Implementation of PID Control for Angular Position Control of Dynamixel Servo Motor

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***Abstract*—Dynamixel servo motors, characterized by their compact size and high torque output, are made of high-quality materials that ensure the necessary strength and structural robustness against external forces. However, these motors are prone to overheating under certain internal conditions, such as temperature or supply voltage fluctuations during prolonged use. This research aims to design and apply PID control methodology to regulate Dynamixel servo motors. The research includes motor implementation using the PID method and subsequent testing with varying voltage inputs ranging from 11V to 12V. Addressing these issues involves using the Proportional Integral Derivative (PID) control method, widely recognized for its reliability in controlling motor speed. The research successfully designed Dynamixel servo motors capable of PID-controlled rotation according to predefined reference values. The motor's PID control design involved multiple trial runs - up to 5 instances - for each proportional, integral, and derivative control. The default PID parameter implementation did not match the setpoint; however, a re-tuned PID method yielded optimal results with parameter values Kp = 0.01000; Ki = 0.02703; Kd = 0.00005. Test results showed that the PID-controlled Dynamixel servomotor accurately achieved the expected angular output of 75°. In addition, tests using voltage inputs ranging from 11.00 to 12.00 volts showed stable operation without changing the servo motor's angular position before applying the PID control value, ensuring consistent motion even as the voltage drops.**

***Keywords*—Servo Motor, Dynamixel, OpenCM 9.04, PID, Angular Position**

I. Introduction

Humanoid robots rely on Dynamixel servo motors as integral drive components. These motors embody intelligent modular actuators consisting of gear reducers, DC motors, and embedded control circuits with networking capabilities that integrate different functionalities into a single unit [1]. A notable feature of Dynamixel servo motors is their ability to sense and respond to internal conditions such as temperature and voltage variations [2]-[4]. However, these adaptive responses can occasionally result in sluggish or desynchronized motion, potentially leading to overheating problems within the motors.

This research focuses specifically on Dynamixel's MX-28AR servo motor, known for its compact design, high torque output, and use of premium materials to ensure the necessary strength and structural integrity against external forces. Despite these attributes, internal factors such as temperature variations or voltage fluctuations can cause overheating [5] after extended periods of operation.

When integrated into humanoid robotic systems [6]-[8], Dynamixel servo motors typically have pre-configured PID parameters. Therefore, this research aims to recalibrate these parameters to achieve optimal PID values, ensuring a smoother and stable response [9]-[12] in the servo motor's angular position. The primary concern addressed in this research revolves around the angular position instability of the motor caused by internal conditions.

The approach chosen to mitigate this problem involves using the Proportional Integral Derivative (PID) control method, known for its effectiveness in many applications such as UAV [13], [14] water level control [15], and regulating motor speeds [16]. In particular, the PID control method generates smooth motor movements and maintains stability more effectively.

This research used Robotis OpenCM software and analysis as a coding and microcontroller programming platform. The experimental procedure focused primarily on evaluating the servo motor's response to varying voltage inputs, validating the accuracy of the data presented for each resulting angular position, and evaluating the communication interface between the motor and a computer/PC (personal computer).

II. Methods

A. PID Controller

The methodology involves using the PID (Proportional Integral Derivative) controller as the primary system for motor speed control. Its widespread integration into industrial frameworks underscores its central role, which is used in many of industrial processes [17]. Beyond the primary function of motor speed control, PID controllers promote stability and smoothness in speed control operations due to their unique blend of proportional, integral, and derivative control systems [18].

The proportional element of the PID controller responds immediately to error signals, producing an output proportional to the current error. At the same time, the integral component accumulates past error signals and corrects persistent steady-state errors, thereby increasing the system's ability to reach the desired setpoint. The derivative element enhances these functions by predicting system behavior by evaluating the rate of change of error signals, enabling the controller to anticipate and proactively counteract potential overshoot or undershoot conditions [19], [20].

Furthermore, the PID controller's adaptability and versatility in accommodating varying system dynamics support its prevalence in industrial applications. Its ability to fine-tune parameters allows for precise adaptation to the varying operational requirements of industrial processes [21]. As a result, the PID controller is emerging as a cornerstone of industrial control systems, representing a sophisticated yet indispensable tool for achieving optimized and efficient motor speed control. Fig. 1 show the block system PID.

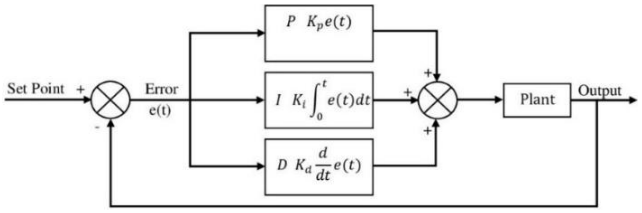

Fig. 1. PID block system

Based on Fig. 1, the error signal represents the variance between the set point and the output of the plant. It is systematically expressed equation (1) and the equation (2) shows the PID Calculation:

$$e(t) = SP(t) - PV(t) \tag{1}$$

Where:

$SP(t)$: (Set Point) Desired position value
$PV(t)$: (Present Value) Actual position value
$e(t)$: (Error Value) Calculation of SP-PV

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{2}$$

Where:

$u(t)$: Output signal of the PID Controller
K_p : Proportional constant
K_i : Integral constant
K_d : Differential constant
$e(t)$: Error signal

B. System Design

The design of the control system for the Dynamixel servo motor focuses on the Dynamixel MX-28AR servo motor, which is the primary element of this research. This research uses a PID methodology. This servo motor aims to generate outputs that represent the position of the engine to align with the intended target position. The control mechanism is orchestrated by the OpenCM 9.04 microcontroller, which acts as a central hub connected to the Dynamixel servo motor via a dedicated Dynamixel cable.

Execution of the PID method is facilitated by the Robotis program embedded in the OpenCM, with outputs directed to the Dynamixel servo motor. These outputs include essential data such as the Dynamixel servo motor ID, its model, temperature, and the input voltage applied to the motor. Proper calibration of the PID values is critical to achieving or approximating a servo motor position aligned with the position encoder. This alignment is determined by observing the output results, manifesting as graphical representations of the position target, position encoder, and PID values.

The power source for the system is a 3-cell 2600 mAh Li-Po battery that provides 11 to 12 volts of power for system operation. The role of the OpenCM 9.04 is twofold: first, it collects angular position data and transmits it to the microcontroller; second, the processed angular position data is transferred from the microcontroller to the Dynamixel servo motor. Notably, the Dynamixel servomotor is initially powered from the battery source, as shown in Fig. 2, a block diagram of the Dynamixel servomotor control system design.

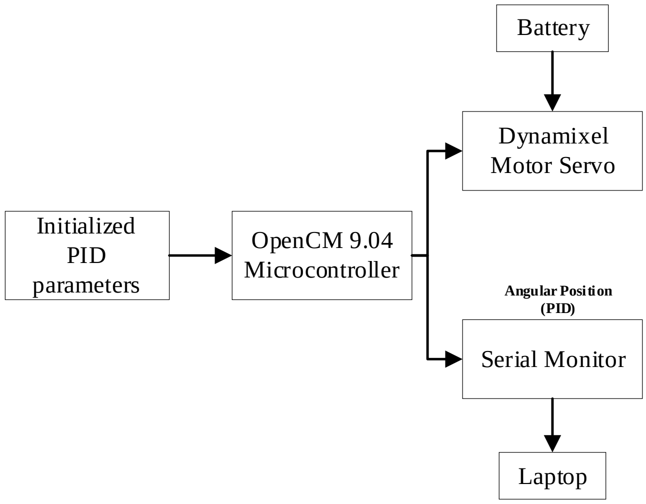

Fig. 2. Block diagram

The PID controller processes a reference input to generate an angular position output sensed and indicated by the angular position sensor (encoder sensor). In cases where the angular position output deviates from the target setpoint, the controller detects this deviation. As a result, the controller initiates the transmission of control signals to the Dynamixel servo motor, as shown in Fig. 3. Conversely, when the angular position output exactly matches the setpoint input, the controller stops sending data to the Dynamixel servo motor. This mechanism ensures that the system dynamically adjusts and corrects for deviations from the desired angular position through orchestrated control signal transmissions, optimizing the motor's performance in response to the specified setpoint.

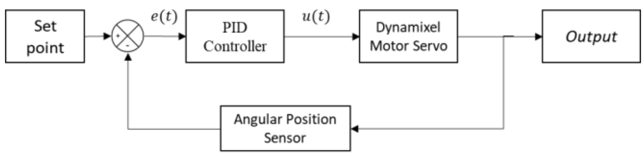

Fig. 3. Control system block diagram

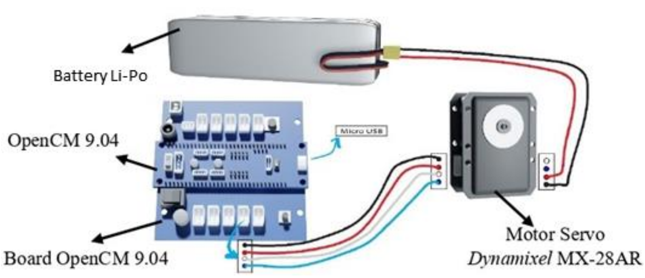

Fig. 4. Wiring diagram system

The hardware design progression involves the creation of a comprehensive wiring diagram outlining the interconnections among the system components, as depicted in Fig. 4. The system's circuitry is powered by a 3-cell Li-po

2600 mAh battery, delivering a test voltage ranging between 11 to 12 volts. Fig. 4 shows the wiring diagram, a blueprint detailing the intricate connections and electrical pathways among the various components employed in the system architecture. Through meticulous schematic representation, this diagram elucidates the systematic arrangement and integration of the hardware elements, ensuring coherence and accuracy in the electrical connections for practical functionality and performance of the designed system.

C. Software Design

The software design phase focuses on configuring the OpenCM 9.04 controller, accomplished through programming using the Robotis OpenCM software. The results of this programming effort are then transferred to the OpenCM 9.04 board using a USB cable. Additionally, MATLAB (SIMULINK) software serves as an adjunct to assist in processing PID calculation data into a graphically understandable format.

In this research, software design is paramount as it serves as the basic framework for implementing the controller on the system. The Robotis OpenCM software allows researchers to organize and monitor the functionality of the OpenCM 9.04 hardware efficiently. In addition, the MATLAB (SIMULINK) application allows visualization of PID calculation data, facilitating in-depth analysis and graphical presentation of results for a more intuitive understanding of system performance.

At the initial stage of the software design process, the researchers use OpenCM Robotis to create a PID controller program. This program is transferred to the microcontroller, which generates an angular position output through the Dynamixel servomotor, as shown in Fig. 5.

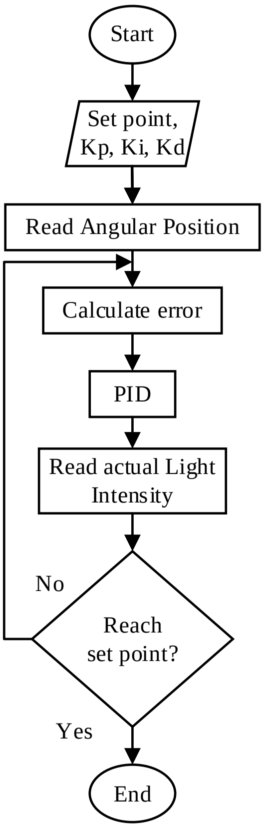

Fig. 5. Flowchart system

Based Fig. 5, the operation of the Dynamixel servo motor control system, using the PID control method, begins with the initialization and execution of the compiled program. This program encapsulates critical parameters such as Kp, Ki, and Kd, which represent the PID control parameters, along with a setpoint that represents the desired angular position for the Dynamixel servo motor.

When the program is executed, the system processes the PID control input values to produce an output that reflects an angular position aligned with the predetermined setpoint. At the same time, the system makes a comparison between the actual motor position, as measured by the encoder, and the target setpoint. Discrepancies between these values trigger the generation of an error value.

The PID control mechanism then processes and corrects the error value, which facilitates the calculation and provision of appropriate input values. These inputs enable the Dynamixel servomotor to modulate its position and align it with the predetermined setpoint. This iterative process is continuous, ensuring that the servomotor dynamically corrects its position whenever there is a deviation between the actual position and the setpoint. The robustness of this system is underlined by its ability to achieve high stability and precision in the position adjustment of the Dynamixel servomotor, adapting it to the specific requirements of the intended application through the use of PID control.

III. Results and Discussion

A. Hardware

The hardware design encompasses a frame structure interconnecting each constituent system, ensuring seamless integration among all components. Furthermore, the hardware assembly adheres to a meticulously planned three-dimensional (3D) design, as depicted in Fig. 6.

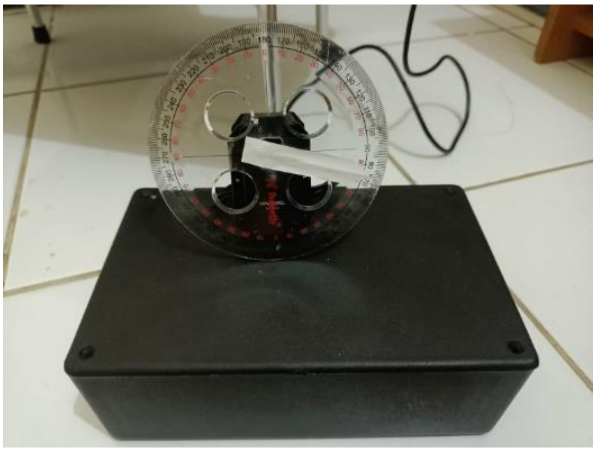

Fig. 6. Hardware real

This hardware configuration establishes a robust communication linkage between the OpenCM 9.04 steering device and the Dynamixel servo motor. The design specifications of the Dynamixel servo motor control system, incorporating PID control, delineate dimensions measuring 8.3 cm in length, 11.5 cm in width, and 6.3 cm in height. A well-conceived hardware arrangement plays a pivotal role in upholding the stability and overall performance of the entire system. Additionally, it serves as a proactive measure in mitigating potential technical issues that may arise during system operation, ensuring optimal functionality and minimizing disruptions.

B. Calibrating Motor Servo

The system testing phase begins with evaluating the Dynamixel servomotor, which includes an experiment of its operational status through an automatic ID search, as visually depicted in Fig. 7. This initial test aims to determine the functionality and readiness of the servomotor for subsequent integration and use within the system setup.

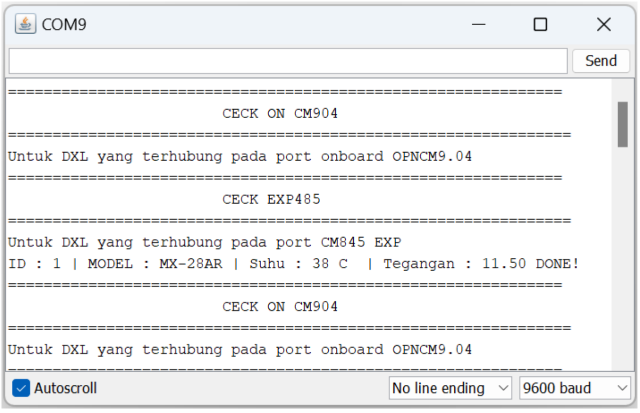

Fig. 7. Motor servo dynamixel status (suhu: means temperature in motor servo, tegangan: means voltage input in motor servo)

This research continued with the calibration of the Dynamixel servo motor to convert the angular position value from BIT units to angular degree units with the program command, as shown in Fig. 8. The servo identification is defined using the constant "ID," set to 1. Next, a conversion process is performed to convert the value to an angular position in degree units, exactly 74°. This conversion process is essential because it allows us to understand and analyze the angular position data of the Dynamixel servo motor.

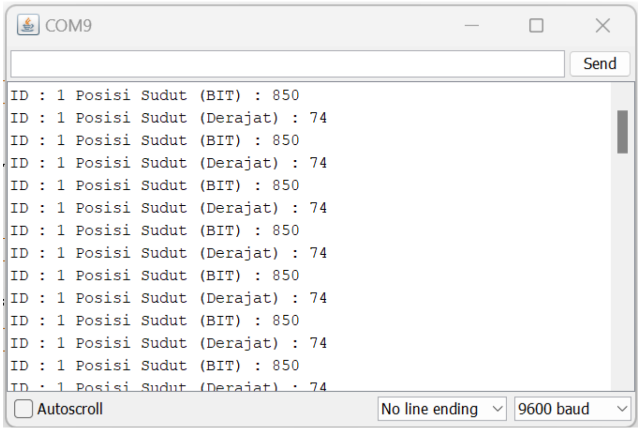

Fig. 8. Calibration data to angular position (posisi sudut (derajat): means angular position)

Based Fig. 8, the program has effectively displayed the angular position reading of servo ID 1 by presenting an analog data value in BIT units, specifically registering at 850 BIT. This reading corresponds to an angular position of 74° in degree units. These recorded readings contribute significantly to the angular position calculation, which is calculated by dividing the analog data by the appropriate conversion factor-resulting in the formula: angular position = analog data / 11.37777777777778 or angular position = 850 / 11.37777777777778. The calculated result is then meticulously displayed on the serial monitor for analysis.

C. P Controller

The system underwent a proportional control test through five data trials using different Kp parameter values: Kp = 0.01000; Kp = 0.02000; Kp = 0.03000; Kp = 0.04000; Kp = 0.05000. Notably, this test was performed without changing the integral (Ki) and derivative (Kd) control values, maintaining the parameter values of Ki = 0 and Kd = 0 within the Dynamixel servomotor test program, as shown in Table 1. This careful evaluation examines the isolated effect and effectiveness of the proportional control parameters on the performance of the Dynamixel servomotor, thereby delineating the response characteristics of the motor under varying Kp parameter configurations.

Table 1. Response analysis P Controller

Kp	Rise Time (TR)	Overshoot (Mp)	Peak Time (TS)	Settling Time (ST)	Steady State Error
0.01000	NaN	0	1	NaN	75
0.02000	NaN	0	1	NaN	75
0.03000	NaN	0	1	NaN	75
0.04000	NaN	0	1	NaN	75
0.05000	NaN	0	1	NaN	75

Based on Table 1, variation of the Kp parameter is systematically varied to determine the effect of the proportional control system on the research tool being tested. Throughout this evaluation, the response of the Dynamixel servomotor is observed under a 75° setpoint input condition. However, it's worth noting that for Experiments 1-5, the rise time (TR) and settling time (ST) data are shown as NaN, indicating an undefined or unattainable value. In addition, the step response shows a consistent steady-state error of 75, indicating a persistent discrepancy between actual and desired output values, reflecting the influence of the proportional control system on the tool's behavior during testing. Fig. 9, shows the angular position responses applying P Controller.

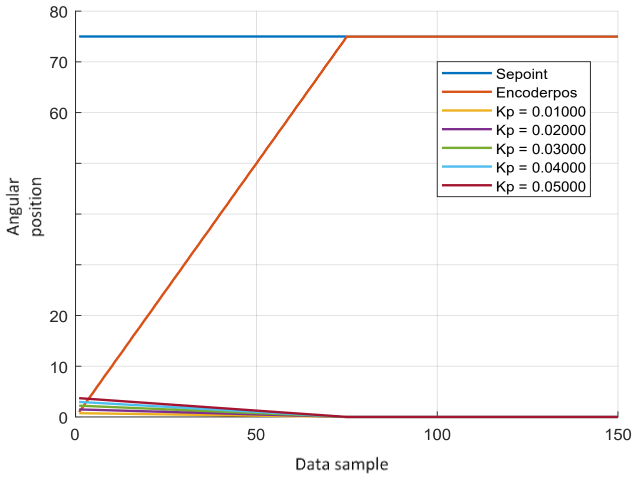

Fig. 9. Angular position response P Controller

During each experiment, the servomotor is moved from an initial angle to a specified angle. However, despite these adjustments, the servo motor's responses after applying the Kp values do not reach the desired setpoint. This observation underscores the need to fine-tune the Kp parameter to optimize system performance and achieve the expected operating efficiency.

D. PI Controller

The integral control (Ki) evaluation was conducted through five experiments, each using different values for the Ki parameter: Ki = 0.01503; Ki = 0.01803; Ki = 0.02103; Ki = 0.02403; Ki = 0.02703. These experiments were meticulously performed by keeping the proportional control (Kp) and derivative control (Kd) values constant or setting the parameter value Kd = 0 within the Dynamixel servo motor test program. The comprehensive results of these experiments are presented in Table 2, which provides a systematic overview of the various effects and results resulting from modifying the Ki parameter.

Table 2. Response analysis PI Controller

Kp	Ki	Rise Time (TR)	Overshoot (Mp)	Peak Time (TS)	Settling Time (TS)	Steady State Error
0.01000	0.01503	NaN	0	74	NaN	33.2900
0.01000	0.01803	NaN	0	73	NaN	24.9700
0.01000	0.02103	NaN	0	74	NaN	16.6400
0.01000	0.02403	NaN	0	74	NaN	8.3200
0.01000	0.02703	46.2218	0.0267	74	63.7407	-0.0100

Based on Table 3, the variation of the Ki parameter value, while keeping the parameters Kp = 0.01000 and Kd = 0.00000 constant, is used to evaluate the combined effect of the proportional control system and the integral control on the research tool under research. Throughout this test, the response of the Dynamixel servomotor was examined over an angular range of 0° to 75°. However, for experiments 1-4, the rise time (TR) and settling time (ST) data were reported as NaN, meaning an indeterminate or unattainable value. In addition, these experiments showed unstable steady-state error step responses. In contrast, Experiment 5 had a rise time of 46.2218, a minimum overshoot of 0.0267, a settling time of 63.7407, and a steady-state error of -0.0100. In addition, peak times were consistently observed at 74, indicating the time taken for the response to reach its first, second, third, fourth, and fifth peaks. These results delineate the varying responses of the system under different Ki parameter values, manifesting themselves in different performance results and system behaviors. Fig. 10 shows the angular position response applying PI Controller.

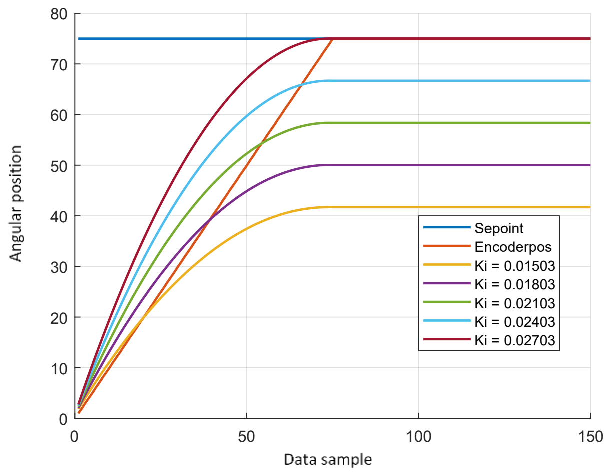

Fig. 10. Angular position response PI Controller

E. PID Controller

The Proportional-Integral-Derivative (PID) system research was conducted through a series of five experiments, each of which varied the Kd parameter values: Kd = 4.00001; Kd = 3.00002; Kd = 2.00003; Kd = 1.00004; and Kd = 0.00005. Notably, these tests were performed without changing the previously recorded values for proportional control (Kp) and integral control (Ki) within the Dynamixel servo motor test program. Further details and results of these tests are systematically presented in Table 3, providing a comprehensive insight into the system responses under different Kd parameter configurations.

Based on Table 3, the experiments involving variations in the Kd parameter were carried out while keeping the values of Kp and Ki constant at Kp = 0.01000 and Ki = 0.02703, respectively. The purpose of this systematic variation was to meticulously analyze the effect of PID control - the combination of proportional, integral, and derivative control - on the performance of the tested research tool. Throughout these evaluations, the response of the Dynamixel servomotor was closely monitored over the angular range from 0° to 75°.

The results obtained from the system's performance under alternative Kd controls revealed distinct trends. Experiments 1-4 consistently showed a peak time value of 1, indicating a fast response within the system. However, Experiment 5 exhibited a peak time value of 74, indicating a delay in reaching the peak response. In addition, a consistent and stable steady-state error value of -0.0100 was observed across all five experiments, indicating a constant deviation between the desired and actual outputs of the system. These results provide nuanced insights into the system's behavior under varying Kd parameter configurations, shedding light on its response dynamics and performance characteristics. Fig. 11 shows the angular position response applying PID Controller.

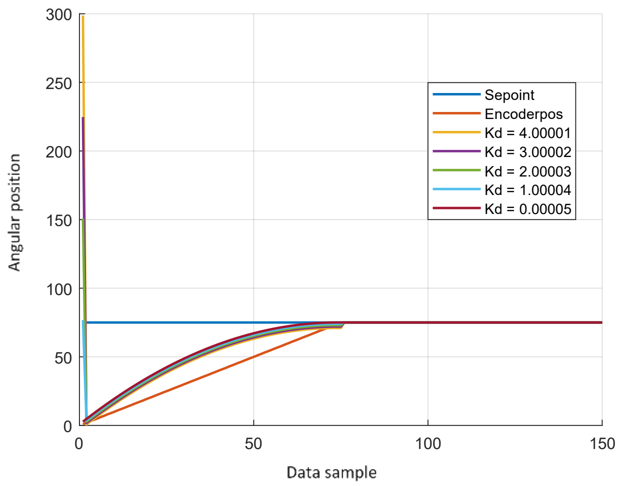

Fig. 11. Angular position response PID Controller

F. System Experiments with 11-12V Voltage Input

The experiments were carried out with input voltage variations from 11.10 volts to 12.00 volts. The test results show that the Dynamixel servo motor operates efficiently and stably at each voltage level. The temperature of the servo motor was recorded from 37°C to 47°C during the test. The performance of the dynamixel MX-28AR servo motor with ID 1 showed performance according to the expected specifications. The tests positively confirmed the performance and robustness of the dynamixel servo motor in the face of voltage fluctuations. Table 4 shows the results experiments.

Table 3. Response analysis PID Controller

Kp	Ki	Kd	Rise Time (TR)	Overshoot (Mp)	Peak Time (TS)	Settling Time (TS)	Steady State Error
0.01000	0.02703	4.00001	0.6006	298.3200	1	63.1013	-0.0100
0.01000	0.02703	3.00002	0.5371	199.6533	1	73.2600	-0.0100
0.01000	0.02703	2.00003	0.4093	100.9867	1	75.2376	-0.0100
0.01000	0.02703	1.00004	0.0191	2.3200	1	68.4267	-0.0100
0.01000	0.02703	0.00005	46.2218	0.0267	74	63.7407	-0.0100
0.01000	0.02703	0.00005	46.2218	0.0267	74	63.7407	-0.0100

Table 4. Effect of input voltage on servo motor temperature

Temperature (℃)	Voltage (V)
47	12.00
45	11.90
46	11.80
47	11.70
41	11.60
44	11.50
37	11.40
43	11.30
46	11.20
46	11.10
41	11.00

IV. CONCLUSION

Significant conclusions have been made after extensive design, meticulous testing, and systematic observation of the angular position control of the Dynamixel servo motor using PID control. The successful implementation of a Dynamixel servo motor controlled by the Proportional-Integral-Derivative (PID) control method underscores the meticulous stages of design and rigorous testing, including multiple iterations of testing the proportional (Kp), integral (Ki), and derivative (Kd) control parameters. The initial implementation using default PID parameter values failed to match the setpoint, while recalibration of the PID control yielded optimal results with parameter values Kp = 0.01000; Ki = 0.02703; Kd = 0.00005. Notably, the PID-controlled Dynamixel servomotor flawlessly achieved the expected 75° output angle, confirming its desired responsiveness.

Subsequent tests, which included voltage variations between 11.00 volts and 12.00 volts, further underscored the stability and reliability of the system. The pre-PID Dynamixel servomotor exhibited consistent performance with no angular position variations and maintained this stability even during voltage fluctuations. This research demonstrates the effectiveness of PID control in controlling the Dynamixel servo motor, especially when using the specified Kp, Ki, and Kd parameter values. It also reflects the motor's ability to operate seamlessly under varying input voltage conditions, confirming its stability and reliability in real-world applications.

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