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PID Parameter Optimization Using Particle Swarm Optimization For Motor Speed Control In An Automatic Cardiopulmonary Resuscitation Device

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Abstract. Chest compression in an automatic cardiopulmonary resuscitation (CPR) device requires stable and accurate motor speed control to keep the compression rate consistent within the 100–120 compressions-per-minute range recommended by the 2020 American Heart Association (AHA) guidelines. This study designs and evaluates speed control of the PG45 DC motor driving the crank-slider mechanism of an Arduino Mega 2560-based automatic CPR device using a Proportional-Integral-Derivative (PID) controller whose parameters are tuned through the Particle Swarm Optimization (PSO) algorithm with an Integral Time Absolute Error (ITAE) objective function. Speed feedback is obtained from a Hall-Effect incremental rotary encoder, supported by integral anti-windup, a low-pass filter, and feedforward control. PSO optimization yielded Kp = 5.0000, Ki = 2.9519, and Kd = 0.5000 with a minimum ITAE of 2.3586. MATLAB simulation showed a fast, stable speed response toward the 120 RPM reference without excessive overshoot. Testing on a CPR manikin showed an average actual speed of 91.95 RPM with an RMSE of 30.12 relative to the simulation, attributed to the viscoelastic load resistance of the chest wall and internal mechanical friction under peak load. Compression depth remained consistent at 55.8–56.0 mm in line with the AHA standard, although motor-speed performance in the real implementation still requires further improvement, particularly through selection of a higher-torque actuator.

Keywords: *PID control; Particle Swarm Optimization; motor speed; ITAE; automatic CPR device*

INTRODUCTION

Sudden cardiac arrest is one of the leading causes of death worldwide, requiring fast and appropriate intervention to prevent damage to vital organs such as the brain and heart. Cardiopulmonary resuscitation (CPR) is a life-saving procedure aimed at maintaining blood circulation and oxygen supply to vital organs through effective, continuous chest compressions. According to American Heart Association (AHA) guidelines, chest compression depth in adult patients is recommended to be 5–6 cm at a rate of 100–120 compressions per minute to keep blood circulation optimal during resuscitation (American Heart Association, 2020).

This compression rate is directly determined by the rotational speed of the drive motor, which converts rotary motion into the translational motion of the chest-pressing element through a crank-slider mechanism. When motor speed is unstable or deviates from its reference value, the resulting compression rate also deviates from the AHA standard range, reducing the effectiveness of the automatic CPR device. Motor speed control is therefore one of the most decisive components in the success of an automatic CPR device, alongside the chest-compression mechanism itself.

Previous studies have developed various automatic CPR devices with different control strategies. Syam and Maruddani (2024) developed an Arduino-based portable CPR prototype, but still faced difficulties in maintaining consistent drive speed under varying mechanical loads on the patient's chest. Studi et al. (2024) integrated a monitoring system into an automatic CPR device, but the control system used still relied on manual tuning, making it prone to compression-depth and compression-rate errors. Lescher et al. (2025) showed that Proportional-Integral-Derivative (PID) control has good stability in medical systems requiring high real-time precision, while Sanoj and Dhanya Ram (2024) compared several PID tuning objective functions (ITAE, IAE, ISE, ITSE) and showed that ITAE provides a good balance between response speed and oscillation damping.

Manual PID tuning methods such as Ziegler-Nichols generally require a trial-and-error process that does not guarantee optimal parameters, especially for systems with time-varying load dynamics such as the crank-slider mechanism in a CPR device. Metaheuristic algorithms such as Particle Swarm Optimization (PSO) offer a more systematic parameter-search approach by evaluating many parameter combinations in parallel based on an objective function (Freitas, Lopes, & Morgado-Dias, 2020; Ab Wahab, Nefti-Meziani, & Atyabi, 2015).

Based on this review, several research gaps were identified: (1) metaheuristic-based PID tuning has not been widely applied to motor speed control systems in automatic CPR devices; (2) quantitative evaluation of the agreement between simulation and real implementation for motor speed control in CPR applications remains limited; and (3) integration of anti-windup, low-pass filtering, and feedforward control into optimized PID implementations for high-precision medical applications is still restricted. The novelty of this study lies in applying a PID controller, tuned via the PSO algorithm with an Integral Time Absolute Error (ITAE) objective function, to control the DC motor speed driving the crank-slider mechanism of an automatic CPR device, together with a quantitative simulation-implementation agreement evaluation using the Root Mean Square Error (RMSE) method.

Globally, this study supports Sustainable Development Goal (SDG) 3, Good Health and Well-Being, and nationally aligns with the Asta Cita vision of strengthening the independence of an innovative, effective, and affordable medical-device industry. Based on the foregoing, this study aims to design and implement PG45 DC motor speed control using a PID controller whose parameters are optimized through the PSO algorithm, to evaluate control performance through MATLAB simulation, and to test and compare that control performance in the physical implementation of an automatic CPR device.

METHOD

This research was carried out at the Automation Engineering Technology Laboratory, Faculty of Engineering, Universitas Negeri Jakarta over 6 (six) months, covering the literature review, system modelling, control design, simulation, implementation, and testing and reporting stages. The main actuator being controlled is a 24V PG45 DC motor with a 71:1 gearbox ratio, driving the crank-slider mechanism of the automatic CPR device. The electronic system consists of an Arduino Mega 2560 as the main controller, a Hall-Effect incremental rotary encoder as the speed feedback sensor, a BTS7960 43A motor driver for PWM actuation, a 4.3-inch TFT LCD for the user interface, and a 24 VDC power supply. The software used includes the Arduino IDE for control implementation, and MATLAB for modelling, PSO optimization, and control-system simulation.

System Modelling and PID Control Design

The rotational speed of the PG45 DC motor is controlled using a PID controller, mathematically expressed in Equation (1).

$$u(t) - K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

where e(t) is the difference between the 120 RPM reference speed and the actual speed read by the rotary encoder, while Kp, Ki, and Kd are the gain constants determined through the optimization process. The PID equation is implemented in discrete form on the microcontroller, equipped with integral anti-windup to prevent excessive error accumulation when the actuator saturates, a low-pass filter ($\alpha = 0.75$) on the speed reading to suppress noise from mechanical vibration, and feedforward control to accelerate the motor's initial response toward the target speed.

PID Parameter Optimization Using PSO

The Kp, Ki, and Kd parameters were not determined manually but obtained through optimization using the Particle Swarm Optimization (PSO) algorithm with an Integral Time Absolute Error (ITAE) objective function, expressed in Equation (2).

$$ITAE = \int_0^T t \mid e(t) \mid dt \tag{2}$$

Each particle represents one combination of Kp, Ki, and Kd, evaluated based on the ITAE value from the closed-loop control-system simulation against the 120 RPM target speed. The PSO algorithm parameters and the PID parameter search range used are shown in Table 1 and Table 2.

Table 1. Particle Swarm Optimization algorithm parameters.

Parameter	Value
Number of particles	15
Maximum number of iterations	20
Inertia weight (w)	0.6
Cognitive coefficient (c_1)	1.5
Social coefficient (c_2)	1.5

Table 2. PID parameter search range.

Parameter	Lower bound	Upper bound
Kp	0.1	5.0
Ki	0.5	10.0
Kd	0.0	0.5

Simulation and Testing

Simulation was carried out in MATLAB over 6 seconds with a sampling time of 0.005 seconds and a target motor speed of 120 RPM to produce a compression rate of 120 CPM in accordance with the AHA standard. After the optimized PID parameters were verified through simulation, they were implemented in the Arduino Mega 2560 program to control the PG45 DC motor on the CPR device prototype. Implementation testing was carried out on a CPR manikin, including motor speed testing using the rotary encoder and a digital tachometer. The agreement between simulation and implementation results was evaluated using the Root Mean Square Error (RMSE) method in Equation (3).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(r_i - y_i)^2} \quad (3)$$

where r_i is the simulated data, y_i is the implementation data, and N is the number of test data points.

RESULTS AND DISCUSSION

PID Parameter Optimization Results Using PSO

The PSO-based optimization process successfully obtained a combination of PID parameters with a minimum ITAE objective-function value of 2.3586, as shown in Table 3.

Table 3. PSO-optimized PID parameters.

Parameter	Value
Kp	5.0000
Ki	2.9519
Kd	0.5000
ITAE value	2.3586

The PSO convergence curve shows the Global Best ITAE value decreasing from 3.1617 at the first iteration to 2.3586 at the fifth iteration, then remaining relatively constant up to the 20th iteration. This indicates that the algorithm had converged and no better solution was found within the defined search space.

Simulation Results

Simulation using the optimized PID parameters showed that motor speed was able to rise quickly toward the 120 RPM reference value and maintain its rotation with very small fluctuations, without excessive oscillation. This good tracking performance was supported by the feedforward control, the low-pass filter on the speed reading, and the integral anti-windup. The resulting PWM signal was in the range of 245–255, indicating that the motor requires a relatively high voltage to maintain 120 RPM while driving the crank-slider mechanism.

Implementation and Motor Speed Testing Results

The PSO-optimized PID parameters were applied to the Arduino Mega 2560 program to control the PG45 DC motor through the BTS7960 driver based on rotary encoder feedback. The physical realization of the resulting portable CPR device is shown in Figure 1.

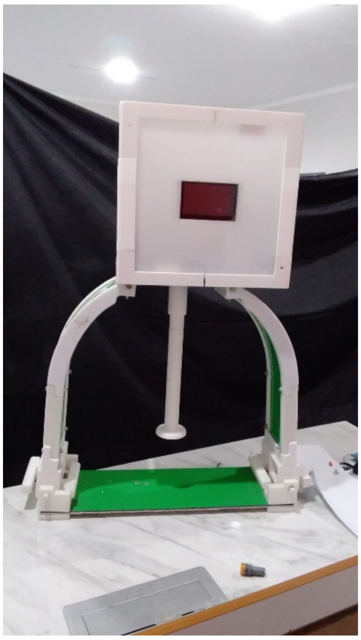

Figure 1. Prototype of the developed cardiopulmonary resuscitation device (Source: personal documentation)

Motor speed testing was conducted with a reference target of 120 RPM. The results showed that actual motor speed under implementation conditions varied between 80.1 RPM and 110.7 RPM, with the error percentage decreasing from about 33% at the beginning of testing to about 7.8% as the system approached steady state, as shown in Table 4.

Table 4. Motor speed test results (summary).

Target RPM	Actual RPM	Error (%)
120	80.1 – 87.3	27.3 – 33.3
120	98.2 – 103.4	13.8 – 18.2
120	108.2 – 110.7	7.8 – 9.8

Comparison of Simulation and Implementation

The comparison between simulation and implementation results for the motor speed parameter is shown in Table 5. The average motor speed in implementation was 91.95 RPM, lower than the 120 RPM simulation target, with an average difference of 28.05 RPM. RMSE analysis of the motor speed data yielded a value of 30.12, indicating a fairly significant deviation between the simulation model and the real implementation conditions.

Discussion

The MATLAB simulation results show good control performance because the model used still assumes ideal conditions without the effects of mechanical friction, dynamic loading, component tolerances, or hardware disturbances. Under real implementation conditions, motor speed exhibited a transient response with overshoot at the start of operation before reaching a relatively stable condition, but was unable to reach the 120 RPM reference value and remained in the 80–110 RPM range while the system worked against the compression-mechanism load.

This difference is influenced by several factors. First, the accuracy of the rotary encoder as the feedback sensor can be reduced by missing pulses or noise caused by mechanical vibration, so the RPM value calculated by the microcontroller may deviate from the actual speed. Second, the speed-torque characteristic of the PG45 DC motor causes rotational speed to decrease as load increases due to mechanical friction in the crank-slider mechanism, bearings, and the efficiency of the 71:1 gearbox. Third, the speed specification on the motor datasheet is generally the no-load speed, whereas in implementation the motor operates under a mechanical load that varies throughout the compression cycle, thus requiring greater torque to maintain constant rotation.

Although motor speed in the implementation did not fully reach the simulation target, compression depth remained consistent within the 55.8–56.0 mm range (about 5.6 cm) with an error below 0.4%, because compression depth is determined mechanically by the crank-slider geometry and does not depend entirely on achieving the motor's reference speed. This shows that the main strength of the PID-PSO control developed in this study lies in the optimization's convergence speed and response stability in the simulation domain, while the motor-speed aspect in the physical implementation still requires further improvement, particularly through the selection of a higher-torque actuator and improved quality of the encoder feedback signal.

Table 5. Comparison of simulated and implemented motor speed.

Parameter	Simulation	Implementation	Difference
Target RPM	120.0	120.0	0
Average RPM	120.0	91.95	28.05
Minimum RPM	120.0	80.1	39.9
Maximum RPM	120.0	110.7	9.3

CONCLUSION

Speed control of the PG45 DC motor driving the crank-slider mechanism of an Arduino Mega 2560-based automatic CPR device was successfully designed using a PID controller whose parameters were optimized through the PSO algorithm with an ITAE objective function. Optimization yielded Kp = 5.0000, Ki = 2.9519, and Kd = 0.5000 with a minimum ITAE of 2.3586, producing a fast and stable motor-speed response in MATLAB simulation with a 120 RPM target. In implementation, motor speed only reached the 80–110 RPM range out of the 120 RPM target, with an RMSE of 30.12, due to the viscoelastic load resistance of the manikin chest wall, internal mechanical friction, and the torque limitations of the PG45 DC motor under peak load. Nevertheless, compression depth remained consistently within the AHA standard of 5–6 cm with an error below 0.4%, showing that the developed PID-PSO control is effective in the simulation domain and requires further refinement in physical implementation, particularly through the use of a higher-torque actuator, improved encoder feedback quality, and the application of adaptive control methods such as Adaptive PID or Fuzzy-PID in future research.

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