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A Pid Control System Using Ziegler-Nichols Method on Wheeled Soccer Robot Movement System

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ABSTRACT

The rapid advancement of robotics has impacted various sectors, including education. The Indonesian Robot Contest (KRI), organized by the Indonesian Talent Development Center, serves as a platform for innovation, featuring events like the Wheeled Indonesian Soccer Robot Contest (KRSBI-B). This study focuses on implementing a PID control system on a PG 45 type DC motor in a wheeled soccer robot, utilizing the Ziegler-Nichols method to determine optimal PID parameters. The goal is to design a stable PID control system and analyze how Kp, Ki, and Kd parameters influence robot movement. The research employs a scientific, rational, empirical, and systematic approach, using the Ziegler-Nichols method in quantitative research. The results demonstrate the successful design and implementation of the PID control system on the PG45 DC motor, with a rotary encoder used for RPM output and three-wheel kinematics for varied movements. While the Kp, Ki, and Kd values were optimal in motor tests without a load, some values failed to reach the setpoint during road tests due to additional motor load. Adjusting Kp, Ki, and Kd significantly affects the robot's movement, enhancing quick error response, reducing constant errors, and improving overshoot responsiveness. Future research should consider the test environment, use additional sensors for better data accuracy, and conduct repeated tests and evaluations to ensure system performance. This study offers practical and theoretical insights for the development of wheeled soccer robots and contributes significantly to future robotics research.

1. INTRODUCTION

Rapid developments in robotics are now taking hold in various fields, including education. In Indonesia, higher education appreciates this technology through the Indonesian Robot Contest (KRI), organized by the Indonesian Talent Development Center (BPTI) of the National Achievement Center of the Ministry of Education and Culture Research and Technology (Puspresnas Kemendikbud Ristek). KRI aims to enhance student creativity in robotics engineering technology and includes various categories, one of which is the Wheeled Indonesian Soccer Robot Contest (KRSBI-B). The contest consists of two stages: regional matches conducted online and national matches conducted offline.

The Wheeled Soccer Robot is an attacking robot that is remotely controlled via Wi-Fi and operates autonomously. The robot is designed with a sturdy body, using a microcontroller for actuator control and a laptop or miniPC for image processing control. The movement system is holonomic, allowing the robot to move in any direction using the kinematics of three omni-directional wheels with an angle of 120 degrees between each wheel. With its various systems, the robot is equipped with algorithms to operate according to contest regulations

The speed of the DC motor is set so that the robot moves stable and constant according to a preset setpoint. To maintain this stability, PID (Proportional Integral Derivative) control is often used, which involves three parameters: P (proportional), I (integral), and D (derivative), each of which is affected by constants Kp (proportional constant), Ki (integral constant), and Kd (derivative constant). PID control is needed to regulate motor speed as needed, thus ensuring high efficiency and optimal performance [1]. In general, PID is a control system that uses close loop and open loop methods. PID controllers are widely used in industry because the algorithms are simple and easy to understand. The PID that regulates the stability of the robot's movement continuously improves the error value of the given setpoint. For soccer robots on wheels, the comparison of the setpoint value with the error value should not be more than 10% in order to achieve the desired accuracy and stability of movement [2].

2. METHOD

According to the 2022 National KRI Guidebook, the wheeled soccer robot has a maximum weight of 40 kg with a free form and black color. The contest rules state that the robot control must be activated remotely using a remote method that relies on a WiFi connection in a network. In this network, there is a controlling computer (base station) in charge of controlling Robot 1 and Robot 2. Once activated, the robots must not be controlled manually, but must move autonomously when finding the ball, dribbling, and kicking it [3].

2.1. Materials

Table 1. Materials to Soccer Robot

Materials	Functions
Base Soccer Robot	Provudes the physical foundations of the system soccer robot movements such as wheels,DC Motors,etc
Microcontroller	Control the robot and run PID
Tachometer	To measures rotational speed or rotational speed in RPM
DC Motor PG45	Soccer Robot Movement
24VDC Battery	As a power supply for Motor

2.2. Method

Movement System

To understand the basis of omni-directional robot development, we can study the kinematics system used by the robot [4]. To move the robot from its initial position, it is important to understand the various interconnected and controllable variables, such as the position of the robot's movement and the speed of each wheel individually. Kinematics is a branch of robotics that analyses the motion and position of a robot without considering external factors such as forces and torques.

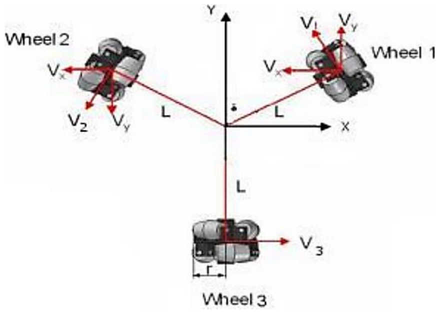

Figure 1. Shape of Three Omnidirectional Drive Robots

In Figure 2 there is some information about the x and y coordinates of the robot using omni wheels, namely in the cartesian coordinate system Vi (1,2,3) represents the relative speed of the robot on wheel 1, wheel 2 and wheel 3. The main focus on the movement of the omni wheel which can move freely in all directions with an angle of 30 degrees to the Y axis. L is the distance between the center of the robot and the center point of the omni wheel which determines how far the wheel is placed from the center of the robot. δ is the angle of the omni wheel to the Y axis where this angle allows the wheel to rotate around the Y axis in omnidirectional motion. The usefulness of this formula is that we can calculate the X and Y coordinates of the robot when moving using the omni wheel. These coordinates are important to navigate and control the movement of the robot with precision and accuracy. Kinematics representation of the robot movement system.

$$V_x = V_3 - V_1 \cos\delta - V_2 \cos\delta \tag{1}$$

$$V_y = V_1 \sin\delta - V_2 \sin\delta \tag{2}$$

$$V\emptyset = V_1/L + V_2/L + V_3/L \tag{3}$$

$$V_i(1,2,3) = w.r \tag{4}$$

To measure the speed of each wheel in the Three Omni-directional Drive Robot can use the multiplication method between the angular velocity of the wheel and the radius of the wheel. In the matrix equation of the Three Omni-directional Drive Robot, the variable δ is also involved, which is 30° [5].

PID Control System

To regulate the movement to achieve stable and accurate, a control system is used. In the book Control System Engineering written by [6] explains that the control system consists of sub-systems and processes that are assembled for the purpose of obtaining the desired output with the expected performance with the specified input. The proportional control action is proportional to the current control error, based on equation 5.

$$u(t) = K_p e(t) = K_p\big(r(t) - y(t)\big) \tag{5}$$

Where Kp is the proportional gain, e(t) is the error between the setpoint r(t) and the system output y(t). The error e(t) is multiplied by the proportional gain (Kp) to produce proportional control action. This means that the larger the error, the larger the control signal generated. Whatever the actual mechanism and mode of operation, the proportional controller power is basically an amplifier with adjustable gain levels.

The integral action is proportional to the integral of the control error. Integral controllers have a role in generating system responses that achieve zero steady-state error values. The output of the controller is strongly influenced by changes in line with the value of the error signal. The output of the controller reflects the continuous accumulation of changes in its inputs. This can be explained in Equation (6).

$$u(t) = K_i \int_0^t e(\tau)\, d\tau \tag{6}$$

Where Ki is an integral gain.

The derivative action is based on a control value that predicts the error. The output of a derivative controller exhibits similar characteristics as the derivative operation. When a sudden change occurs in the controller input, it results in a noticeable and rapid change in the output. In other words, the output response of this controller is very responsive to changes that occur in the input, giving a large and rapid impact to the overall system. An ideal derivative control can be expressed in Equation (7).

$$u(t) = K_d \frac{de(t)}{dt} \tag{7}$$

Where Kd is the derivative gain.

Table 2. Ziegler-Nichols Rule Based on the Response Step of the Plan [6]

Type Control	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

Ziegler and Nichols proposed rules for determining the values of proportional gain Kp integral time Ti and derivative time Td based on the transient response characteristics of a given system. Described by two parameters namely Lag Time L and Time Constant T [6]. Lag Time or Delay Time is the time required by the system to respond to changes in input. Changes in input or in other words the time required by the motor to move. While Time Constant is a depiction of how fast a motor reaches maximum speed. A small Time Constant indicates a faster response from the system to changes in input [7].

System Response Characteristics

The performance characteristics of a control system are defined through its transient response to unit-step inputs. Transient response refers to the response of a system from its start until it reaches a desired value. To facilitate comparison between the transient responses of various systems, a standard initial condition can be used where the system is initially at rest, with the output and all its time derivatives equal to zero. With this approach, the response characteristics of the systems can be compared more easily [8].

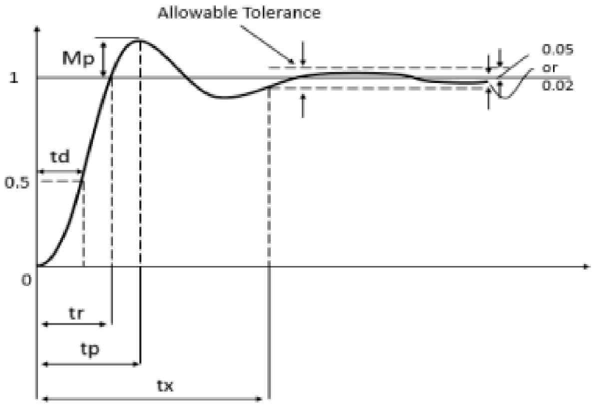

Figure 2. Response Unit Steps

The control system response shows oscillations that subside before reaching steady-state conditions [8]. Based on Figure 2, to determine the appropriate characteristics, the system response can be described as follows: a) Delay Time (Td): Delay time is the duration taken by the response to reach half of the final value at the time of the initial response. b) Rise Time (Tr): Rise Time is the time taken by the response to increase from 0% to 90%, 5% to 95%, or from 0% to reach 100% of its final value. c) Peak Time (Tp): Peak Time is the duration required by the response to reach the first peak point of overshoot. d) Maximum Overshoot (%), Mp: Maximum overshoot refers to the highest peak value of the measured response curve, starting from an initial value of one. If the response's final steady state differs from one, the maximum overshoot percentage is generally used. Its definition is described by Equation (7). The maximum overshoot amount (%) directly indicates the relative stability of the system.e) Settling Time (ts): Settling Time is the duration required by the response curve to reach and remain within a range of final values defined by an absolute percentage of the final values (generally 2% or 5%). f) Steady State Error (Ess): Represents the discrepancy at steady state which is usually calculated in Equation (8).

$$Max\ \%\ overshoot = \frac{c(tp) - c(\infty)}{c(\infty)} x100\% \tag{7}$$

$$Ess = Setpoint\ Value - Output\ System\ Value \tag{8}$$

Preparation of Research Design

The design of the hardware design refers to the implementation of the PID control system on the soccer robot, the selection of PID parameters based on the Ziegler-Nichols method and the experimental test scenario.

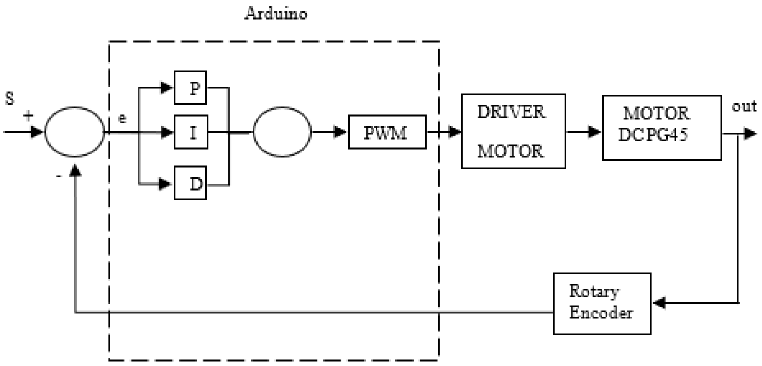

Figure 1. Research Design

In Figure 3 is a design process that refers to the structure of the use of components in the control system. The goal is to determine the components that will be used and to detail the control system created. Setpoint is a value that is set as a reference for controlled variables. In this final project, the setpoint value is the desired RPM value and is initialized on the Arduino. The value range is between 0-400 RPM. Rotary Encoder is a sensor that functions to detect motor speed in RPM units. The process is obtained from the pulse calculation of each motor rotation. This research uses a Rotary Encoder with a resolution of 7PPR (Pulse Per Revolution).

To carry out hardware implementation, software is needed, namely Arduino IDE to run all systems that have been designed on the Arduino Mega 2560 microcontroller. The system that has been implemented will organize the components to work according to the command. The following flowchart will be done on the Arduino IDE software in Figure 4

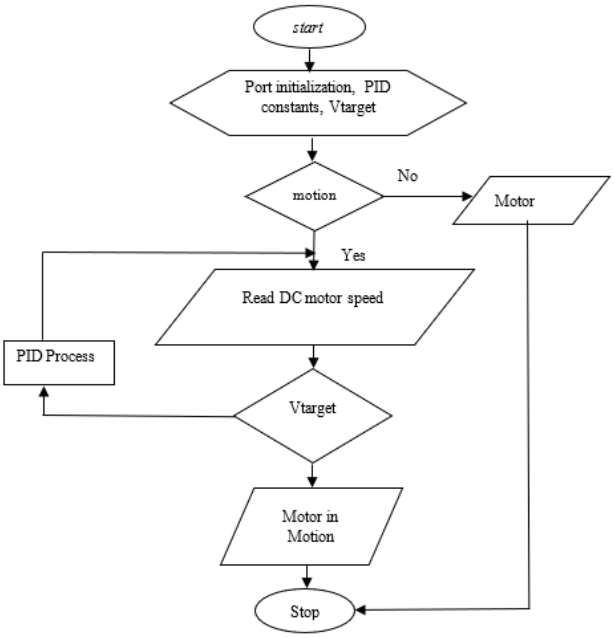

Figure 4. Robot Movement Flowchart

3. RESULTS AND DISCUSSION

3.1. RPM Testing on DC Motor Encoder

This rotary encoder sensor is already present on the DC motor. This test is carried out by activating the three DC motors with 25 RPM to 255 RPM speeds. Where the process that Arduino will carry out is obtained with a unit value of RPM and compared with a tachometer with the DT-2234C model as a real condition sensor. with the DT-2234C model as a real condition sensor. The following data is obtained in Table 3.

Table 3. Rotary Encoder RPM Testing on Motor

Actual Speed	Measurement speed	Accuracy
25 RPM	24.96	0.99
45 RPM	43.75	0.97
65 RPM	65.78	1.01
85 RPM	84.34	0.99
105 RPM	105.76	1.00
125 RPM	124.98	0.99
145 RPM	145	1
165 RPM	165.98	1.05
185 RPM	184.9	0.99
205 RPM	203.65	0.99
225 RPM	225.98	1.00
245 RPM	245.96	1.00
255 RPM	253	0.99

Based on Table 3, there are results from the measurement value of the actual value of the measuring instrument which is the accuracy of the measurements taken. It can be concluded that the values represented have a range that is quite close to the value of 1 which indicates that the measurement has a high relative accuracy. Testing using a tachometer on this DC motor gives the conclusion that this rotary encoder sensor is feasible to use as feedback in the PID control system.

Accuracy is the level of conformity or closeness of the measurement results to the actual price [9]. If the accuracy value is above 70%, the tool is said to be good and can be used in the system [10]. With this reference, it can be seen that the value close to 1 indicates that the measurement has a relatively high accuracy and the rotary encoder on the DC motor is suitable for use as feedback in the PID control system.

3.2. PID Control System Testing Without Test Run

Testing the PID control system without a test run is a test conducted without putting the robot on the floor or wheels hanging with wooden media. The results of these tests can be seen in Figure 5.

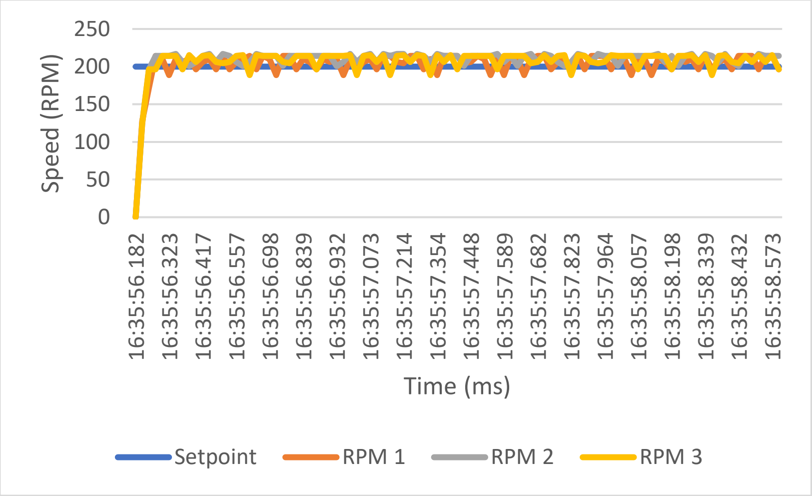

Figure 5. Motor Testing When the Motor is on Whood Media

In Figure 5, the PID control value used has reached the setpoint. In this case, the PID control value on motor 1 and motor 2 (Kp = 1.2; Ki = 12.76; Kd = 0.0282) while motor 3 (Kp = 0.4; Ki = 0.1128; Kd = 0.282) can maintain the speed at the setpoint despite overshoot or fluctuations in the rotation of the DC motor.

Testing 200 RPM of each motor for each movement can explain that these three parameters are very influential for the performance of the movement system. Using the ziegler-nichols method is appropriate to produce a stable system and provide system parameters only close to the desired system response and overshoot no more than 10% [2]. This is proven by testing without a road test with a setting of 200 RPM at the specified setpoint value with an overshoot in motor 1 of 7%, motor 2 of 8.45%, and motor 3 of 7.65%.

3.3. DC Motor Testing with Road Test

This test is done by directly placing the DC motor connected to the wheel with the road media, namely the carpeted floor. The robot's movement is done using wheel kinematics. This test performs two movements: forward and left. PID control in each movement can be seen in Figure 6 below.

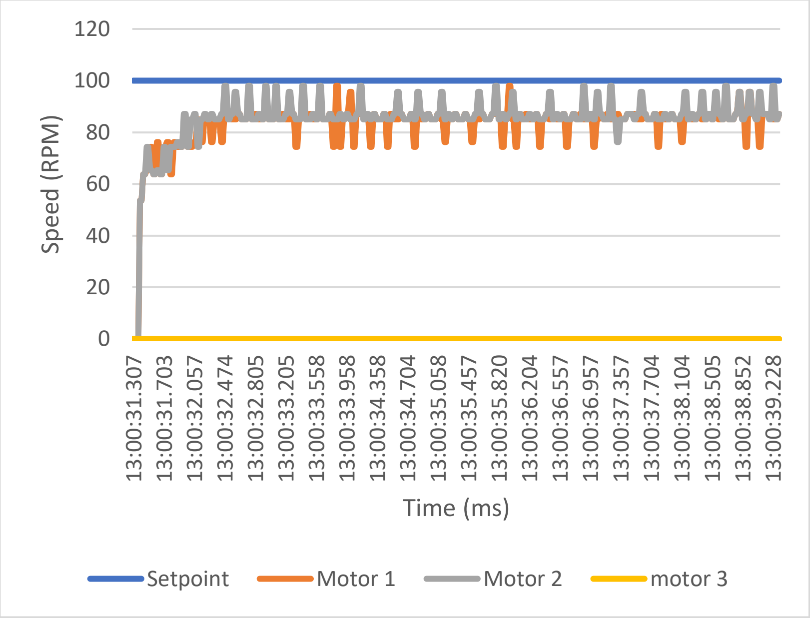

Figure 6. Testing on DC Motors with Forward Moving Wheel Kinematics

Based on Figure 6, it can be concluded that in testing DC motors using forward direction wheel kinematics (movement of wheel 1 to the left and wheel 2 to the right) has a speed that is far from the predetermined setpoint with an average motor speed of 82.72 RPM on motor 1 and 85.19 RPM on motor 2.

Observing the system response is to evaluate the PID parameters used. This is explained through Table 3 and Table 4, so that the appropriate system response is obtained [11]. The system response results related to applying PID control to the forward movement of the robot are in Table 5.

Table 4. System Response Results for DC Motors in Forward Motion

Motor	Rise Time (Tr)	Delay Time (Td)	Settling Time (Ts)	Overshoot (Mp) (%)	Error Steady State (Ess)
Motor 1	0.693 s	0.381 s	0.985 s	0%	4.34 RPM
Motor 2	0.592 s	0.381 s	1.093 s	0%	2 RPM

Table 5 shows that motor 1 reaches 90% of the setpoint in about 0.694 s after the input signal is given while motor 2 responds 0.592 s. In this case motor 2 responds faster than motor 1. This indicates that motor 2 is more responsive to initial input changes than motor 1. The delay time required by motor 1 and motor 2 to respond to the input change is 0.381 s. Settling time in motor 1 takes 0.985 s and motor 2 takes about 1.093 s to be within the specified tolerance range (usually 2% of the setpoint) and no longer fluctuates significantly. Motor 1 reaches steady state faster than Motor 2. The shorter settling time of Motor 1 indicates that it stabilizes faster after a change in input than Motor 2. Overshoot is 0% which indicates that both motors do not have a larger output change than the setpoint. While the steady state error on motor 1 has an error of 4.34 RPM and motor 2 of 2 RPM. In this case motor 2 is more accurate in reaching the reference than motor 1.

Overall, the forward movement for motor 2 showed better performance in terms of response speed and accuracy than motor 1, although Motor 1 achieved stability faster after the input change. Both motors have good control over overshoot indicating good stability in both. Furthermore, the wheel movement for the left movement can be seen in Figure 7.

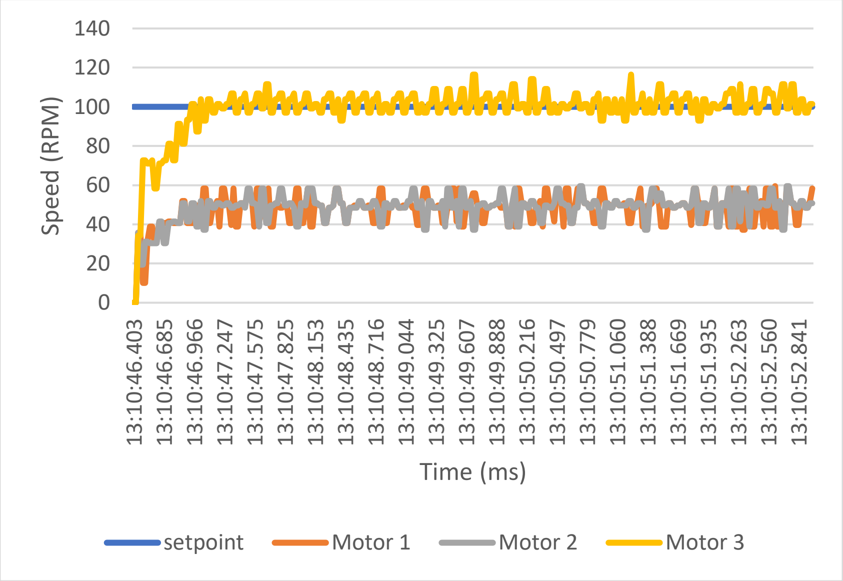

Figure 7. Testing on DC Motor with Left Moving Wheel Kinematics

Based on Figure 7, it can be explained that the RPM of motor 3 reaches the setpoint while motor 1 and motor 2 have values of half the RPM of motor 3. The results of the system response related to the application of PID control to the left movement of the robot are in Table 6.

Table 6. System Response Results on Dc Motor When Moving Left

Motor	Rise Time (Tr)	Delay Time (Td)	Settling Time (Ts)	Overshoot (Mp) (%)	Error Steady State (Ess)
Motor 1	0.375 s	0.114 s	0.469 s	0.16%	8.23RPM
Motor 2	0.235 s	0.114 s	0.469 s	0.16%	8.23RPM
Motor 3	0.375 s	0.188 s	0.516 s	0.01%	1.46 RPM

Table 6 displays that motor 1 reaches 90% of the setpoint in about 0.375 s after the input signal is given while motor 2 responds 0.235 s and motor 3 responds 0.375 s. In the Rise Time, motor 2 has the fastest rise time. Delay time required by motor 1 and motor 2 to respond to input changes is 0.141 s and motor 3 0.375 s. Settling time on motor 1 and motor takes 0.469 s and motor 3 0.516 s to be within the specified tolerance range (usually 2% of the setpoint) and no longer fluctuates significantly. Overshoot is 0.16% for motor 1 and motor 2 while motor 3 is 0.01 s which indicates that both motors do not have output changes greater than the setpoint. While the steady state error in motor 1 and motor 2 has an error of 8.23 RPM and motor 2 of 1.46 RPM this is the difference between the setpoint and the motor output when it reaches stability.

Overall, motor 3 shows better performance in terms of overshoot and accuracy, although it has a longer delay time and settling time. Motor 2 has the fastest initial response performance, but along with Motor 1, has a larger steady-state error. Motor 1 and Motor 2 have similar performance in many aspects, with the main difference being the rise time.

4. CONCLUSION

Based on the results of testing and data analysis and discussion of the PID control system, several conclusions can be presented from the research. The design and implementation of the PID control system on the PG45 DC motor has been implemented by using a rotary encoder as an RPM output. The design and implementation are also combined with three-wheel kinematics for forward and left movements. The Kp, Ki and Kd values obtained for each motor are motor 1 (Kp= 1.2; Ki= 0.094; Kd=0.0235), motor 2 (Kp= 1.2; Ki= 0.094; Kd=0.0235) and motor 3 (Kp=0.4; Ki=0.1128; Kd=0.282). These values get the optimal motor speed conditions in motor testing without road tests. As for road testing, several values have not reached the setpoint due to the load given to the motor. The effect of Kp, Ki and Kd on the movement of the soccer robot. For setting the Kp value, Kp is set to see how fast the response to the error between the desired setpoint and the specified speed, the higher the Kp value the faster the robot's response to errors but will also increase the risk of overshoot. This is evident in the movement of the robot road test there is no overshoot exceeding 5% due to the small Kp value. For the Ki value, the Ki value is set to reduce the steady-state error. This is evident in the motor that maintains the speed value that has been set. For the Kd value, the Kd value is set to reduce the robot's responsiveness to overshoot.

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DECLARATIONS

Authorship contribution

Hanifah Nur Ismail: Conceptualization, methodology, formal analysis, software and writing -original draft. **Yulkifli and Rio Anshari**: Validation, review and editing. **Dani Harmanto**: Validation and review.

Competing Interest

The authors **declare** no conflict of interest in this study.

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Ethical Clearance

There are no human subjects in this manuscript, and informed consent is not applicable.

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