has advanced rapidly, leading to significant improvements in teleoperation and inter-device communication capabilities [1-3]. This technology has made a significant impact in industrial applications and has also created substantial opportunities in education, particularly as a medium for STEM (Science, Technology, Engineering, and Mathematics) learning [4,5]. In the context of modern education, STEM learning has become a primary focus in preparing a generation capable of facing technological challenges in the future [6]. Traditional learning approaches that are theoretical in nature are often less effective in providing a deep understanding of complex concepts in science and technology. Therefore,

innovation in learning methods that can provide direct and interactive experiences for students is necessary.

Mecanum wheel robot systems represent one of the robotics platforms that is interesting to develop as a learning medium [7]. The unique feature of mecanum wheel robot systems that allows omnidirectional movement provides appropriate complexity for understanding kinematics, dynamics, control systems, and data communication concepts in an integrated manner [8, 9].

The use of robotics in education has shown an increasingly upward trend in recent years [10-13] Recent meta-analysis research conducted by [14] demonstrates that the implementation of robotics in STEM learning can significantly improve student performance and learning attitudes. This comprehensive study analyzes various research findings and provides empirical evidence of the effectiveness of robotics in education. Most robot applications in education are directed toward enhancing STEM capabilities across various school levels [15-17]. Globally, educational institutions are increasingly integrating robotic technology into their curricula [18]. Recent research [19] indicates that the field of educational robotics is advancing rapidly through diverse and innovative implementation strategies. Despite this progress, significant challenges persist, particularly regarding system complexity and the demand for platforms that are more user-friendly and accessible to both teachers and students.

Mecanum wheels, first developed by Bengt Ilon in 1973, represent an innovation in robot mobility systems that enables omnidirectional movement [20]. This system consists of four wheels, each equipped with rollers positioned at a 45° angle to the wheel axis. This unique configuration allows robots to move in all directions without requiring prior rotation. Recent research [21] indicates that mecanum wheels robots possess enhanced maneuverability, enabling omnidirectional movement, including forward, backward, lateral, diagonal, and axial rotation.

Furthermore, study [22]shows that mecanum robots can serve as excellent platforms for learning control algorithms. Their dynamic characteristics require sophisticated control strategies for optimal performance. Research by [7,23] also highlights their educational value. The control complexity offers students practical opportunities to understand control theory through direct experimentation.

MQTT (Message Queuing Telemetry Transport) is a communication protocol developed specifically for Internet of Things (IoT) applications that require low bandwidth and high reliability. This protocol uses a publish-subscribe architecture to enable efficient, asynchronous communication between multiple devices with minimal overhead. Its main benefits are low latency, high reliability, and minimal network resource usage, making it well-suited for real-time teleoperation systems. Recent research by [24]highlights these advantages, demonstrating MQTT's effectiveness in Virtual Reality-based industrial robot teleoperation systems.

Research published by [25] demonstrates that MQTT offers advantages such as simplicity, a small memory footprint, scalability, and an effective publisher-subscriber communication model, which make it suitable for resource-constrained devices. These characteristics facilitate the implementation of MQTT in educational environments with infrastructure limitations. Additionally, MQTT's lightweight nature allows this protocol to run on various platforms, from microcontrollers to cloud servers. Research by [26]shows that MQTT can be used efficiently with common publish-subscribe mechanisms for multiple entities in a system to interact with connected objects, robotic arms, or mobile robots. This research reveals the possibility of multimodal MQTT interactions in collaborative robot-human systems, proving that the MQTT architecture is highly suitable for learning applications as it allows multiple users to interact with the system simultaneously without interference.

Teleoperation, or remote operation, is a technology that allows operators to control robotic systems remotely through communication interfaces [27]. In the educational context, this technology opens possibilities for learning that are not limited by physical

proximity or geographical constraints. Research by [27] states that teleoperation in education not only provides practical skills but also develops systems thinking and understanding of human-machine interaction. This is highly relevant in the industry 4.0 era, where the ability to interact with automated systems becomes increasingly important.

In recent years, STEM has become a primary focus in global education systems due to its critical role in preparing the workforce for the digital era. Recent meta-analysis by [15] shows that active learning methods in STEM can significantly improve student performance and reduce failure rates, especially when integrated with robotics technology.

Interactive learning in STEM involves hands-on activities, problem-based learning, and real-world applications that allow students to directly experience the concepts being learned [28-32]. A systematic review by [33] demonstrates that interactive learning environments can significantly improve retention and understanding compared to passive learning methods. Robotics, which combines all STEM domains, provides an ideal platform for interactive learning. Robotics in education can integrate theoretical knowledge with practical applications, providing a comprehensive understanding of engineering principles [18]. A Mecanum wheels robot with teleoperation capabilities adds a new dimension to interactive learning by enabling remote experimentation and collaborative learning. Research by [34] emphasizes that interactive STEM learning tools must have several key characteristics: accessibility, scalability, real-time feedback, and the ability to demonstrate complex concepts visually and tangibly. Mecanum wheels robot teleoperation systems with MQTT integration meet all these criteria, making the Mecanum wheels robot a powerful tool for STEM education.

Despite having great potential, the implementation of robotics in education still faces various challenges. Recent research identifies several main barriers: high initial costs [35], technical complexity, lack of teacher training [36, 37], and students' own digital competence [38]. Therefore, teleoperation systems using the MQTT protocol offer a potential alternative approach, as they can be implemented with relatively low costs and minimal maintenance.

This research aims to develop and evaluate a mecanum robot teleoperation system integrated with the MQTT protocol as an interactive STEM learning tool. Expected contributions include: (1) development of a cost-effective and scalable educational robotics platform, (2) demonstration of MQTT effectiveness in educational teleoperation applications, (3) evaluation of learning outcomes from mecanum robot-based STEM education, and (4) a framework for implementing similar systems in various educational contexts.

This research has several significant aspects that contribute to advances in educational technology and STEM pedagogy. The research results can be directly applied in educational institutions to enhance STEM learning experiences. The developed platform can serve as a model for similar implementations across various educational levels.

2. Materials and Methods

2.1 System Architecture for Teleoperation

The teleoperation system architecture uses a three-tier design: the user interface layer, MQTT communication middleware, and mecanum wheels robot actuation layer. First, the user provides instructions via the app. These are then transmitted to the MQTT Broker HiveMQ Cloud, which acts as a bridge between the mobile application and the microcontroller in the robot. Through this setup, the MQTT Broker HiveMQ Cloud enables real-time data transfer, creating seamless and prompt exchanges between the mobile device and the robot, even at a distance.

The Raspberry Pi 3B+, connected to the HiveMQ cloud MQTT Broker, receives processed control information. Its Wi-Fi capability allows the robot to access the internet and retrieve commands from the HiveMQ cloud MQTT Broker. Upon receiving these commands, the Raspberry Pi 3B+ processes the data and transmits it to the L298N motor driver. The L298N driver module controls two DC motors: one connected to the front left and rear left Mecanum wheels, and the other to the front right and rear right Mecanum wheels. By adjusting the duty cycle of the PWM signals sent to the motor controller, the Raspberry Pi 3B+ precisely regulates the speed and orientation of each motor. This system architecture provides an integrated solution for robot control by combining mobile technology, cloud computing, and motor control into a unified framework [9]. Figure 1 presents the complete teleoperation mecanum wheels robot system architecture.

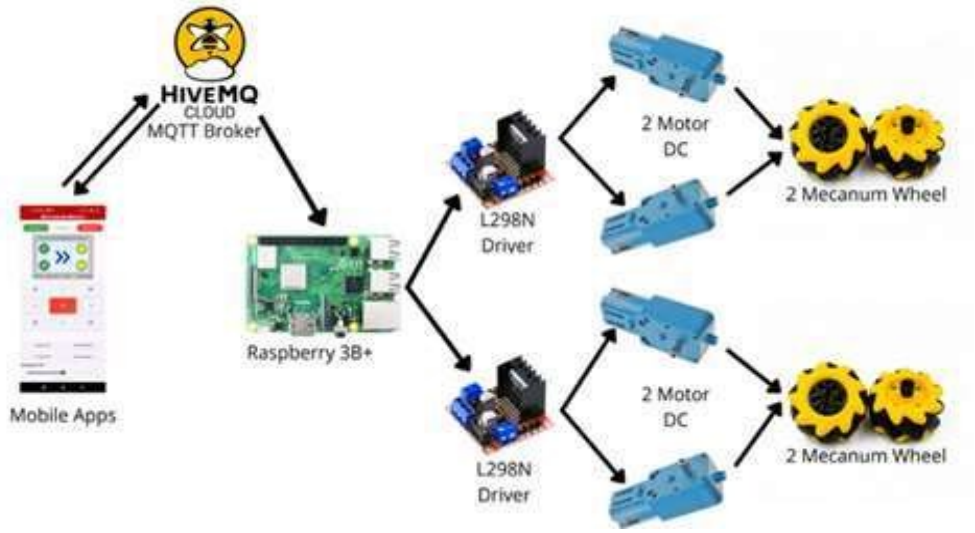


Figure 1. Teleoperation Mecanum wheels robot System Architecture

2.2 Mecanum Wheel Actuation Mechanics

The mecanum wheel actuation system employs four wheels with angled rollers, enabling omnidirectional movement through coordinated wheel speed control. This capability is achieved by uniquely arranging the rollers at 45° angles on each wheel, allowing the mecanum wheels robot to move in any direction.



Figure 2. Free Body of Mobile Robot with Mecanum Wheels

Figure 2 illustrates a mecanum wheeled mobile robot configuration featuring a coordinate framework positioned at the wheel hubs central point, with unit axes represented by ($\boldsymbol{Xw}, \boldsymbol{Yw}$). The robot's spatial configuration is characterized by its position coordinates $\boldsymbol{xr}$, $\boldsymbol{yr}$ and its rotational orientation $\boldsymbol{\theta r}$. The robot's translational velocity

components are expressed as $(\boldsymbol{vxr}, \boldsymbol{vyr})$, while $\boldsymbol{\omega r}$ represents its rotational velocity. For each wheel $\boldsymbol{i}$, the rotational speed is denoted by $\boldsymbol{\omega mi}$, and the corresponding tangential velocity at the wheel's contact point is represented by $\boldsymbol{vmi}$.

The orientation of the passive roller axis relative to the wheel hubs rotational axis is characterized by an angular offset of either $+\mathbf{45}°$ or $-\mathbf{45}°$, which is determined by the wheel's placement on the left or right side of the robot. Two distinct velocity vector components are identified: $\boldsymbol{vdriver}$, which corresponds to the tangential velocity generated by the wheel's rotation, and $\boldsymbol{vslider}$, which represents the velocity component along the freely rotating roller elements.

The kinematic relationship connecting the robot's central body velocities $(\boldsymbol{vxr}, \boldsymbol{vyr})$ with the driving velocity component $\boldsymbol{vdriver}$ and the sliding roller velocity component $\boldsymbol{vslider}$ can be expressed as follows:

$$\begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \end{bmatrix} = \boldsymbol{v_{driver}} \begin{bmatrix} \mathbf{1} \\ \mathbf{0} \end{bmatrix} + \boldsymbol{v_{slider}} \begin{bmatrix} -\boldsymbol{\sin\gamma} \\ \boldsymbol{\cos\gamma} \end{bmatrix} \tag{1}$$

The kinematic correlation linking the rotational speed ωm of the wheel to its driving velocity component $vdriver$ is established through the following expression:

$$\boldsymbol{v_{driver}} = \omega_m X r_m \tag{2}$$

By integrating equations (1) and (2), a more condensed representation for the $\boldsymbol{i_{th}}$ wheel can be derived as follows:

$$\begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \end{bmatrix} = \begin{bmatrix} r_i & -\boldsymbol{\sin\gamma} \\ 0 & \boldsymbol{\cos\gamma} \end{bmatrix} \begin{bmatrix} \omega_{ir} \\ v_{ir} \end{bmatrix} = \begin{matrix} \omega i \\ pi \end{matrix} T \begin{bmatrix} \omega_{ir} \\ v_{ir} \end{bmatrix} \tag{3}$$

The coordinate transformation matrix that converts from the wheel reference frame to the mobile robot reference frame is expressed as:

$$\begin{matrix} R \\ pi \end{matrix} T = \begin{bmatrix} cos\ (\theta_r) & sin\ (\theta_r) \\ -sin\ (\theta_r) & cos\ (\theta_r) \end{bmatrix} \tag{4}$$

Meanwhile, the linear velocity components of the mobile robot derived from individual wheel velocities can be expressed as:

$$\begin{bmatrix} \boldsymbol{v_{ixr}} \\ \boldsymbol{v_{iyr}} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -a_i \\ 0 & \mathbf{1} & b_i \end{bmatrix} = \begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} = T \begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} \tag{5}$$

By combining equations (3), (4), and (5), the following relationship is obtained:

$$\begin{bmatrix} \boldsymbol{\omega_{mi}} \\ \boldsymbol{v_{mi}} \end{bmatrix} = \begin{bmatrix} \frac{1}{r_{mi}} & \frac{tan\,\gamma}{r_{mi}} & \frac{-a_i + b_i tan\gamma}{r_m i} \\ 0 & \frac{1}{cos\gamma} & \frac{b_i}{cos\gamma} \end{bmatrix} \begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} \tag{6}$$

Under the assumption of no-slip conditions between the wheels and the ground surface, the independent variables vmi and ωmi become interconnected. The first row extracted from equation (6) is utilized to construct the Jacobian matrix for the inverse kinematic transformation, which maps the mobile robot's task-space velocity to its joint-space velocity as shown below:

$$\begin{bmatrix} \boldsymbol{\omega_{m1}} \\ \boldsymbol{\omega_{m2}} \\ \boldsymbol{\omega_{m3}} \\ \boldsymbol{\omega_{m4}} \end{bmatrix} = \begin{bmatrix} \frac{1}{r_{mi}} & \frac{tan\,\gamma_i}{r_{mi}} & \frac{-a_i + b_i tan\gamma}{r_m i} \\ \frac{1}{r_{mi}} & \frac{tan\,\gamma_i}{r_{mi}} & \frac{-a_i + b_i tan\gamma}{r_m i} \\ \frac{1}{r_{mi}} & \frac{tan\,\gamma_i}{r_{mi}} & \frac{-a_i + b_i tan\gamma}{r_m i} \\ \frac{1}{r_{mi}} & \frac{tan\,\gamma_i}{r_{mi}} & \frac{-a_i + b_i tan\gamma}{r_m i} \end{bmatrix} \begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} \tag{7}$$

For the wheel arrangement where $\gamma = -45°$ applies to wheels 1 and 4, and $\gamma = 45°$ applies to wheels 2 and 3, equation (7) transforms into:

$$\begin{bmatrix} \boldsymbol{\omega_{m1}} \\ \boldsymbol{\omega_{m2}} \\ \boldsymbol{\omega_{m3}} \\ \boldsymbol{\omega_{m4}} \end{bmatrix} = \begin{bmatrix} 1 & -1 & -a-b \\ 1 & 1 & a+b \\ 1 & -1 & a+b \\ 1 & 1 & -a-b \end{bmatrix} \begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} \tag{8}$$

Equation (8) establishes the kinematic relationship between individual wheel angular velocities and the overall velocity of the mobile platform. These velocity components enable the mobile robot to achieve omnidirectional motion. Figure 3 illustrates the directional movement patterns of the mobile robot corresponding to various mecanum wheel rotation configurations. The forward kinematic model is derived by computing the inverse of the matrix in equation (8) through the application of the left pseudo-inverse method:

$$\begin{bmatrix} \boldsymbol{v_{xr}} \\ \boldsymbol{v_{yr}} \\ \omega_r \end{bmatrix} = \frac{1}{4r_m} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ -\frac{1}{a+b} & \frac{1}{a+b} & \frac{1}{a+b} & -\frac{1}{a+b} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega_{m1}} \\ \boldsymbol{\omega_{m2}} \\ \boldsymbol{\omega_{m3}} \\ \boldsymbol{\omega_{m4}} \end{bmatrix} \tag{9}$$

The mecanum robot achieves omnidirectional movement through differential wheel actuation. By controlling the velocity and direction of each wheel independently, the robot can excute various movement patterns. Table 1 summarizes the actuation patterns for each movement type. The kinematic equations for the robot motion are the actuation equations for different movement patterns are:

Table 1. Mecanum Wheel Actuation Patterns

Movement Type	Front Left	Front Right	Rear Left	Rear Right
Forward	+V	+V	+V	+V
Backward	-V	-V	-V	-V
Left slide	-V	+V	+V	-V
Right slide	+V	-V	-V	+V
Rotate CW	+V	-V	+V	-V
Rotate CCW	-V	+V	-V	+V
Diagonal FL	0	+V	+V	0
Diagonal FR	+V	0	0	+V

Table 1 presents the actuation patterns for various types of motion. The symbol +V denotes forward wheel rotation, while –V represents reverse wheel rotation. By appropriately controlling the direction of each wheel, the robot can perform forward and backward translation, lateral (side) movement, diagonal movement, and rotation about its vertical axis.Where V represents the base velocity applied to each wheel actuator. These actuation patterns demonstrate how the independent control of each wheel's angular velocity allows the robot to achieve complex movements in both translation and rotation without changing its orientation.

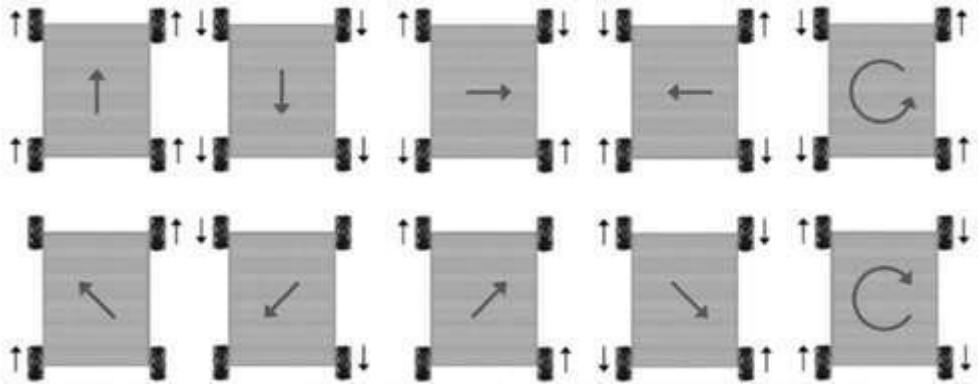


Figure 3. Direction of mobile robot motion based on mecanum various velocities each mecanum wheel

Figure 3 depicts the motion directions of a Mecanum-wheel mobile robot under different combinations of wheel rotational velocities. The orientation of each wheel's rollers generates motion vectors in both longitudinal and lateral directions, which facilitates omnidirectional movement. Uniform rotation of all four wheels at the same velocity and direction results in forward or backward movement. In contrast, rotating the wheels in opposite directions on each side produces lateral translation to the left or right. Diagonal movements are accomplished by applying specific velocity patterns to diagonal wheel pairs. rotation about the robot's center, either clockwise (CW) or counterclockwise (CCW), occurs when the left and right wheels rotate in opposite directions. In Figure 3, the arrows indicate the rotation direction of each wheel, and the central arrows show the resulting motion of the robot platform. This visualization illustrates that independent control of each wheel's angular velocity enables smooth and continuous movement in any planar direction without requiring a change in the robot's orientation.

2.3 Teleoperation Control Algorithm

The teleoperation control algorithm processes MQTT messages and translates them into actuation commands:

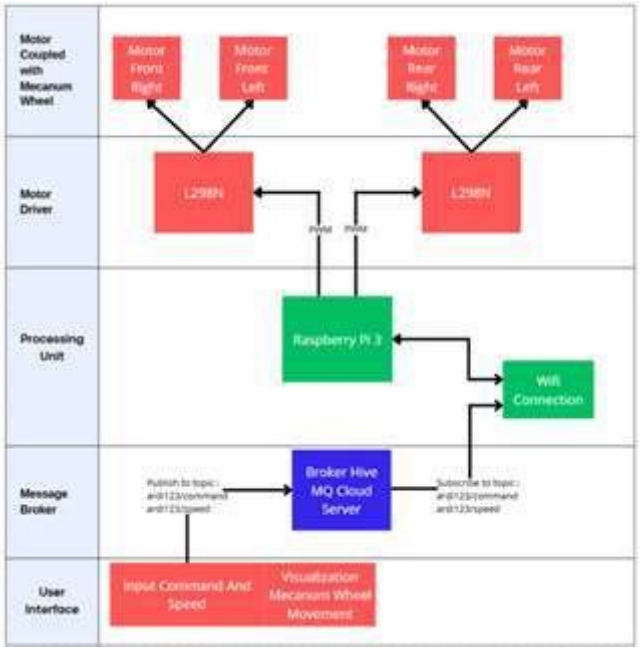


Figure 4. Block Diagram Mecanum wheels robot

Figure 4 presents a block diagram of the mecanum wheels robot teleoperation control algorithm that converts user intent into robotic motion. The algorithm operates across several layers, as shown in the diagram. The User Interface layer facilitates command input, speed adjustment, and visualization of mecanum wheel movement. Commands are sent to specific MQTT topics through the Message Broker layer, which employs a Broker Hive MQ Cloud Server as the communication hub. The Processing Unit layer, powered by a Raspberry Pi 3 B+, maintains a WiFi Connection and subscribes to the same MQTT topics to receive incoming commands. When a message arrives, the Raspberry Pi decodes the command and executes the corresponding motor control logic. The system then transmits the commands via PWM signals to the Motor Driver layer, which contains two L298N motor driver modules. These drivers convert the PWM signals into suitable voltage and current levels for the motors.

Testing was performed in a controlled grid environment with lines spaced 20 cm apart. Test distances included 20, 40, 60, 80, 100, 120, and 140 cm. For each distance and movement type, three trials were conducted. Deviation was defined as the perpendicular distance from the target line.

3. Results and Discussion

3.1 Teleoperation System Implementation

The teleoperation system was implemented as an integrated hardware-software platform, thereby validating the architectural design presented in Figure 1. In doing so, this implementation demonstrated seamless interoperability among all system tiers: the Flutter-based mobile application as the user interface layer, the HiveMQ Cloud as the message broker layer for MQTT communication middleware, and the processing unit layer comprising the Raspberry Pi 3B+ with motor drivers for robot actuation.

The system's robustness depended on the Raspberry Pi 3B+ maintaining a steady connection to the MQTT broker. In real-world educational settings with variable networks, the system showed strong resilience. After a simulated or real connection loss, the device averaged just 2.3 seconds to reconnect. This rapid recovery keeps learning sessions moving without major disruption from brief network issues. The Raspberry Pi converted incoming MQTT messages to GPIO commands for the L298N motor drivers, running smoothly at 300Hz frequency, ensuring precise voltage control for the four DC motors.

On the user interface front, the Flutter application proved to be a highly responsive and intuitive control hub. The application's performance, which updates the visual feedback at a consistent 60 frames per second (FPS), provides users with a fluid and real-time representation of the robot's state. This high refresh rate means that any command issued by the user is almost instantly reflected in the UI, creating a closed-loop feeling of direct control. The visual cues—such as the dynamic wheel state indicators—were instrumental in bridging the gap between the abstract command (e.g., a joystick input) and the physical actuation of the mecanum wheels. The successful implementation of this tier confirms that consumer-grade hardware and cloud services can be effectively leveraged to create a robust, low-latency teleoperation system suitable for demanding educational applications.

The implementation phase demonstrated that the system is functional, reliable, and user-friendly. Stable MQTT connection management and a high-performance mobile interface provide a robust foundation for the effective exploration of robotics and Internet of Things concepts, as further examined in the analysis of learning effectiveness and system performance.

3.2 Mecanum wheels robot Actuation Accuracy Analysis

Systematic evaluation of actuation accuracy was performed for four primary movement types across varying distances. Figure 5 and Table 2 present the deviation measurements based on forward, backwards, left slide, and right slide movement.

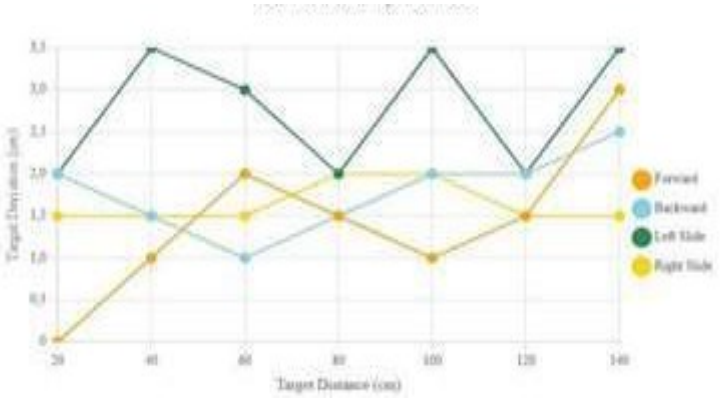


Figure 5. Visualisation Experimental Result for Robot Mobile Mecanum Wheel Movement

Figure 5 shows that straight movement has a relatively small deviation (0–3 cm). Deviations tend to be stable below 2 cm, except at a distance of 140 cm, where they increase to 3 cm. Backwards movement shows that stable drift in the range of 1–2.5 cm, indicating quite good control when moving backwards. Left slide movement has the largest deviation (2–3.5 cm). This shows that the left sliding movement is less stable than the right sliding movement. Right slide movement is the most consistent and has the smallest deviation (1.5–2 cm), indicating that it is more precise than the left slide.

Table 2. Teleoperation Actuation Deviation Results

Distance	Forward	Backward	Left Slide	Right Slide
20 *cm*	0 *cm*	2 *cm*	2 *cm*	1.5 *cm*
40 *cm*	1 *cm*	1.5 *cm*	3.5 *cm*	1.5 *cm*
60 *cm*	2 *cm*	1 *cm*	3 *cm*	1.5 *cm*
80 *cm*	1.5 *cm*	1.5 *cm*	2 *cm*	2 *cm*
100 *cm*	1 *cm*	2 *cm*	3.5 *cm*	2 *cm*
120 *cm*	1.5 *cm*	2 *cm*	2 *cm*	1.5 *cm*
140 *cm*	3 *cm*	2.5 *cm*	3.5 *cm*	1.5 *cm*
Average	1.43 *cm*	1.79 *cm*	2.79 *cm*	1.64 *cm*
Std Dev	0.87	0.49	0.73	0.23

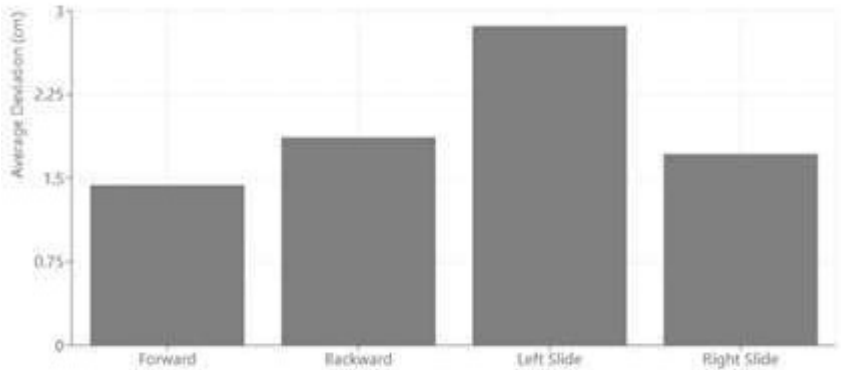


Figure 6. Visualisation Experimental Result for Average Deviation

Based on Table 2, Figures 5 and 6 indicate that the robot is more stable when moving straight and sliding to the right, whereas the left sliding movement exhibits the largest deviation. This could be due to differences in the distribution of mecanum wheel forces

3.3 MQTT Communication Performance

The analysis of the MQTT communication performance based on Table 3 reveals a highly reliable and responsive teleoperation system suitable for educational applications. The data presented in Table 3 indicates that the system achieved a perfect 100% success rate for all command types, including basic movements (Forward, Backward, Left slide, Right slide). This flawless delivery record underscores the robustness of the MQTT protocol, particularly when integrated with the HiveMQ Cloud broker, in maintaining a stable connection and ensuring that no actuation commands are lost in transit.

Table 3. MQTT Teleoperation Response Times

Command Type	Average Response (ms)	Min (ms)	Max (ms)	Success Rate (%)
Forward	200	90	300	100
Backward	300	124	400	100
Left Slide	200	92	242	100
Right Slide	200	98	250	100
Overall	225	90	400	100

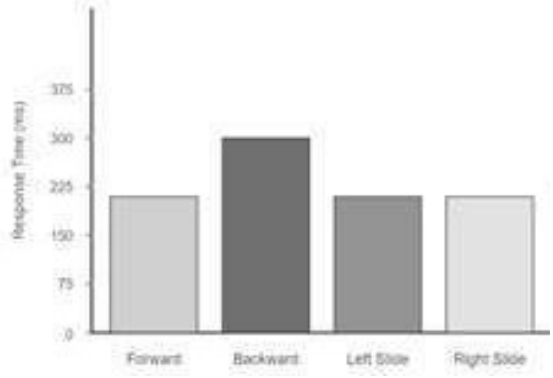


Figure 7. Visualisation Average Response Time by Command

In terms of latency, the system demonstrated performance that aligns well with the requirements for real-time teleoperation in a learning context. The average response time was 225 ms, a value typically imperceptible to human operators in non-industrial settings. Analysis of command-specific latencies indicates that most directional movements, including forward, left slide, and right slide, exhibited low average latencies of 200 ms, with minimum values below 100 ms. These results indicate that the system is highly responsive during the most common operations.

The backward commands exhibited slightly higher average latencies of 300 ms. This variation may result from processing delays in the Raspberry Pi during specific command sequences or from variability in public internet connectivity to the cloud broker. The maximum recorded latency of 400 ms for the backward command remains acceptable for the intended educational use, where the focus is on understanding robotic control concepts rather than achieving high-speed precision. The consistent performance, demonstrated by a narrow range between minimum and maximum values for core movements, supports the conclusion that the MQTT-based architecture offers a reliable communication backbone for the teleoperation system.

3.4 Teleoperation Learning Effectiveness

The teleoperation system was developed as a comprehensive pedagogical tool rather than solely as a functional robot. Its effectiveness in STEM education is evidenced by several key features, each supported by educational theory and prior research. The Real-time Feedback component utilizes a Flutter-based interface to provide immediate visual

representations of the mecanum wheel actuation states. This feature converts abstract control commands into observable visual outcomes, aligning with constructivist learning theory. For example, when a student initiates a left lateral movement, the interface displays which wheels rotate forward and which rotate backward, directly correlating user input with mechanical execution. Such instant feedback is essential for reinforcing the understanding of complex kinematic principles underlying omnidirectional movement and aids students in constructing accurate mental models of the system. As noted by [39], immediate visual feedback is vital in transdisciplinary STEM learning because it enables students to connect theoretical concepts with observable phenomena, thereby enhancing conceptual understanding.

Actuation Complexity from controlling a mecanum wheels robot is inherently more complex than controlling a standard differential drive robot. It requires students to grasp the concept of vector addition, where the individual force vectors from each wheel combine to produce a net movement in the desired direction. This pushes learners beyond simple joystick control and into the realm of coordinated systems and kinematics, offering a more advanced and enriching challenge. The work of [40] supports this, stating that omnidirectional robots like those with mecanum wheels provide exceptional learning value by physically demonstrating advanced concepts in kinematics and dynamics that are typically only covered theoretically. This complexity fosters critical thinking and problem-solving skills.

3.5 Mobile Application Development and Interface Design

The mobile app interface used several screen layouts for different control options and movement types. Figure 8 shows the whole interface, with each movement (forward, backward, left slide, right slide, turn clockwise, and turn counterclockwise) on its own control screen. This simple screen setup lets users focus on one movement at a time, while keeping the same interface pieces on every screen, including the status bar, wheel display, control buttons, and sliders for adjusting settings.

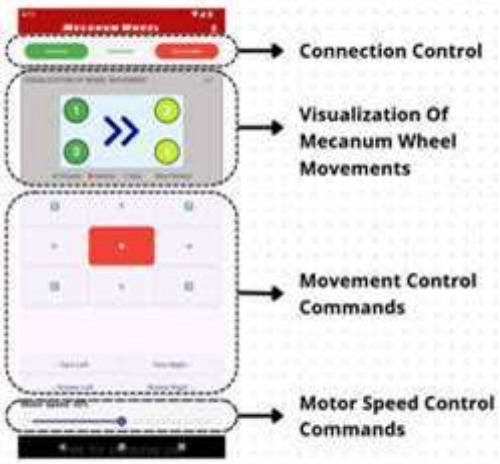


Figure 8. Interface Result for Robot Mobile Mecanum Wheel

The Flutter framework was successfully utilized to develop a cross-platform mobile application that serves as the primary user interface for the teleoperation system. The application was designed with a focus on usability and educational value, providing an intuitive gateway for students to interact with the robotic system. Key features implemented in the application, as shown in Figure 8, include real-time Connection Status Monitoring, which features a persistent connection status indicator that visually informs the user whether the application is successfully connected to the HiveMQ Cloud broker. This immediate feedback is crucial for troubleshooting and helps users understand the

state of the IoT communication link, preventing commands from being sent while the system is disconnected.

Visualization of the mecanum wheel movements is a central feature of the interface. It includes a dynamic, real-time graphical display of all four mecanum wheels, clearly showing each wheel's current state, such as spinning forward, spinning backward, or stopped, in direct response to movement commands. This makes the complex kinematics of mecanum wheel actuation easier for students to grasp by providing a concrete, visual understanding. Directional Control with Icon Indicators is another core feature. The interface offers a full set of directional control buttons, each labeled with concise text and intuitive icons. These controls encompass all possible movement directions, including forward, backward, lateral sliding, diagonal paths, and on-the-spot rotations. Clear labeling and logical arrangement enable users to quickly learn and utilize the robot's full range of motion.

Precise Speed Control Adjustment Slider is a slider input that allows for continuous adjustment of the robot's speed, corresponding to a 0-100% duty cycle of the PWM signals sent to the motor drivers. This feature enables users to perform precision maneuvers and understand the relationship between software control parameters (duty cycle) and physical actuation outcomes (wheel velocity). Connection Management is dedicated to connecting and disconnecting buttons, giving users full control over the MQTT session. This managed connection lifecycle ensures efficient resource utilization on both the mobile device and the cloud broker, reinforcing the concept of establishing a network session before data exchange can occur.

The implementation of this Flutter application successfully creates an engaging and educational control interface. Its intuitive design lowers the barrier to entry for students, allowing them to focus on understanding robotic actuation and IoT communication without being hindered by a complex interface. The combination of real-time visual feedback and precise control options makes it an effective centerpiece for the interactive STEM learning experience.

4. Conclusions

This research successfully demonstrates the development and implementation of a teleoperation system for mecanum wheels robot actuation. The system integrates the MQTT protocol as an effective interactive STEM learning tool. The system reliably actuates remotely with average position deviations ranging from 1.43 to 2.79 cm across different movement types, which is sufficient for educational applications. Integrating the MQTT protocol provides robust communication, achieving a 100% success rate in delivering command and acceptable latency of an average 225 ms for real-time teleoperation.

The Flutter interface provides intuitive control and real-time visualization of wheel actuation states, enhancing user understanding of mecanum wheels robot kinematics. This platform bridges theoretical and practical learning, enabling hands-on exploration of robotics, control systems, and IoT communication principles.

Future work will focus on implementing closed-loop control with an inertia measurement unit sensor (IMU) feedback to improve actuation accuracy and movement, as well as conducting broader field studies to assess learning outcomes across diverse student populations.

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Tunjung Genarsih, Sihmaulana Dwianto, Nuzula Afianah, Salsabila Liandra Putri. Resources: Salsabila Liandra Putri. Data Curation: Ardianto Syaifur Rohman, Tunjung Genarsih, Nuzula Afianah, Mochamad Irwan Nari, Ahmad Rofi;I, Fendik Eko Purnomo, Syamsiar Kautsar. Writing: Ardianto Syaifur Rohman, Tunjung Genarsih, Sihmaulana Dwianto. Visualization: Sihmaulana Dwianto. Supervision: Tunjung Genarsih, Nurul Zainal Fanani, Mochamad Irwan Nari, Fendik Eko Purnomo. Project Administration: Ardianto Syaifur Rohman, Nuzula Afianah, Salsabila Liandra Putri.

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