Design and Implementation of a Single-Axis Solar Tracking System Optimized by the Chimp Optimization Algorithm (CHOA)

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***Abstract*—The utilization of solar energy as a renewable energy source continues to be developed due to its abundant availability and environmentally friendly characteristics. However, the output power of a solar module is strongly influenced by the direction of incoming sunlight, causing a statically installed solar module to not always receive optimal light intensity throughout the day. This research designs and implements a single-axis solar tracking system using the Chimp Optimization Algorithm (CHOA) to optimize the PID control parameters governing the angle of the solar module. The designed system uses an ESP32 microcontroller, LDR sensors as light-intensity detectors, a DC motor as the actuator, and an L298N motor driver. Testing compared the solar module output without and with the tracking system over 12 hours (06.00–18.00). The module without tracking produced an average voltage of 5.87 V, current of 445.77 mA, and power of 2804.31 mW, while the module with tracking produced 6.41 V, 532.31 mA, and 3673.93 mW — an increase in output power of 31.01%. In addition, CHOA-optimized PID control enabled the system to reach the 90° angle setpoint with a settling time of 3 s, an overshoot of only 0.5%, and a steady-state error of ±0.5°, clearly outperforming conventional ON-OFF and manually tuned PID control.**

Keywords*—*Solar tracker, single-axis, solar module, Chimp Optimization Algorithm (CHOA), PID control, angle optimization.

I. INTRODUCTION

Solar energy is one of the most abundant and environmentally friendly renewable energy sources, and global installed capacity continues to expand rapidly [1]. Indonesia, located on the equator, has substantial solar energy potential that remains underutilized relative to its resource availability [4], and interest in photovoltaic (PV) deployment for both grid-connected and standalone applications continues to grow [3], [6]. However, the power output of a PV module is strongly dependent on the angle of incidence of sunlight, since incoming irradiance on tilted and horizontal surfaces varies substantially throughout the day [2]. A statically mounted solar module is therefore unable to maintain optimal light absorption as the sun's position changes.

Solar tracking systems address this limitation by continuously adjusting the orientation of a PV module to follow the sun. Prior studies report that tracking systems, whether single-axis or dual-axis, consistently outperform fixed installations in output power and energy yield [11], [12]. Various tracking and control strategies have been implemented, including fuzzy-logic-based single-axis trackers [7], Internet-of-Things-based tracking optimization [10], and irradiance-responsive designs evaluated under real installation conditions [5], [9], [13]. Despite these advances, many implementations still rely on conventional ON-OFF or manually tuned PID controllers, which often exhibit oscillation, overshoot, and steady-state error when driving the tracking actuator toward a target angle.

Metaheuristic optimization algorithms offer an effective way to automatically tune controller parameters without exhaustive manual trial and error [14]. Among these, the Chimp Optimization Algorithm (CHOA), inspired by the cooperative hunting behavior of chimpanzees, has demonstrated competitive convergence speed and solution stability across nonlinear optimization problems [15] and has been extended and applied to combinatorial matching [16], general engineering optimization [17], and energy-management problems in microgrids [18]. CHOA-based optimization has also shown strong results in photovoltaic maximum-power-point tracking [19] and in tuning proportional–integral controllers for renewable-energy-integrated microgrids [20], motivating its application to PID tuning in a solar tracking context.

This paper proposes a single-axis solar tracking system in which CHOA is used to optimize the PID controller that drives the tracking motor toward the target module angle. The system uses an ESP32 microcontroller, dual LDR sensors, an L298N motor driver, and a DC actuator. Its performance is evaluated against conventional ON-OFF control and manually tuned PID control, and the resulting solar module output power with and without tracking is compared to quantify the practical energy benefit of the proposed system.

II. SYSTEM DESIGN AND CHOA-BASED OPTIMIZATION

A. System Overview

The solar tracking system consists of a solar module mounted on a single-axis mechanical frame, driven by a geared DC motor through an L298N driver. Two LDR sensors, positioned on the left and right sides of the module, measure the incoming light intensity from each side. An ESP32 microcontroller reads the LDR data, runs the CHOA-tuned PID control loop, and issues PWM signals to the motor driver to rotate the module toward the side receiving stronger illumination. Fig. 1 shows the overall system block diagram.

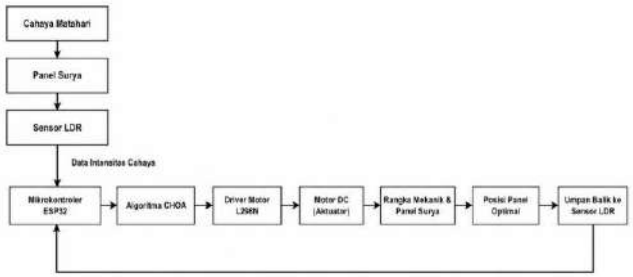

Fig. 1. Block diagram of the single-axis solar tracking system.

B. Objective Function

The optimization objective is to maximize the output power of the solar module by finding the optimal module angle θ:

$$\text{Maximize } f(\theta) = P(\theta) \tag{1}$$

where the output power is the product of the module's output voltage and current:

$$P(\theta) = V(\theta) \times I(\theta) \tag{2}$$

subject to the mechanical range of the tracking actuator:

$$\theta_{min} \le \theta \le \theta_{max} \tag{3}$$

Rather than searching the angle directly, CHOA is applied to tune the gains (Kp, Ki, Kd) of the PID controller that drives the module toward the light-intensity-balanced setpoint, so that the resulting closed-loop response minimizes tracking error, oscillation, and settling time.

C. Chimp Optimization Algorithm (CHOA)

CHOA is a population-based metaheuristic inspired by the cooperative hunting behavior of chimpanzees, in which individuals take on the roles of attacker, chaser, barrier, and driver [15]. The algorithm proceeds through four stages.

1) Searching: initial positions are generated randomly within the search space:

$$X_i = X_{min} + r \times (X_{max} - X_{min}) \tag{4}$$

2) Attacking: individuals move toward the best-known position, guided by coefficients A and C:

$$X(t+1) = X^*(t) - A \times |C \times X^*(t) - X(t)| \tag{5}$$

$$A = 2a \times r_1 - a\,, \quad C = 2 \times r_2 \tag{6}$$

where a decreases linearly from 2 to 0 over the course of the iterations, and r_1, r_2 are random numbers in [0, 1]. 3) Hunting: each individual updates its position based on the average of the four role positions (attacker, driver, barrier, chaser):

$$X(t+1) = (X_1 + X_2 + X_3 + X_4) / 4 \tag{7}$$

4) Chasing: as parameter a approaches zero, all individuals converge around the best solution found, completing the exploitation phase. Compared with PSO and GA, CHOA requires no selection, crossover, or mutation operators, giving it lower computational overhead suitable for embedded implementation on the ESP32, while its multi-role exploitation mechanism gives it more adaptive convergence behavior than a single-leader algorithm such as GWO.

D. CHOA–PID Integration

CHOA is applied offline to search for the PID gain combination (Kp, Ki, Kd) that minimizes tracking error, motor oscillation, and energy consumption during the step response toward the 90° setpoint. Each candidate gain set is evaluated by simulating the system's response and computing its fitness; candidates are iteratively updated through the CHOA search stages until the best-performing combination is obtained. The optimized gains are then loaded into the ESP32 firmware to control the DC motor in real time, allowing the module to track the sun's position more quickly and with less oscillation than a manually tuned controller.

III. Results and Discussion

A. Hardware Implementation

The complete single-axis solar tracking system was implemented and tested, consisting of a solar module mounted on a mechanical frame driven by a geared DC motor, with the ESP32 controller, LDR sensors, and L298N driver housed at the base of the structure, as shown in Fig. 2.



Fig. 2. Hardware implementation of the single-axis solar tracking system.

B. Control Method Comparison

Three control strategies were tested for driving the module toward the 90° setpoint: conventional ON-OFF control, manually tuned PID control, and CHOA-optimized PID control. The measured step responses are shown in Fig. 3–5.

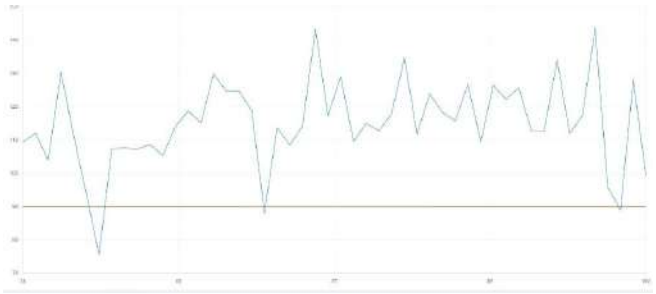

Fig. 3. Step response of the ON-OFF control method.

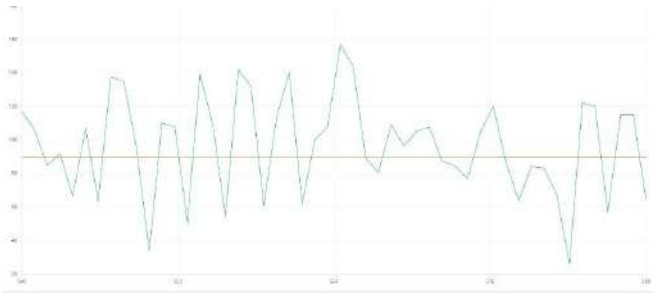

Fig. 4. Step response of the manually tuned PID control method.

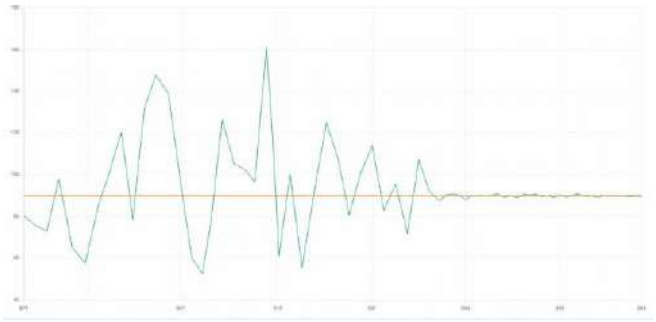

Fig. 5. Step response of the CHOA-optimized PID control method.

As shown in Fig. 3–5, ON-OFF control exhibits large, sustained oscillation around the setpoint because it only has two discrete actuation states. Manual PID control substantially smooths the response but still shows a noticeable overshoot and a lingering steady-state offset. CHOA-optimized PID control settles quickly with minimal overshoot and converges tightly around the 90° setpoint. Table I and Table II summarize the qualitative and quantitative comparison.

TABLE I. Qualitative Performance Comparison of Control Methods

Parameter	ON-OFF	PID	PID+CHOA
Overshoot	High	Moderate	Low
Oscillation	High	Low	Very low
Settling time	Slow	Moderate	Fast
Steady-state error	Large	Small	Very small
System stability	Low	Fairly stable	Very stable

TABLE II. Quantitative Transient Response Comparison

Parameter	ON-OFF	PID	PID+CHOA
Rise time (s)	1.5	3.0	2.2
Settling time (s)	> 10 (unstable)	6.0	3.0
Overshoot (%)	8	5	0.5
Steady-state error	±5°	±2°	±0.5°

The quantitative results in Table II confirm that CHOA-optimized PID control achieves the fastest settling time (3.0 s versus 6.0 s for manual PID and over 10 s, unstable, for ON-OFF), the lowest overshoot (0.5% versus 5% and 8%), and the smallest steady-state error (±0.5°). ON-OFF control has the fastest rise time because it applies full actuation immediately, but this comes at the cost of instability and large steady-state error.

C. CHOA-Optimized PID Parameters

Table III compares the PID gains obtained through manual tuning with those obtained through CHOA optimization.

TABLE III. PID Parameters: Manual Tuning vs. CHOA Optimization

Parameter	Manual PID	PID + CHOA
Kp	2.0	6.0
Ki	0.05	0.02
Kd	1.0	1.5

CHOA increased the proportional gain (Kp: 2.0 → 6.0) for a faster error response, reduced the integral gain (Ki: 0.05 → 0.02) to limit error accumulation and oscillation, and increased the derivative gain (Kd: 1.0 → 1.5) to damp overly fast transitions. This combination explains the smoother, faster, and more accurate response observed in Section III-B.

D. Solar Module Output Power Comparison

Output voltage, current, and power were logged over a 12-hour period (06.00–18.00) for the module without tracking and, on a separate day under comparable conditions, with the CHOA-PID tracking system active. Table IV summarizes the average values.

TABLE IV. Average Solar Module Output With and Without Tracking

Condition	Voltage (V)	Current (mA)	Power (mW)
Without tracking	5.87	445.77	2804.31
With tracking	6.41	532.31	3673.93

The tracking system increased the average output power from 2804.31 mW to 3673.93 mW, an improvement of **31.01%**, by continuously reorienting the module toward the direction of maximum light intensity rather than remaining in a fixed position. This result confirms that the accuracy and stability gained from CHOA-optimized PID control translate directly into a measurable increase in harvested solar energy.

IV. CONCLUSION

This paper presented the design and implementation of a single-axis solar tracking system in which a Chimp Optimization Algorithm (CHOA) was used to tune the PID controller governing the tracking motor. Compared with conventional ON-OFF and manually tuned PID control, the CHOA-optimized PID controller achieved the fastest settling time (3.0 s), the lowest overshoot (0.5%), and the smallest steady-state error (±0.5°) in reaching the 90° angle setpoint. In a 12-hour field test, the tracking system increased the solar module's average output power by 31.01% compared with a fixed installation. These results indicate that CHOA-based PID tuning is an effective and computationally lightweight approach for improving the accuracy, stability, and energy yield of embedded solar tracking systems, and that the resulting system can contribute to more efficient utilization of solar energy in Indonesia's high-irradiance regions. Future work includes extending the system to dual-axis tracking, incorporating long-term real-time data logging, adding an IoT-based remote monitoring layer, and evaluating

robustness under external disturbances such as wind and partial shading.

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