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Position control of AX-12 servo motor using proportional-integral-derivative controller with particle swarm optimization for robotic manipulator application

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ABSTRACT

This study proposes a control method for servo motor position using a proportional-integral-derivative (PID) controller with particle swarm optimization (PSO). We use an AX-12 servo motor that is commonly used for robotic manipulator applications. The angular position of the servo motor will be controlled using the PID control method with PSO as a controller gain optimizer. Firstly, the transfer function model of the servo motor is generated using open-loop model identification. Then, the integral error of the closed-loop system is used as PSO input in producing PID controller gain. As an objective function of the PSO algorithm, the integral time absolute error (ITAE) index performance is used. The proposed controller was tested and compared with PID with the Ziegler-Nichols (ZN) method. We also conduct the hardware experiment using Arduino Uno as a microcontroller using one AX-12 servo motor on the base joint of the manipulator robot. Based on the simulation result, the PID-PSO controller can achieve the best control response performance if compared to PID-ZN with a rise time is less than 0.5 s, a settling time of fewer than 8 s, and an overshoot under 1.2%. The effectiveness of the proposed PID-PSO controller is also validated by hardware experimental results.

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1. INTRODUCTION

A robotic arm or commonly called a robot manipulator is a mechanical device inspired by a human arm and can be programmed to do a certain task [1]. It is usually used to perform heavy or repetitive work and requires accuracy. Robotic manipulator is played the most important role in recent years in industrial automation such as automotive, electronics, foods, and even rehabilitation [2]. To achieve the desired target, the robot must be controlled and programmed to obtain accurate and smooth movements like human behavior. The original idea of the application of robotic manipulators is position motor control. To function correctly in many applications, the motor as a joint in the robotic manipulator must be controlled using appropriate methods, as well as conventional or intelligence control [3]–[8]. Generally, these controller aims to optimize the robot's functions and guarantee its stability during the task.

One of the controlling methods widely used in industrial applications is proportional-integral-derivative (PID) control. This PID control system works by processing calculations based on the control gain Kp, Ki, and Kd to achieve conditions according to the expected set point. PID controllers were designed and implemented to control the robot manipulator for several given tasks [9]–[11]. However, until now the main problem in designing the PID controller is how to get the optimal PID constant. Based on the results of a literature study, the meta-heuristic optimization method is one of the methods currently being extensively researched for the problem of determining PID constants, one of which is the particle swarm optimization (PSO) method. PSO can be used for localization, path-planning, optimization, and other related problems effectively, providing robustness and optimal solutions to these systems [12].

Several studies have been carried out in recent years on the application of the PID control method with the PSO method, especially in controlling the position of the robot manipulator servo motor. In [13], the PID controller was designed for controlling the joint of the robotic manipulator using PSO. The tuning of the PID controller is formulated as an optimization problem to optimize two or more objective functions. PID controller with PSO is also applied to control the gait position of the humanoid robot [14]. Simulation and experiment results show that the PID-PSO controller can reduce stabilization and overshoot times by up to 25%. Another application had been investigated in the upper limb rehabilitation [15]. The PID-PSO controller can stabilize the system and produce an efficient response. The PID-PSO configuration has also been applied to the quad-rotor tracking system [16] and load frequency control in the distribution system [17]. Furthermore, apart from being combined with PID, the PSO algorithm can also be used to solve inverse kinematic problems on arm robots and combined with robust control methods [18], [19].

This study aims to design and implement a PID-PSO controller on a servo motor for a robot manipulator application. We use the type of AX-12 servo motor which is used as a joint in the manipulator robot. This study was adapted from [20], which was designed to control the angular position of a servo motor with a PID-PSO controller. However, this research was only carried out through MATLAB simulations. Our contribution is to apply the PID-PSO controller by simulation and also validated by experimental results. As a preliminary study, in this study position control was only carried out on one AX-12 servo motor which functions as a joint-base robot manipulator.

2. METHOD

2.1. AX-12 servo motor model

The AX-12 servo motor is commonly used in the six degrees of freedom (6-DoF) AX-12 arm robot as shown in Figure 1. The AX-12 servo motor is used in the 6-DoF AX-12 arm robot as shown in Figure 1. In the manipulator robot, each motor acts as a joint that will move each link based on the commands given based on kinematics principles. This AX-12 servo motor has three pins, namely Vcc, Gnd, and data. At the data pin, we can provide control signals and simultaneously get position feedback using half-duplex communication.

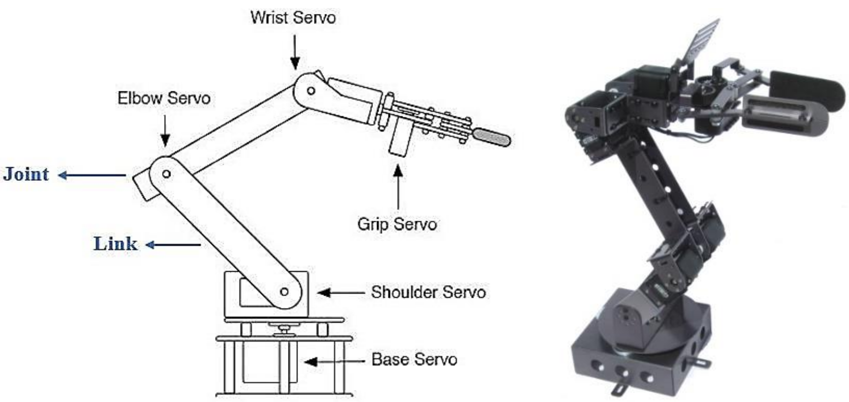

Figure 1. AX-12 manipulator robot

In general, the dynamic model of a servo motor consists of mechanical and electrical models that work based on Newton's and Kirchhoff's laws. The transfer function of the DC servo motor is shown in (1). Based on the equation, Θ is angular position as output, V is the voltage as input, K is motor constant, J is a moment of inertia, b is friction constant, L is inductance, and R is resistance.

$$\frac{\Theta(s)}{V(s)} = \frac{K}{LJs^3+(RJ+Lb)s^2+(Rb+K^2)s} \quad (1)$$

2.2. Proposed controller

PID controller is one of the most common feedback control methods used in industry in many applications such as process control, motor control, and others. PID controllers are very popular because of their good and powerful performance in various operating conditions and also because of the simplicity of their functions that allow operators to operate simply and easily. The equation of the PID control transfer function is given as in (2) with K_p, K_i, and K_d are proportional, integral, and derivative gains, respectively.

$$C(s) = K_p + \frac{K_i}{s} + K_d s \quad (2)$$

The main problem in designing PID controllers is how to determine K_p, K_i, and K_d constants. In this research, the PSO algorithm is proposed to produce optimal PID constants. The designed controller design can be seen in Figure 2. PSO is an evolutionary optimization technique developed by Kennedy and Eberhart in 1995. The PSO is based on the social behavior of flocks, birds, and fish foraging. This behavior is based on the intelligence of each individual and the entire herd. In PSO, populations are called swarms, and individuals are called particles [21].

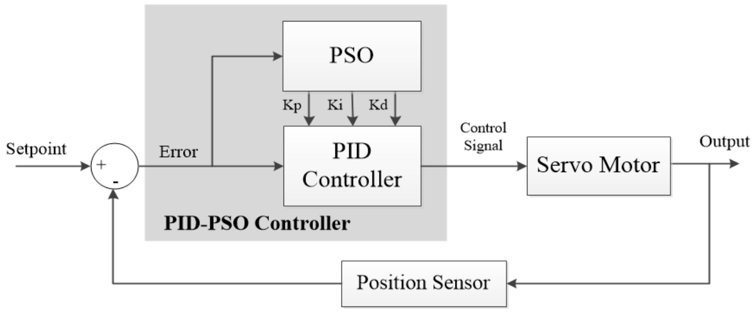

Figure 2. PID-PSO controller design

Creating a swarm is a basic phenomenon of the PSO. The potential solution to the problem is called particles, which move in the space of the problem. Each particle has its position and speed. After each iteration, the particle updates its position and speed and moves towards the best value of the swarm. Particle position update has two components, p_best, and g_best. p_best is the newest position of the particle and g_best is the global best position of the entire swarm. The process repeats until the iteration reaches its maximum. The speed and position of the particle are represented by (3) and (4),

$$v_{ij}(t+1) = wv_{ij}(t) + r_1c_1 \left(p_{ij}(t) - x_{ij}(t) \right) + r_2c_2 \left(g_j(t) - x_{ij}(t) \right) \quad (3)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (4)$$

where $x_{ij}(t)$, $x_{ij}(t+1)$, $v_{ij}(t)$, and $v_{ij}(t+1)$ are the position, updated position, speed, and speed updated, respectively. r_1 and r_2 are two random variables, the values of which are located between 0 to 1. c_1 and c_2 are the coefficients of acceleration, and w is the inertial tribe. p_best is represented by $p_{ij}(t)$ and g_best is represented by $g_j(t)$.

The flowchart of PSO for the PID controller is shown in Figure 3. The PSO algorithm begins by generating a population of a certain size, each of which will be initialized with a random position and speed. After that, it continued with the evaluation of fitness values for each particle in the current position. Next, find the best position of each particle (p_best), then the best position of all existing particles is made the best global value (g_best). The iteration is done by updating the speed and position of each particle. This algorithm will continue to repeat until the iteration reaches its maximum and provides the best g_best value as the optimal solution.

Particles in this case are the parameters K_p, K_i, and K_d. The purpose of this algorithm is to minimize errors or error values in the system response. The objective function used in this work is an integral time absolute error (ITAE) as in (5) with e_θ is the error of angular position. The ITAE criterion was chosen because it was able to overcome the long settling time when compared to the integral absolute error (IAE) and integral square error (ISE) criteria [17]. The PSO parameters used in this study are presented in Table 1.

$$J = \int_0^\infty t\,|e_\theta(t)|\,dt \quad (5)$$

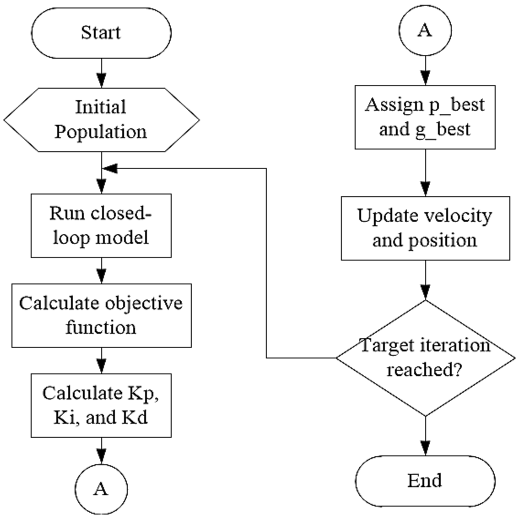

Figure 3. PID constant calculation using PSO

Table 1. Parameters of PSO

Parameters	Values
c_1 and c_2	2
w	0.8
Number of particles	20
Number of iterations	100
Number of variables	3

2.3. Hardware design

The system block diagram for the hardware is shown in Figure 4. The AX-12 servo motor is capable to provide position feedback. For controlling the angular position, Arduino Uno is used as a microcontroller and connected to a personal computer to display the position feedback from the servo motor. IC 74LS241 is used as a connection between the servo motor and Arduino Uno to display the position feedback on the serial monitor. This IC functions as a half-duplex communication protocol between the microcontroller and the motor. Thus, two-way communication between control signals and feedback can be done even though they cannot occur simultaneously.

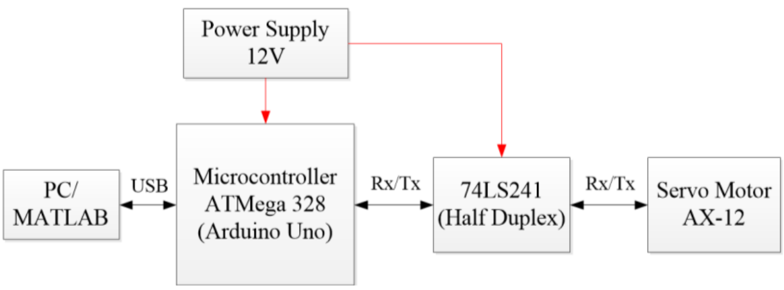

Figure 4. Hardware system design

3. RESULTS AND DISCUSSION

In this section, a simulated PID-PSO controller test was carried out compared with the Ziegler-Nichols (ZN) optimization method. The error is then analyzed using ITAE index performance criteria. The open loop transfer function model of the servo motor was obtained from MATLAB. This process is assisted by the identification toolbox feature where the open-loop system input and output data are used as toolbox input. From the identification of the plant model, the transfer function is obtained as in (6).

$$G(s) = \frac{90.49}{s^2 + 4.053s + 7.284} \quad (6)$$

3.1. Simulation result

The first test was carried out in a simulation using MATLAB. The goal is to determine the response to controlling the motor angle position using PSO. The control response was compared with the optimized PID controller using the ZN method. The constants resulting from the two methods can be seen in Table 2, PID constants using the ZN method are obtained using the first method, where the L and T parameters of the open-loop response are first determined. Then from these parameters, the values of Kp, Ki, and Kd are calculated using the ZN table. The PID constants using the PSO method are generated from the PSO flowchart with the iteration result depicted in Figure 5.

The PSO iterations are performed up to 100 times. From errors of about 400 in the first iteration, smaller errors were found in subsequent iterations until they reached the smallest error value of 90 in the 100 iterations. The control response and its error can be seen in Figure 6(a) and (b), respectively, with the response parameters listed in Table 3.

Table 2. PID constants

Constants	Ziegler-Nichols	PSO
Kp	0.698	1.12
Ki	2.6	1.38
Kd	0.44	0.24

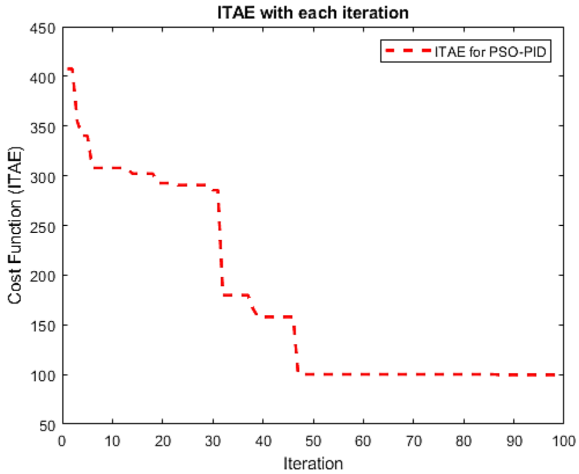

Figure 5. PSO iteration result

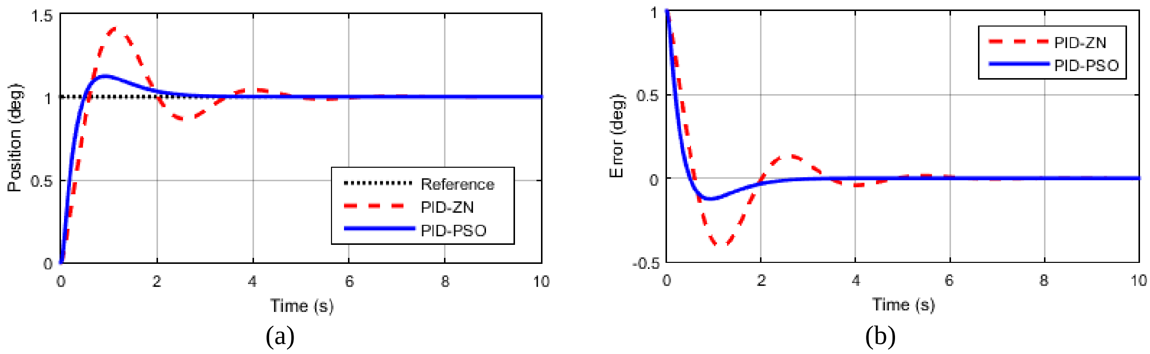

Figure 6. Responses of (a) angular position using PID-ZN and PID-PSO and (b) its error

Table 3. Simulation responses performance

Parameters	Ziegler-Nichols	PSO
Rise Time (Tr)	0.58 s	0.49 s
Settling Time (Ts)	17.5 s	7 s
Overshoot (OS)	1.41%	1.12%
Error Steady State (Ess)	0%	0%
ITAE	1.077	0.217

Based on the simulation results, it was found that the angle control response using the PID-PSO controller was able to produce better performance when compared to the PID-ZN controller. This can be seen in the resulting transient parameters where the PID-PSO controller produces a faster transient time and smaller overshoot. For the steady-state response parameters, both controllers produce no errors. The PID-PSO controller also produces a smaller ITAE value than the PID-ZN controller as shown in the error response surface.

3.2. Hardware testing

The second test was carried out experimentally to see the control performance of the AX-12 servo motor. Testing was carried out by embedding the PID program on the Arduino Uno microcontroller, both with ZN optimization and PSO. For simplicity, the PID constants are not calculated online on the microcontroller but on MATLAB. The calculation results are then entered into the microcontroller program. The implementation of the hardware experiment can be seen in Figure 7, while the control responses and its error are depicted in Figure 8(a) and (b), respectively. The control response parameters are also presented in Table 4.

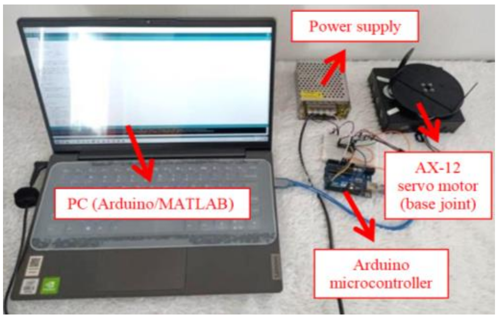

Figure 7. Hardware experiment of AX-12 position control

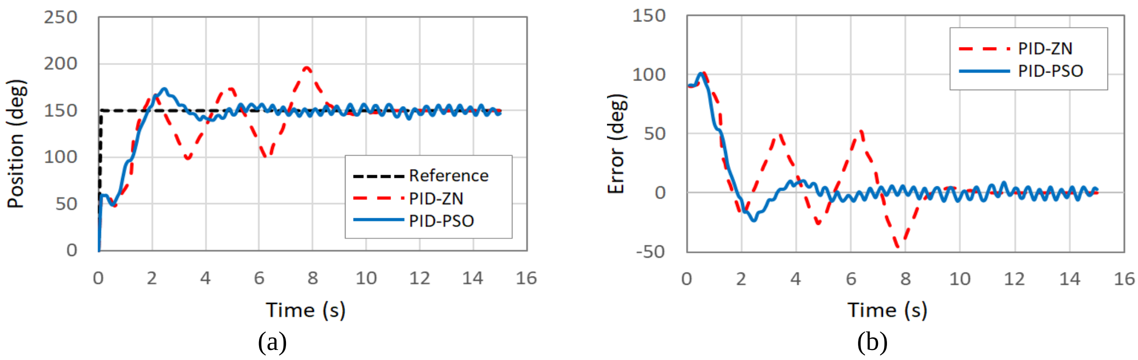

Figure 8. Position response in (a) experimental testing and (b) its error

Table 4. Experiment responses performance

Parameters	Ziegler-Nichols	PSO
Rise Time (Tr)	1.7 s	1.9 s
Settling Time (Ts)	9 s	5 s
Overshoot (OS)	30.6%	15.3%
Error Steady State (Ess)	0%	0%
ITAE	984.8	266.6

Based on the experimental results, it can be seen that the PID-PSO controller also produces a better control response when compared to the PID-ZN. This is proven by the resulting response performance where the PID-PSO controller produces smaller settling time, overshoot, and ITAE values. For the rise time, the PID-ZN controller produces a slightly faster time of around 0.2 seconds, while for the steady-state error, both are zero. Similar to the simulation results, the ITAE value produced by the PID-PSO is also smaller when compared to the PID-ZN.

3.2. Discussion

Based on the test results, there is a difference between the simulation and the hardware experiment. Several things that might be the cause include inaccuracies in the model obtained. Modeling through identification is one approach that can be done, but the resulting level of accuracy is no better than the method of deriving physical parameters [22]. In addition, the existence of a half-duplex communication protocol provided by the AX-12 servo motor can also be the cause. This motor has only one pin for communication with the microcontroller so that the sending of control and feedback signals cannot be sent at the same time. Thus, the delay parameter will appear which should be involved in the modeling in the simulation. As it is known that the delay parameter in a closed-loop system can cause a decrease in control performance [23]–[25]. This is one of the uniqueness of the AX-12 servo motor type and is a challenge in designing controls for further research.

4. CONCLUSION

The PID-PSO controller has been successfully designed and implemented to control the angular position of the AX-12 servo motor. The results of the simulation and experimental tests show that the PID-PSO controller can produce better control performance when compared to the PID-ZN controller. This can be seen in the smaller settling time and overshoot response transient parameters with a smaller ITAE performance index as well. In future studies, it is possible to improve the results of the control response, one of which is by modifying the objective function by involving transient response criteria.

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