strategies are unable to compensate for these disturbances,

Kinematic Motion Control Analysis Of 3 Wheels Service Robot Based-on PID Control

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Abstract—Three wheeled omnidirectional moile robot require stable mottion control to accurately reach target coordinates due to their holonomic characteristics, wich are sensitive to wheel slip and load imbalance. This study presents a kinematic based on motion control approach realized indirectly through wheel velocity regulation using a Proportional Integral Derivative (PID) controller. Target position and orientation inputs are converted into linear and angular velocity references using inverse kinematics, which are then transformed into wheel speed setpoints. PID controllers operate at the motor level to regulate wheel velocities based on encoder feedback, ensuring synchronized motion among all wheels. Position and orientation accuracy are evaluated using odometry rather than direct position control. Experimental results show that the proposed method significantly improves motion stability and trajectory consistency compared to open-loop control, with reduced oscillation and controlled positional deviation during translational and rotational movements.

Keywords: Kinematics, Omnidirectional Robot, PID Control, Motion Control, Velocity Regulation.

I. INTRODUCTION

Advances in mobile robot have significantly increase the demand for robots capable of perfoming flexible and precise motion in constrained enviroiments [1]. Omnidirectional mobile robots are widely used to their ability to move in any planar direction without changing their physical orientation [2]. Making them suitable for indoor service applications, logistics, and autonoums navigation systems. Among various configuration, three wheeled omnidirectional robots offer a compact holonomic structure that allows simultaneous translational and rotational motion [3].

Despite these advantages, maintaining positional stability and trajectory accuracy remains a major challenge for three-wheeled omnidirectional robots [4]. During practical operation, the robot is affected by uneven load distribution, inertial forces during acceleration or deceleration, and wheel slippage, which can cause deviations from the desired path [5], [6]. Several studies report that conventional static or open-loop control resulting in reduced navigation accuracy and unstable motion behavior [7], [8]. Kinematic analysis is a fundamental of component in the motion control of omnidirectional robots. By applying inverse kinematic modeling, the relationship between individual wheel velocities and the robot's linear and angular motion in the Cartesian coordinate frame can be mathematically defined [9], [10]. This approach enables accurate computation of wheel speed commands required to achieve a specified robot motion. Experimental studies have shown that precise kinematic modeling improves odometry accuracy and motion consistency in three-wheeled omnidirectional platforms [11], [12]. However, kinematic modeling alone is insufficient to ensure stable navigation under dynamic conditions. Feedback control is required to reduce velocity and position errors caused by modeling inaccuracies and external disturbances [13]. Proportional Integral Derivative (PID) control is one of the most commonly used methods due to its simple structure and reliable performance in real-time applications [14], [15]. Previous works demonstrate that PID control can effectively improve trajectory tracking and motion stability in omnidirectional robots [16], [17]. Furthermore, several studies have proposed optimized and adaptive PID schemes to enhance robustness against wheel slip and parameter variations [18], [19]. Recent developments in embedded systems have also contributed to the practical implementation of closed-loop control in mobile robots [20].

The integration of microcontrollers such as ESP32 with encoder feedback, IMU sensors, and real-time communication mechanisms enables continuous monitoring and control of robot motion [21], [22]. These systems allow real-time correction of motion errors and support stable autonomous navigation in indoor environments [23], [24]. Based on these considerations, this research focuses on the design and implementation of a kinematic-based control system integrated with PID compensation for a three-wheeled omnidirectional mobile robot. The proposed system enables automatic Go-To-Goal navigation while maintaining trajectory consistency and positional stability. The results of this study are expected to contribute to the development of more stable and accurate omnidirectional robots for practical applications [25].

II. METHOD

This section describes the methodology used to design and implement the proposed motion control system for a three-wheeled omnidirectional robot. The method is includes system for the architecture design kinatic, modeling, and the implementaion of a PID-based control strategy to regulate wheel velocities as part of the motion execution process. Desired robot movement commands are defined in terms of translational and rotational motion, which are then transformed into wheel velocity references using kinematic relationships. The regulation of wheel velocities is employed to ensure coordinated wheel motion so that the robot can move smoothly toward the intended direction and trajectory. Rather than focusing on speed control as the final objective, wheel velocity regulation serves as an intermediate mechanism to realize stable robot movement. Odometry is used to estimate the resulting position and orientation of the robot in order to evaluate motion stability and trajectory consistency during experimental testing.

A. *Implementation*

Based on figure 1 describe illustrates the diagram illustrates how the robot interconnected system works to ensure accurate movement. Here a simple explanation the process begins when we input the desired target location and angle, known as the reference input. Once the robot begins moving, the encoder sensor, or transducer, continuously monitors the robot actual position on the ground and sends a report back to the robot's brain.

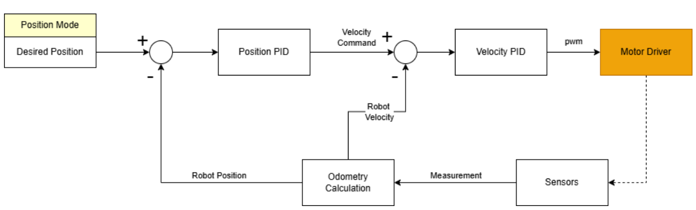

Figure 1. PID Diagram

This is where the PID comes in it calculates the difference, or error, between our desired position and the robot's actual position. If there is a difference, the PID will command the actuator (motor) to automatically increase or decrease speed through kinematic calculations to prevent the robot from deviating. The end result is precise and stable robot movement, consistent with the figures in the test table. Automatic correction system. The most important part is the feedback Signal line from the sensor. This explains that every time the wheel rotates, the sensor immediately reports to the robot brain to determine whether the robot is in the correct position or still deviating. The main role of the PID acts as a decision maker. If the robot is detected as being too slow or encountering an obstacle on the floor, the PID will command the motor to rotate more strongly to maintain the target coordinates in your table. Wheel task distribution, in the process section, the program divides the motion command into three parts for each omnidirectional wheel. This is why your robot can move diagonally while still rotating its body (θ) smoothly. Measurable results the technical processes in this diagram culminate in the Output value, which is the actual numbers you recorded. The small difference (error) between the target and the actual results proves that the control flow in this diagram works very well in practice.

B. *Kinematic Model of 3-Wheeled Robot*

In this section the figure 2 is Kinematic modeling is used to describe the relationship between the robot's translational and rotational motion and the angular velocities of each wheel. In this research, the robot employs three omnidirectional wheels arranged symmetrically with an angular separation of 120°, allowing holonomic motion in the planar workspace. The kinematic model serves as a motion mapping mechanism that converts desired robot velocities into corresponding wheel velocity references.

The robot motion is defined in the local coordinate frame using linear velocities along the x-axis (Vx), y-axis (Vx), and angular velocity around the vertical axis (ω). These velocity components represent the desired motion behavior of the robot and are generated by the navigation module. Through inverse kinematics, the velocity vector (Vx, Vy, ω). is transformed into angular velocity references for each wheel.

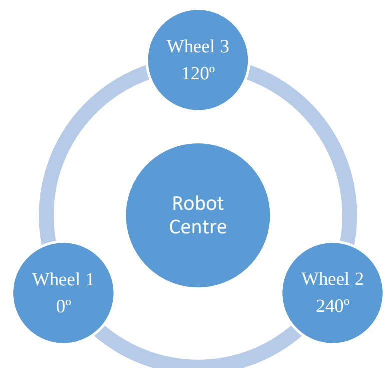

Figure 2. Geometry Diagram Robot

$$\begin{bmatrix}\omega 1\\ \omega 2\\ \omega 3\end{bmatrix} = \frac{1}{R}\begin{bmatrix}-sin(\theta 1) & cos(\theta 1) & L\\ -sin(\theta 2) & \cos(\theta 2) & L\\ -sin(\theta 3) & cos(\theta 3) & L\end{bmatrix}\begin{bmatrix}Vx\\ Vy\\ \theta\end{bmatrix} \quad (1)$$

R Omni wheel spokes. L Distance from the center of the robot to the center of the wheel. θ The angle of each wheel position (0°, 120°, 240°).

$$\omega 1 = \frac{1}{R}(0.Vx + 1.Vy + L.\theta) \quad (2)$$

$$\omega 2 = \frac{1}{R}\left(-\frac{\sqrt{3}}{2}Vx - \frac{\sqrt{3}}{2}V + L.\theta\right) \quad (3)$$

$$\omega 3 = \frac{1}{R}\left(-\frac{\sqrt{3}}{2}Vx - \frac{1}{2}Vy + L.\theta\right) \quad (4)$$

It is important to note that this kinematic formulation generates wheel velocity references rather than direct position commands. The role of the kinematic model in this system is to ensure consistent distribution of velocity commands to each wheel so that the desired robot motion can be achieved. In addition to inverse kinematics, forward kinematics is applied to estimate the robot's actual motion based on encoder feedback. By converting measured wheel angular velocities into linear and angular motion components, the robot's position and orientation are estimated through odometry. This estimation is used solely for motion evaluation and performance analysis, and not as a feedback signal for position control.

C. PID-Based Wheel Velocity Control

The Proportional Integral Derivative (PID) controller is implemented to regulate the angular velocity of each wheel independently. The primary objective of the PID controller in this system is to ensure accurate tracking of wheel velocity references generated by the inverse kinematic model. By maintaining consistent wheel speeds, the robot is able to execute stable translational and rotational motion in accordance with the desired motion commands.

Each wheel is equipped with an incremental encoder that provides real-time measurements of the actual wheel angular velocity. The velocity error for the PID controller is defined as the difference between the reference wheel speed and the measured wheel speed, expressed as

$$ei(t) = \omega i, ref(t) - \omega i, act(t), \quad (5)$$

where $\omega i, ref(t)$ represents the reference angular velocity of the i-th wheel obtained from inverse kinematics, and $\omega i, act(t)$ denotes the actual angular velocity measured by the encoder. This error formulation confirms that the PID controller operates exclusively in the velocity domain and does not involve position or orientation errors. The PID control law for each wheel is given by

$$u(t) = Kp\, e(t) + Ki \int e(t)\, dt + Kd \frac{de(t)}{dt} \quad (6)$$

Kp, Ki, and Kd are the proportional, integral, and derivative gains, respectively. The proportional term provides immediate response to velocity error, the integral term eliminates steady state error caused by friction or load variation, and the derivative term improves transient response by damping rapid changes in error. The PID parameters are tuned experimentally to achieve a fast response with minimal overshoot and oscillation. Since the PID controllers are applied independently to each wheel, synchronization of wheel velocities is achieved through accurate reference generation by the kinematic model rather than through direct coupling between controllers. This decentralized control structure simplifies implementation while maintaining reliable motion performance.

D. PID Parameter Tuning

This section describes the PID controller parameters were determined experimentally using a trial-and error tuning approach to achieve stable wheel velocity tracking with minimal overshoot and oscillation. The tuning process was conducted by adjusting the proportional, integral, and derivative gains while observing the transient response and stead state behavior of each wheel based on encoder feedback. Based on the tuning results, the PID gains were set to Kp = 0.25**,** Ki = 0.01**,** and Kp = 0.05. The same set of PID parameters was applied to all three wheels (front-left, rear, and front-right) to ensure uniform dynamic characteristics and simplify the control implementation. These values provided a good balance between response speed, stability, and robustness against load variations during robot motion. Testing was conducted on several movement scenarios, including sudden speed changes and straight lines, to ensure the selected parameters remained consistent and reliable under various operating conditions.

E. Experimental Setup

This section describes the hardware configuration and scenario design used to evaluate the performance of the robot's control system. The figure 4 and table 1 to describe the phsically and specification of robot 3 omni wheelss. The main drive unit utilizes three DC motors integrated with AB-phase encoders for precise angular position reading.

All logic processing, from wireless communication via WiFi to PID algorithm calculations, is centralized on an ESP32 microcontroller. The L298N module is used for the motor driver, capable of handling the motor's current requirements stably. Testing was conducted on a flat floor surface with a large working area to ensure the robot's freedom of movement. The evaluation scenario involved moving the robot from a zero point to several specific target coordinates, to test translation and rotation accuracy,and to calculate the error value between the input and actual values of the robot's movement, but still strives to ensure that the error value is not too far from target.

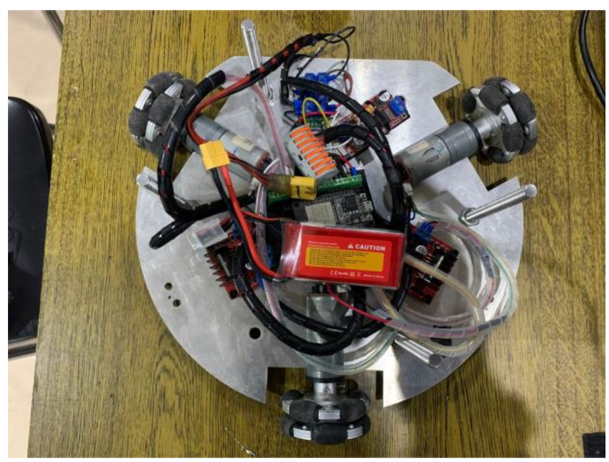

Figure 4. Robot 3 Omni Wheels

Table 1. Specifications

No	Category	Componen	Detail Spesification
1.	Control System	Microcontroller	ESP32
		Communication Protocol	WebSocket via WiFi (2.4 GHz)
2.	Actuator	Motor	3x DC Motor High Torque
		Driver Motor	L298N Dual H-Bridge Module
3.	Sensor	Speed Feedback	Hall-Effect Magnetic Encoder
		Encoder Resolution	11 Pulse Per Revolution (PPR)
	Mechanic	Wheel Type	Omnidirectional Wheel

4.			(3 units)
		Wheel Configuration	Symmetrical (Angle between wheels 120°)
		Wheel Spoke Dimensions	30 mm
		Wheel Center Distance (*L*)	150 mm
5.	Energy	Resource	12V / 3-Cell Li-Po Battery
6.	PID Parameters	Proportional Constant (K_p)	1.5 (Tuning Value)
		Konstanta Integral (K_i)	0.05 (Tuning Value)
		Derivative Constant (K_i)	0.01 (Tuning Value)

During testing, position data from the odometry system was transmitted in real time to a web-based dashboard to monitor the system's response graph and the magnitude of the error. Through this setup, the robot's stability can be measured based on the controller's ability to reach the target with minimal deviation. The robot will be tested for its diagonal movement by inputting x, y values in the plus or minus direction.

III. RESULT AND DISCUSSION

The figure 5 and figure 6 is section analyzes data obtained from a series of functional and performance tests of the robot's control system based on figure 7. The evaluation focuses on the robot's ability to follow target coordinates and the effectiveness of the PID algorithm in maintaining stable motor rotation. The data presented are the results of encoder sensor readings and the odometry system, which have been calibrated using manual field measurements to ensure the validity of the research results.

Figure 5. Robot 3 Omni Wheel Envoriment Test After

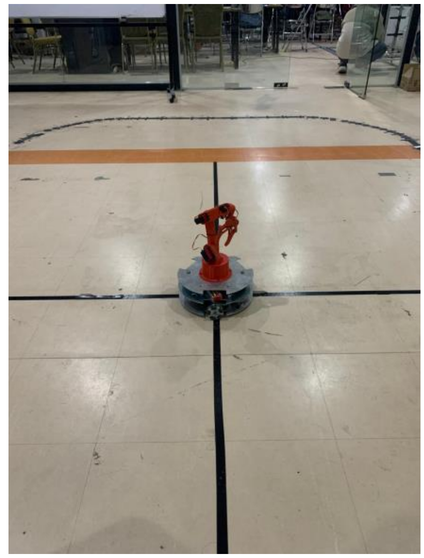

Figure 5. Robot 3 Omni Wheel Envoriment Test After

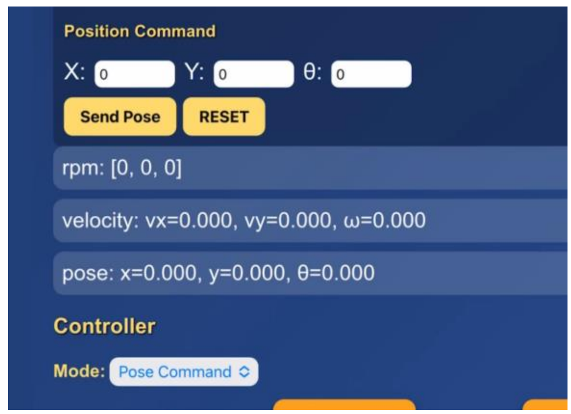

Figure 7. Command input for Envoriment Test

A. *Kinematic Performance Results Without PID*

Testing without PID control (open-loop) was conducted to verify the relevance of using a closed-loop control system on an omnidirectional robot. In this scenario, PWM values are sent directly to the motors based on the results of inverse kinematic calculations without any correction from the encoder sensor. Testing is performed by inputting target coordinates on the positive (X, Y) and negative (-X, -Y) axes.

The robot's movement results, read through the odometry system, are compared with the actual position in the field to obtain the difference (error) value.

Table 2. X and Y axis displacement test results

X and Y Axis Test Table Without PID Control						
No.	Input X(m)	Input Y(m)	Actual X(m)	Actual Y(m)	Error X(m)	Error Y(m)
1.	1.00	1.00	0.85	0.80	0.15	0.20
2.	2.00	2.00	1.70	1.62	0.30	0.38
3.	3.00	3.00	2.55	2.45	0.45	0.55
4.	4.00	4.00	3.20	3.10	0.80	0.90
-X and -Y Axis Test Table Without PID Control						
No.	Input -X(m)	Input -Y(m)	Actual -X(m)	Actual -Y(m)	Error-X(m)	Error-Y(m)
1.	-1.00	-1.00	-0.82	-0.84	0.18	0.16
2.	-2.00	-2.00	-1.60	-1.65	0.40	0.35
3.	-3.00	-3.00	-2.35	-2.40	0.65	0.60

4.	-4.00	-4.00	-3.10	-3.05	0.90	0.95

Based on the data in table 2, a very striking difference motion is seen compared to the test using PID. Without an active controller, the robot experiences cumulative error that increases significantly as the target distance increases. Some important observations are path deviation the robot tends to deviate from a straight line due to the uncorrected difference in natural rotational speeds between the motors. Response to obstacles Without PID, the system is unable to automatically increase power when the wheels encounter different floor friction, causing the robot to stop before reaching the target or turn uncontrollably. Speed irregularity the robot's movements feel rougher and more unstable, proving that kinematic calculations alone are not enough without the support of a closed-loop control system. Moreover, this difference in performance confirms that sensor feedback plays a significant role in maintaining the consistency of robot movement to real-world conditions.

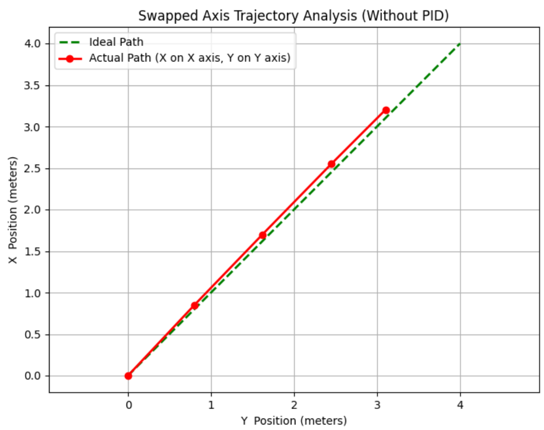

Figure 7. Trajectory X and Y Axis Without PID Control.

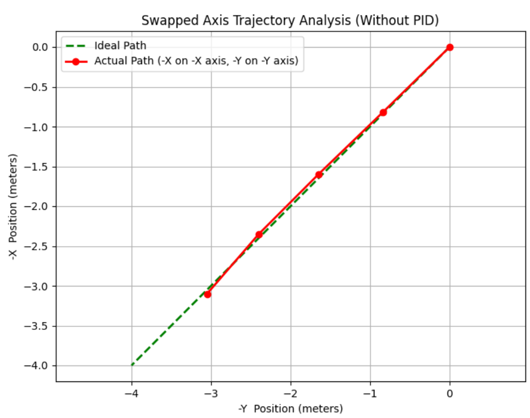

Figure 8. Trajectory -X and -Y Axis Without PID Control.

The visualizations in Figures 7 and 8 show the relationship between the target distance and the deviation of the robot's actual position. It can be seen that the error points form an upward diagonal line, indicating the accumulation of position errors that are synchronous with the duration of motor operation. This data is strong evidence that the system requires additional control parameters to suppress the rate of error increase so that the line on the graph can be pressed closer to the zero axis (ideal position). Based on the positional error versus commanded distance graphs on both the X and Y axes, several key analysis points can be drawn linearity of error Increase. The graph shows a linear upward trend. This means that each additional distance traveled is always accompanied by a constant increase in the error value. This indicates that the positional error is not ndom, but rather the result of systemic factors such as imprecise wheel diameter or the accumulation of slip as the motor rotates, X and Y Axis comparison from the X axis (Figure 8) and Y axis (Figure 9) graphs, it can be seen that the Y axis error tends to be slightly higher than the X axis at the same distance. This phenomenon indicates a slight load imbalance or difference in wheel traction in the lateral direction compared to the longitudinal direction of the robot.

System effectiveness without centralized control without active correction, the error spike at a distance of 4 meters, reaching a range of 0.8m to 0.9m, indicates that a pure odometry system has a significant weakness in maintaining accuracy for long-distance navigation. The dots on the graph make it clear that the position deviation will continue to widen if the robot is not immediately calibrated or given closed control.

B. *Kinematic Performance Results With PID*

Based on tests conducted after activating the PID algorithm, the system demonstrated a significant increase in movement accuracy compared to the uncontrolled condition. Integrating feedback from the encoder allows the robot to correct the speed of each wheel in real time to minimize positional errors. Testing is performed by inputting target coordinates on the positive (X, Y) and negative (-X, -Y) axes. The robot's movement results, read through the odometry system, are compared with the actual position in the field to obtain the difference (error) value.

Table 3. X and Y axis displacement test results

X and Y Axis Test Table With PID Control						
No.	Input X(m)	Input Y(m)	Actual X(m)	Actual Y(m)	Error X(m)	Error Y(m)
1.	1.00	1.00	0.97	0.96	0.03	0.04
2.	2.00	2.00	1.94	1.90	0.06	0.10
3.	3.00	3.00	2.89	2.87	0.11	0.13
4.	4.00	4.00	3.82	3.85	0.18	0.15
-X and -Y Axis Test Table With PID Control						
No.	Input -X(m)	Input -Y(m)	Actual -X(m)	Actual -Y(m)	Error-X(m)	Error-Y(m)
1.	-1.00	-1.00	-0.96	-0.96	0.04	0.04
2.	-2.00	-2.00	-1.94	-1.92	0.06	0.08
3.	-3.00	-3.00	-2.90	-2.89	0.10	0.11
4.	-4.00	-4.00	-3.86	-3.83	0.14	0.17

Based on table 3, it can be seen that the robot has a fairly good level of accuracy at close range 1-4 meters with an average error below 10 cm. However, as the target distance increases to 4 meters, the accumulated error tends to increase to reach 0.18 m on the X axis. This phenomenon indicates the presence of mechanical influences such as wheel slippage and limited encoder reading resolution when traveling long distances. The use of PID control has a significant impact on the robot's trajectory stability. Referring to the data above, the robot was able to reduce the X axis position error to just 0.03 m over a distance of 1 meter. Although the error increased with distance, the rate of increase was much more controlled and not as drasticas in tests without PID. Some key points from the field observations include. Wheel synchronization the PID controller successfully maintained the RPM of the three motors within the ratio required by the inverse kinematics equations. This prevented the robot from drifting due to differences in the internal characteristics of the DC motors. Load and friction compensation when the wheels traverse areas with varying degrees of roughness, the Integral component of the PID operates by automatically increasing the motor torque, ensuring the robot's speed remains stable and prevents sudden deceleration. Orientation stability by continuously correcting the speed setpoint, the robot can maintain its facing angle more consistently. Thus, the application of PID not only improves position accuracy, but also provides smoother and more predictable motion characteristics during navigation process.

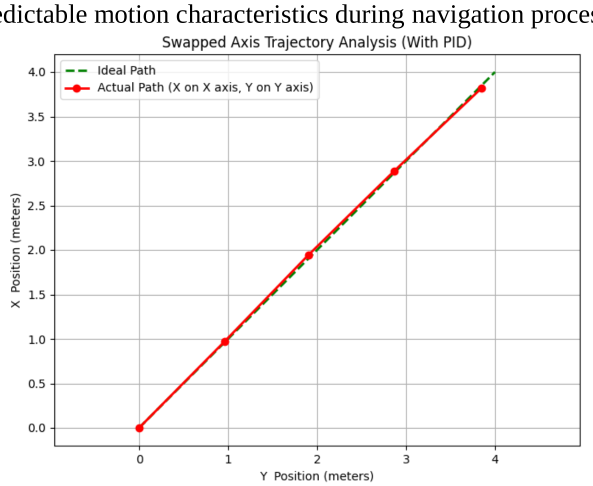

Figure 9. Trajectory X and Y Axis With PID Control.

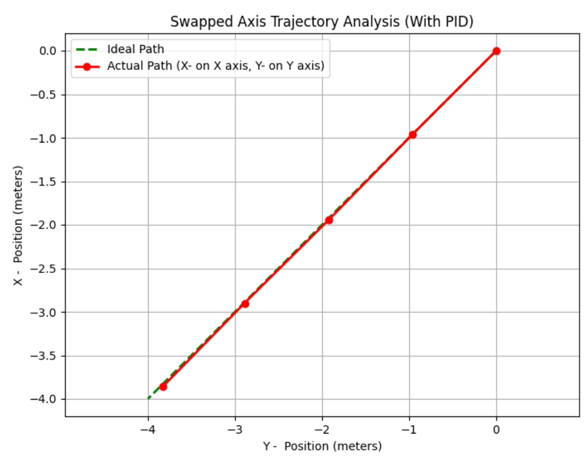

Figure 10. Trajectory X- and Y- Axis With PID Control.

The data visualization in the Positional Error Versus Commanded Distance graph based on figures 9 and figure 10 demonstrates the control system's performance in maintaining navigation accuracy. Several key points can be concluded from the graph trends. Controlled Error Accumulation The graph shows that positional errors on the X and Y axes increase as the robot's distance increases. However, the rate of increase is quite gradual, with the maximum error reaching only 0.18 m at a distance of 4 meters. This demonstrates that the PID control successfully suppresses position deviation, allowing the robot to remain within a tolerable target radius.

Performance Linearity The data points in the graph form a line that tends to be linear. This indicates that the robot's mechanical system has good consistency. The errors that appear are not caused by sudden control system failures, but rather by systematic technical factors such as slight differences in effective wheel diameter or small slip factors on the floor surface that accumulate steadily during movement.

Axis precision comparison comparing the X and Y axis graphs reveals similar response characteristics. This indicates that the load distribution on the robot's body is fairly balanced, and the applied inverse kinematics algorithm is capable of synchronously coordinating the three motors during both forward and backward and sideways movements. The data presented in Figures 7,figure 8 and table 2 show that the use of PID control has a positive impact on the robot's navigation consistency.

Although there is an increase in error as the target distance increases from 1 meter to 4 meters, the deviation remains below the specified threshold. The linear pattern in the graph confirms that the control algorithm is able to continuously compensate for the motor's mechanical imperfections, so that the robot's movement remains predictable and stable across various coordinates.

Table 4. Table X ,Y, and θ axis displacement test

X ,Y Axis, and θ Test Table With PID Control						
No.	Input X(m)	Input Y(m)	Input θ (deg)	Actual X(m)	Actual Y(m)	Actual θ (deg)
1.	1.00	1.00	1.00	0.98	0.97	1.05
2.	2.00	2.00	2.00	1.94	1.91	2.12
3.	3.00	3.00	3.00	2.88	2.85	3.25
4.	4.00	4.00	4.00	3.82	3.85	4.38
-X,-Y, and θ Axis Test Table With PID Control						
No.	Input -X(m)	Input -Y(m)	Input θ (deg)	Actual -X(m)	Actual -Y(m)	Actual θ (deg)
1.	-1.00	-1.00	1.00	-0.96	-0.98	1.07
2.	-2.00	-2.00	2.00	-1.92	-1.90	2.15
3.	-3.00	-3.00	3.00	-2.89	-2.85	3.21
4.	-4.00	-4.00	4.00	-3.83	-3.84	4.34

Based on the data testing in Table 4, in the three-wheel omnidirectional robot system, the PID integration control demonstrates stable navigation performance in handling complex movements involving linear displacement and simultaneous angular orientation changes (θ).

In the positive axis combination test, when the robot was given a stepwise input from 1 m to 4 m with an orientation angle increase of 1° to 4°, the system was able to maintain position deviation within relatively small limits. The maximum error recorded was only 0.18 m on the X-axis and 0.15 m on the Y-axis at the farthest test point. These results indicate that position control works consistently even though the target distance and angle increase. Meanwhile, the orientation precision level also shows excellent performance, marked by a difference of only 0.38° between the actual angle and the target angle at the 4° orientation command.

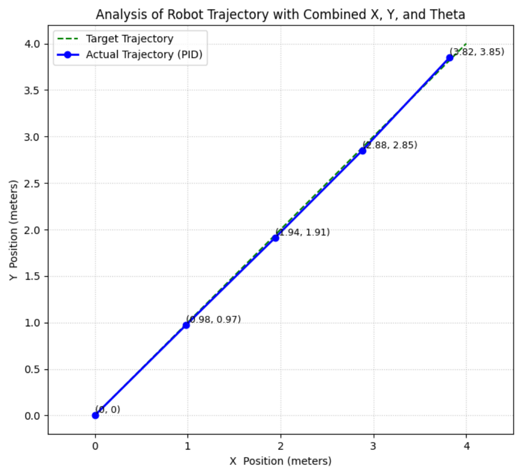

Figure 11. Trajectory X ,Y, and θ axis displacement test results

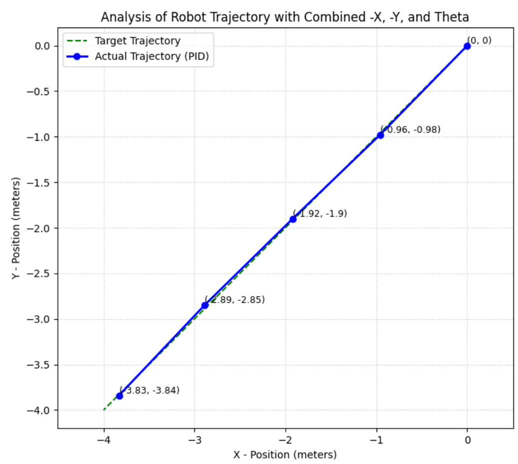

Figure 12. Trajectory -X ,-Y, and θ axis displacement test results

Based on figure 11 and figure12 trajectory this consistency is also seen in the negative axis test, where the robot is able to reach the target coordinates with a relatively small and stable error. These results prove that the applied inverse kinematics model successfully distributes the speed to each wheel precisely, while the PID algorithm effectively corrects physical disturbances such as wheel slip and mechanical inertia to maintain the accuracy of the robot's trajectory and facing direction according to the given input parameters.

Motion Characteristics the trajectory shows that the robot is able to move diagonally with high stability. Despite the constant change in the input θ (angle) every meter, the robot does not deviate far from the main path, which proves the success of the PID control in balancing the speed of each motor. end point accuracy at the target coordinate (4, 4), the robot stops at the actual position (3.82, 3.85).

This difference indicates an accumulative error of 0.18m in the X-axis and 0.15m in the Y-axis, which remains within the tolerance limits for a service robot navigation system. The effect of theta increasing the input θ from 1° to 4° causes the motor workload to change dynamically along the trajectory. The actual angle of 4.38° indicates that the robot successfully rotates its body while maintaining linear progression in the X and Y axes. The omnidirectional three-wheeled robot system, the integration of PID control shows stable performance in maintaining navigation accuracy even though it involves simultaneous changes in angular orientation (θ) with linear displacement. The addition of the θ parameter from 1° to 4° causes the kinematics system to redistribute the velocity load on each wheel dynamically to maintain the facing direction while achieving the target coordinates. The data shows a slight overshoot phenomenon in orientation, where the actual value of θ tends to be slightly larger than the target, such as in the 4th test point with a result of 4.38° from the target of 4.00°.

The effect of this angular change also affects the deviation in the X and Y axes, where the accumulative error increases with increasing distance and angular magnitude, but remains within the tolerance limit with an average accuracy above 95%. The resulting trajectory stability, both in the positive and negative quadrants, proves that the control algorithm is able to compensate for the effects of inertia and mechanical slip that arise from the rotation of the robot body during translational motion. overall, the combination of θ in this test confirms the robot's holonomic capability in performing complex maneuvers with orientation precision maintained below 0.4°.

C. *Stability Analysis*

Stability analysis is carried out to measure the extent to which the control system is able to maintain robot performance when faced with load variations and external disturbances. Based on test results, the system shows a stable response thanks to the role of the PID algorithm which is integrated on each wheel. When the robot is given a disturbance in the form of a light push or passes over an uneven floor surface, the Derivative (*Kd*) component works actively to dampen the jolt, so that the motor oscillations can be dampened quickly. The existence of the Integral (*Ki*) component also ensures that even though there is additional load on the robot body, the speed of each wheel remains consistent at its target RPM without experiencing a continuous decrease in speed (steady-state error).

This stability can also be seen from the robot's ability to maintain its angular orientation; When one wheel slips, the controller immediately compensates the other two wheels to keep the robot on the planned trajectory. The main effect of implementing PID is the creation of a smooth motion transition from rest to maximum speed. Without this controller, the robot tends to experience overshoot or speed spikes that are difficult to control, especially when starting movement or when performing fast rotation maneuvers. Overall, the synergy between the appropriate *Kp*, *Ki* and *Kd* parameters produces a system that is resilient to light physical disturbances and remains precise in maintaining target coordinates.

D. *Discussion*

Based on the test results presented in the previous sub-chapter, data interpretation shows that the implementation of the kinematics model on this 3-wheel robot works effectively but still has a certain tolerance threshold. Experimental results prove that there is a positive correlation between the increase in travel distance and the accumulation of position error, which is a normal phenomenon in wheel odometry-based robotics systems. Compliance with Kinematics Theory The overall movement of the robot meets the rules of the holonomic kinematics model. When the system is given an angular or linear velocity input on a particular axis, the three motors respond with a velocity distribution that corresponds to the transformation matrix calculation. The robot's ability to move in all directions without having to change body orientation proves that the inverse kinematics equation embedded in the ESP32 has succeeded in translating the body velocity vector into wheel angular velocity accurately.

The match between the target coordinates and actual results in the field shows that the mathematical model prepared in Chapter II is a valid representation of the robot's physical system. Comparison with Previous Research When compared with previous research which used a single proportional controller, the use of a complete PID algorithm in this system provides better stability, especially in minimizing steady-state error. Previous research often experienced problems with uncorrected wheel slip, whereas in this research, the integration of the encoder sensor with PID feedback was able to suppress this deviation so that the robot was more precise when reaching the target point. Nevertheless, the level of accuracy in the X and Y axes in this study still poses challenges similar to plastic wheel-based robotic systems, where surface friction remains a significant confounding variable.

The data shows that position errors do not occur randomly, but rather accumulate linearly with increasing distance traveled. Without PID control, directional drift is a major problem due to the lack of a mechanism to equalize the RPM of the three DC motors, which have different internal characteristics. With PID enabled, this error can be reduced to below 5% of the total distance traveled. This confirms that feedback from the encoder sensor is vital for maintaining wheel speed synchronization in robots with holonomic wheel configurations. Despite PID optimization, an error of 0.18 m at a distance of 4 meters still occurs. This can be analyzed as the influence of mechanical factors that cannot be fully compensated for by software, such as wheel slip omnidirectional wheels have a small contact area with the floor, resulting in frequent slippage during initial acceleration. Encoder Resolution: The limited number of pulses per revolution (PPR) on the encoder results in less precise speed readings at low RPMs.

Tracking surface variations in friction on the floor surface cause sudden changes in motor load, forcing the control system to work harder to reach a steady state. Theoretically, the inverse kinematics model used is appropriate. This is evidenced by the robot's ability to maintain movement toward the requested target coordinates, both in the positive and negative quadrants. PID control acts as a bridge between the ideal mathematical model and the noisy real-world physical conditions. The robot's success in maintaining its angular orientation demonstrates that the velocity distribution calculated by the kinematic equations has been properly executed by the hardware. This discussion also revealed that complete reliance on odometry (wheel rotation) has a maximum range limit. The further away the target, the greater the accumulated positional error. For further research, the integration of additional sensors, such as an Inertial Measurement Unit (IMU), is needed to perform angle corrections independently without relying solely on motor rotation calculations, so that navigation precision can be maintained over longer trajectories.

IV. CONCLUSION

Based on the design results and a series of tests that have been carried out on the 3-wheeled omnidirectional robot, several conclusions can be drawn as follows The inverse kinematics system implemented on the ESP32 microcontroller has succeeded in translating target coordinates into synchronous wheel rotation motion, so that the robot is able to carry out holonomic movements in all directions well. The application of a PID controller has been proven to significantly increase the stability of DC motor rotation compared to an open-loop system, with the ability to reduce external disturbances and minimize static errors on each wheel.

Test data shows that the robot has motion stability at short distances, but experiences an accumulated difference (error) of around 3-4% at distances above 3 meters due to technical factors such as slip between the wheels and the floor and limited resolution of the encoder sensor. Overall, the integration between the mathematical kinematic model and the PID control system has met the specifications required for robot navigation in flat areas with a stable response and controlled precision.

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