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An effective energy production and analysis in a solar tracking system

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Abstract: - The PV cells are widely used for the purpose of capturing solar energy and converting it into electricity. Throughout the day, as we know, the Earth moves from west to east and the seasons change, the angle at which its radiation from Sun hits the Earth also changes. Consequently, the output power of PV panels fluctuates. When PV panels are oriented parallel to the sun's path, their output voltage increases. The motive of this research is to upgrade the efficiency of solar tracking systems by minimizing mechanical tracking errors and reducing energy consumption. To achieve this, a PID controller is employed, which is based on the Oppositional-based Chimp Optimization Algorithm (OChOA). The system implements and simulates four energy-saving strategies. The simulation results illustrates that the proposed controller achieves a tracking error of 0.0541^{o} and an energy consumption of 3.56879 Wh, surpassing the performance of existing techniques.

Keywords: Oppositional-based Chimp Optimization Algorithm (OChOA), PID controller, Tracking Error, Solar Tracking System and Energy Consumption.

I. INTRODUCTION

All Conventional energy resources possess substantial implications for climate change, particularly as the availability of fossil fuels diminishes gradually. This has garnered considerable attention towards renewable energy sources, which not only fulfill the current global energy demands, but also offer a plethora of advantages including economic benefits, minimal pollution, and sustainability [1][2]. Consequently, energy potentials such as wind, solar, hydropower, geothermal, biofuels, and biomass [3] have emerged as viable energy alternatives, even in regions abundant in fuel reserves. Consequently, the contribution non-conventional energy to the global energy framework is experiencing exponential growth [4]. The incongruity between power production and consumption, prevalent in both on grid and off-grid contexts, presents challenges within an integrated energy system [5]. Solar systems offer the advantage of being deployable on a limited scale, allowing them to be used for producing both heat and energy, in various structures [6]. Solar energy, due to its numerous advantages, is considered as one of the renewable energy resources (RES). Over the past few decades, photovoltaic systems have made significant progress. PV has the ability to provide power in a consistent, environmentally-friendly, noiseless, and secure manner, keeping low operational cost [7], [8]. Solar photovoltaic (PV) modules capture sunlight and convert it into energy [9]. Besides solar panels, small photovoltaic cells can also be used for power, in small appliances. These panels may be interconnected to create a large-scale solar array [10].

PV panels exhibit a suboptimal efficiency level (ranging from 9 to 17%) and are susceptible to environmental variables such as temperature and irradiation [11], [12]. Given the circuitous nature of its characteristics, the emf of the photovoltaic (PV) system tends to be moderate, potentially making it insufficient for certain load applications. In addition, its performance is affected by the availability of solar energy. Both flat photovoltaic (PV) and concentrated solar power (CSP) systems have the capability to transform solar energy into electrical power. The value of solar energy accumulated by these mechanisms directly affects the resulting electricity output. Aligning the panel orthogonal to the sun's rays maximizes the efficiency of the photovoltaic system. [13]. Consequently, it is imperative to vigilantly monitor the sun's position to optimize PV cell concentration, radiation, and efficiency. Notably, recent advancements have augmented the direct and indirect solar energy generation potential of these technologies. Among these advancements, a sun tracking system (STS) is frequently employed to harness the sun's energy to its fullest extent. These systems are of utmost importance for

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applications such as spaceflight. Sun tracking systems are mechanisms utilized to monitor the motion of the sun across the celestial dome with the intention of preserving solar photovoltaic panels at the most advantageous angles for the purpose of achieving maximum power generation and, by extension, effective energy accumulation [14]. Solar trackers may provide more direct sunlight exposure compared to fixed solar photovoltaic panels. In order to enhance solar energy, numerous sun-tracking systems have been extensively studied in literature, including two axes, one axis, azimuth and another is tilt roll systems [15]. However, only a few of these tracking technologies incorporate ST (solar tracking), which optimizes the tilt angle to capture the greatest amount of solar energy. Nevertheless, these methods have various shortcomings that can only be overcome by ST when properly calibrated and managed. Additionally, CSP systems have the capability to compensate for daily altitude, seasonal latitude, and fluctuations in solar azimuth [16].

In order to optimize the performance of photovoltaic systems and maximize their output, the utilization of complex control mechanisms becomes necessary. These mechanisms are employed to upgrade the performance of solar tracking systems. Among the strategies utilized for controlling solar tracking systems, control models and optimization algorithms play a crucial role. In these control models, various types of controllers are investigated to achieve maximum performance. Solar tracking systems widely employ PID (Proportional Integral Derivative) controls, which are also utilized in other sectors. The installation of PID controllers is quick and cost-effective due to their ease of use and their ability to address most control challenges. However, determining the optimal gain settings to achieve the highest revenue can be a time-consuming and challenging task. The execution of the solar tracking system may be compromised if improper gain settings are used. By appropriately configuring the integral, proportional, and derivative parameters, the PID controller has the potential to enhance the system's performance. To efficiently tune PID controllers, various optimization methodologies such as Cuckoo Search Algorithm, Firefly Algorithm, Particle Swarm Optimization (PSO), and teaching learning-based optimization (TLBO) have been developed. However, evaluating the performance of solar tracking systems and maximizing their output energy in present scenario is focused. One of the methods employed is the fuzzy logic controller, which utilizes a database to identify the nearest location for direct sunlight. Additionally, perturb and observe, iterative learning control, and hybrid techniques are utilized. However, these techniques lack precision, performance, and capability in the context of sun tracking systems. Furthermore, they consume significant amounts of energy and exhibit tracking inaccuracies. The motive of this research is to develop a PID controller-based technique to minimize tracking errors and energy consumption in sun tracking systems.

The later sections of the article are as follows: Section 2 reviews relevant scientific articles, focusing primarily on the sun tracking system. Section 3 presents the proposed system, which incorporates a PID controller and an optimization approach based on OChOA [28]. Section 4 shows the simulation results. Finally, Section 5 provides a conclusion of the research.

II. Literature Review

Table 1 illustrates the precise depiction of the most recent investigations conducted in the respective field. However, the primary element is still deficient in terms of quantity. This objective can be accomplished by means of a recent study employing an Oppositional-based Chimp Optimization Algorithm (OChOA), implemented Sun tracker to the utmost degree. The implementation of an opposition-based algorithm in this particular study would enable a further enhancement in tracking efficiency that follow.

III. Materials and Methods

A. Proposed solar tracking system architecture

Figure 1 illustrates the schematic design of the photovoltaic (PV) system, incorporating the proposed solar tracker. The proposed proportional-integral-derivative (PID) controller is situated in the lower section, while the solar tracker is positioned in the upper section. The calculation of angles can be achieved through azimuth and elevational control, with this data being provided to the Solar tracker controller initially, and subsequently transmitted to the PV panel movement mechanism. Subsequently, the movement of panel will be adjusted to align with the Sun's trajectory. The PID parameters will optimize the motion values and adjust the controller settings for the motor. This optimization process will be refined using the Oppositional based Chimp optimization algorithm, potentially enhancing the findings in current research related to Sun tracking systems.

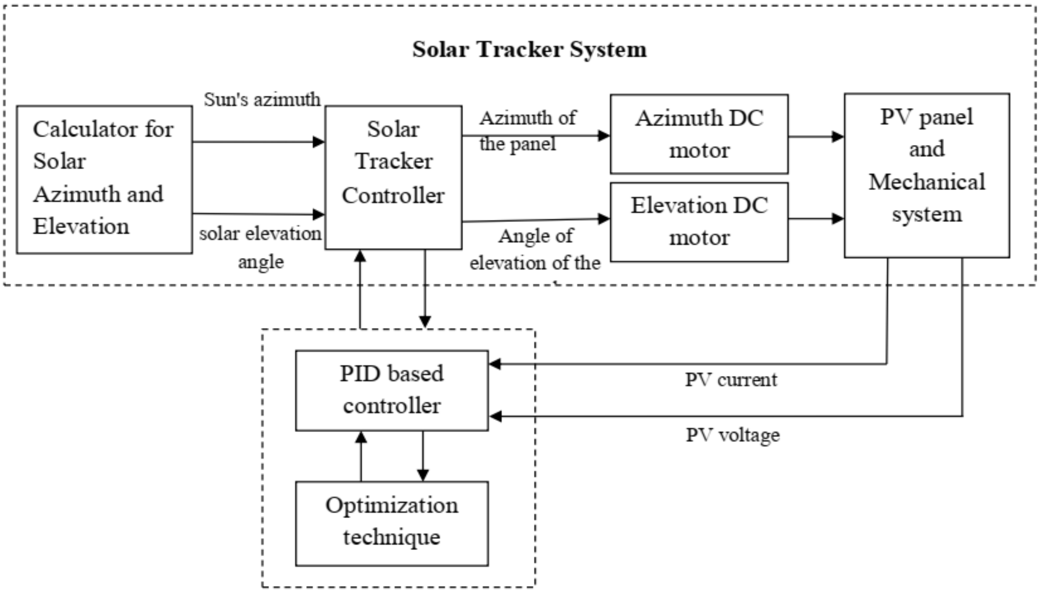


Figure 1: Proposed Solar Tracking System Architecture

In depth analysis will give a focus to solar tracker's solar azimuth and elevation angle calculations. This controller will execute its operation with the help of a wire connects the PV panel supporting structure to the solar beam. The proposed PID controller spins the solar tracker. $R^{2\times2}$ stands for the motor's effective inertia matrix, $C(q,\dot{q}) \in R^{2\times2}$ $\tau \in R^2$.The gravitational effect vector is indicated as g(q) R^2, and $\tau \in R^2$ for the control input. The model's explicit values give a perfect picture on efficiency and tracking error, as per the table 1.

Sl.No	Author	Reference	Tracking error	Power gain in %	Efficiency Of the system
1	Sidek *et al.*	[17]	1.8-2.1%	12.8-26.9%	46.8%
2	Zhu *et al.*	[20]	1.1-1.78%	24.7-37.4%	58-60%
3	Nadia *et al.*	[22]	0.9-1.3%	25.6%	63-68%
4	Batayneh *et al.*	[21]	0.24-0.6%	27.4%	72-74%
5	Flores-Hernandez *et al.*	[18]	0.062 & 0.071%	26.98%	76.5-79%
6	Mirza Muhammad *et al.*	[19]	0.0541%	31%	81.4%
7	Praveen P N *et al.*	[34]	0.034%	43.6%	88.75%

Table 1: Tracking error and Efficiency of various Solar Tracking System designs

B. Tracker modeling

The tracker's kinematic and kinetic models are created [18]. The system dynamics may be characterized by eqn. (1), according to [23]:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \quad (1)$$

The axis angular position, velocity, and acceleration are represented by, $\dot{q}$, $\ddot{q} \in R^2$, respectively.

The word D(q) ∈ $D(q) = \begin{bmatrix} m_2 l_{cm_2}^2 C_2^2 + I_{y_1} + I_{x_2} S_2^2 + I_{y_2} & 0 \\ 0 & m_2 l_{cm_2}^2 + I_{z_1} \end{bmatrix}$ $C(q,\dot{q}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$,

$$q(q) = \begin{bmatrix} 0 \\ m_2 g l_{cm_2} C_2 \end{bmatrix}, \ \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (2)$$

Where $I_i = diag\{I_{x_i}, I_{y_i}, I_{z_i}\}$, i=1,2 represents the inertia tensor of link I, the mass of link 2 is mentioned as m2 .The distance from frame {1} to the center of mass of link 2 is denoted as l_{cm_2} and (S2,C2 stands for sin (q2) and cos (q2), respectively.)

$C_{11} = (I_{x_2} - I_{y_2} - m_2 l_{cm_2}^2) C_2 S_2 \dot{q}_2$, $C_{12} = (I_{x_2} - I_{y_2} - m_2 l_{cm_2}^2) C_2 S_2 \dot{q}_1$ $C_{21} = (-I_{x_2} - I_{y_2} - m_2 l_{cm_2}^2) C_2 S_2 \dot{q}_1$, and $C_{22} = 0$.

This simplifies simultaneous robotic control in the following schemes. The tracker's alternate approximate linear dynamics are:

$$\dot{J}\ddot{q} + B\dot{q} = u + d \quad (3)$$

J ∈ $R^{2\times2}$, $J = diag\{J_1, J_2\}$, J1,J2>0 signifies the efficient inertia matrix, B ∈ $R^{2\times2}$, $B = diag\{b_1, b_2\}$ the linear damping effects, u ∈ R^2 the input vector, and d ∈ R^2 the disregarded dynamics and non-modeled factors, which are considered to be locally constant [24].

C. Proposed PID controller

The simplified model which supports the PID control application, delivers consistent results. To calculate the control action proportionate to the integral of tracking error, we employ three terms: proportional, integral, and derivative. [25, 26] show how to use the PID for two-axis solar trackers, with acceptable tracking errors. The PID's general model is:

$$u(t) = K_p e(t) + \frac{K_i}{T_i}\int_0^t e(\tau)d\tau + K_d T_d \dot{e}(t) \quad (4)$$

Kmax=12 is the maximum number of possible combinations as a result. Because of the STS's use, tracking inaccuracy and energy consumption are of equal importance; as a result, the weights are set at w1=w2 =0:5. Traditional PID controllers, on the other hand, are ineffective in reducing tracking error and energy usage. As a consequence, to decrease the solar tracking system error and energy consumption, the PID controller must be calibrated to maximize the maximum power output and maximum efficiency from the PV panel. Adjusting parameters such as K_P K_I and K_D determines the performance of a PID controller. The OChOA method is inured to enhance the PID controller's performance.

D. Operating Conditions of Proposed Approach for Energy Saving Strategies

There are twelve distinct approaches (p=12) for the ESS based on the hardware's four energy-saving modes and the two ways of tracking system axis activation (sequential or parallel). A proportional-integral-derivative (PID) controller based on OChOA is supplied for TS, taking into account hardware aspects as well as the fact that the actuators are DC motors.

Table 2 depicts four probable ESS (n=4) based on sequential and parallel activation. Sequential movement means the azimuthal axis movement followed by elevation axis. Parallel activation happens when both axes reach the same destination.

E. Tuning the PID Controller Parameters using the Oppositional based Chimp Optimization Algorithm

The modification of the controller is imperative in order to reduce tracking error and energy consumption, thereby maximizing the efficiency of the solar tracking system. To enhance the performance of the PID controller by optimizing the improvement parameters, the Oppositional-based Chimp Optimization Algorithm (OChOA) is employed. Opposition-based learning, which is considered one of the most effective methods for refining the initial solution of the ChOA algorithm (OBL), is utilized.

ESS	Movement	Sleep mode
ESS_1	Sequential	Disabled
ESS_2	Parallel	Disabled
ESS_3	Sequential	Enabled
ESS_4	Parallel	Enabled

Table 2: Energy saving strategies

F. Opposition based learning (OBL)

In principle, all evolutionary algorithms commence with a random population and eventually ascertain the optimal solution and reach the desired state through iterations. The duration of convergence for these algorithms is directly connected to the disparity between the original predictions and the most favorable outcome. If the initial solution is in close proximity to the ideal solution, convergence transpires swiftly; conversely, it takes a longer duration. Opposition based learning (OBL) [27] represents a highly effective approach for enhancing the initial solution by concurrently evaluating the current candidate solution and its opposing solution, and subsequently selecting the most appropriate alternative as the initial response. In accordance with the principles of probability theory, each projected solution is situated at a distance 0.5 times greater from the actual solution in comparison to its opposite option. This technique bears great significance not only in the creation of the initial population, but also in the continual improvement of the final output.

In the context of an optimization problem, the concept of OBL is predicated upon the simultaneous analysis of both the current candidate solution and its opposing solution.

G. Chimp optimization algorithm

The Chimp Optimization Algorithm (ChOA) suggested by Khishe et al. ((2020) [28] and is based on chimp's individual intellect and sexual motivation in collective hunting.

H. Mathematical model and algorithm

The mathematical models for driving, impeding, pursuing, and assaulting a self-contained group are covered in this section. After that, the matching ChOA algorithm is provided.

I. Pursuing and driving the prey

The prey hunt throughout the exploitation and exploration stages, as previously stated. Eqs. (5) and (6) are provided as analytical representations of pursuing and driving the prey [29].

$$D = \left| c.z_{prey}(t) - m.z_{chimp}(t) \right| \tag{5}$$

$$z_{chimp}(t+1) = z_{prey}(t) - a.D \tag{6}$$

Where t be present iteration number, a, m, and c gives the vector coefficients, z_{prey} signifies prey location vector, and z_{chimp} indicates chimp position vector, and z_{prey} signifies prey location vector. The a, m, and c vectors are computed using Eqs. (7) – (9), respectively.

$$a = 2.f.r_1 - f \tag{7}$$

$$c = 2.r_2 \tag{8}$$

$$m = chaotic\_value \tag{9}$$

The non-linear decrease of f is denoted across iterations [0, 2.5], where r1 and r2 are arbitrary values ranging from 0 to 1. The sexual motivations of the chimpanzees are represented by the chaotic vector m. The ChOA commences with a stochastic population of chimpanzees, followed by random assignment into four categories: driver, barrier, attacker, and chaser. The behavior of every group affects the positioning of certain chimpanzees.

J. Proposed Oppositional based Chimp Optimization Algorithm

The notion of opposition based learning is infused into conventional ChOA in the proposed approach to increase the ChOA's performance as well as their convergence speed. The following is a full explanation of OChOA's method for determining the appropriate gain setting for a PID controller. The flowchart of OChOA is shown in Figure 2.

Step 1: Opposition based initialization

To control the opposition's step size, ai and bi should be modified constantly. Instead of utilising fixed interval boundaries, the opposite solution is discovered by considering the lowest and highest values for each dimension in the current population ($[a_i, b_i]$). Pigeons will be able to pick better locations due to the dynamic opposition, and convergence will be faster. The following is how the new opposition-based technique is calculated:

$$OP_{i,j} = a_j^p + b_j^p - P_{i,j} \tag{10}$$

Where $P_{i,j}$ symbolizes j-th position vector of the population's i-th chimp, $OP_{i,j}$ implies inverse of $P_{i,j}$, and a^p_j and b^p_j represents j-th dimension's low and high values.

Step 2: Initialization

At first, the chimp population parameters and number of iterations are initialized. Also, the PID controller gain parameters such as K_P, K_I and K_D are initialized. In addition, set the values for i=1, j=1, n=0, m=0, K=1 and Kmax =n.m. Then create a random initial combination $C_{ini_{i,j}}$.

Step 3: Calculate each chimp's location.

Step 4: Divide the chimpanzees into groups at random until they reach the stopping condition.

Step 5: Figure out how to use the fitness feature.

The major goal of this research is to reduce the PID controller's steady state inaccuracy. Generally, when response has reached the steady state, difference between desired value and actual value of system is called as steady-state error. Fitness function (Fit) of every search element of chimp of this algorithm is computed as follows,

$$Fit = \min imize\ U(C_{i,j}) \tag{11}$$

Step 6: The following are computed for all iterations::

- Find out the best component of search = $\mathbf{x}_{Attacker}$
- Find out the best component of search =$\mathbf{x}_{Chaser}$
- Find out the best component of search =$\mathbf{x}_{Barrier}$
- Find out the best component of search =$\mathbf{x}_{Driver}$

Step 7: If the current iteration is less than the total iterations t < Max_{item}

Step 8: Taking a group of chimpanzees and updating c, m, f, and then utilizing the group's strategy to calculate a, d.

Step 9: The Eq.(5) updates the current search agent's location.

Step 10: By using the Eq.(9) you may update the location of the current search.
Step 11: Update f, m, a and c and Update $z_{Attacker}$, z_{Driver}, $z_{Barrier}$, z_{Chaser}

Step 12: If the criteria is met, then the operation will be repeated until the convergence criteria values are achieved. Then the iteration will be updated and return $\mathbf{z}_{Attacker}$.

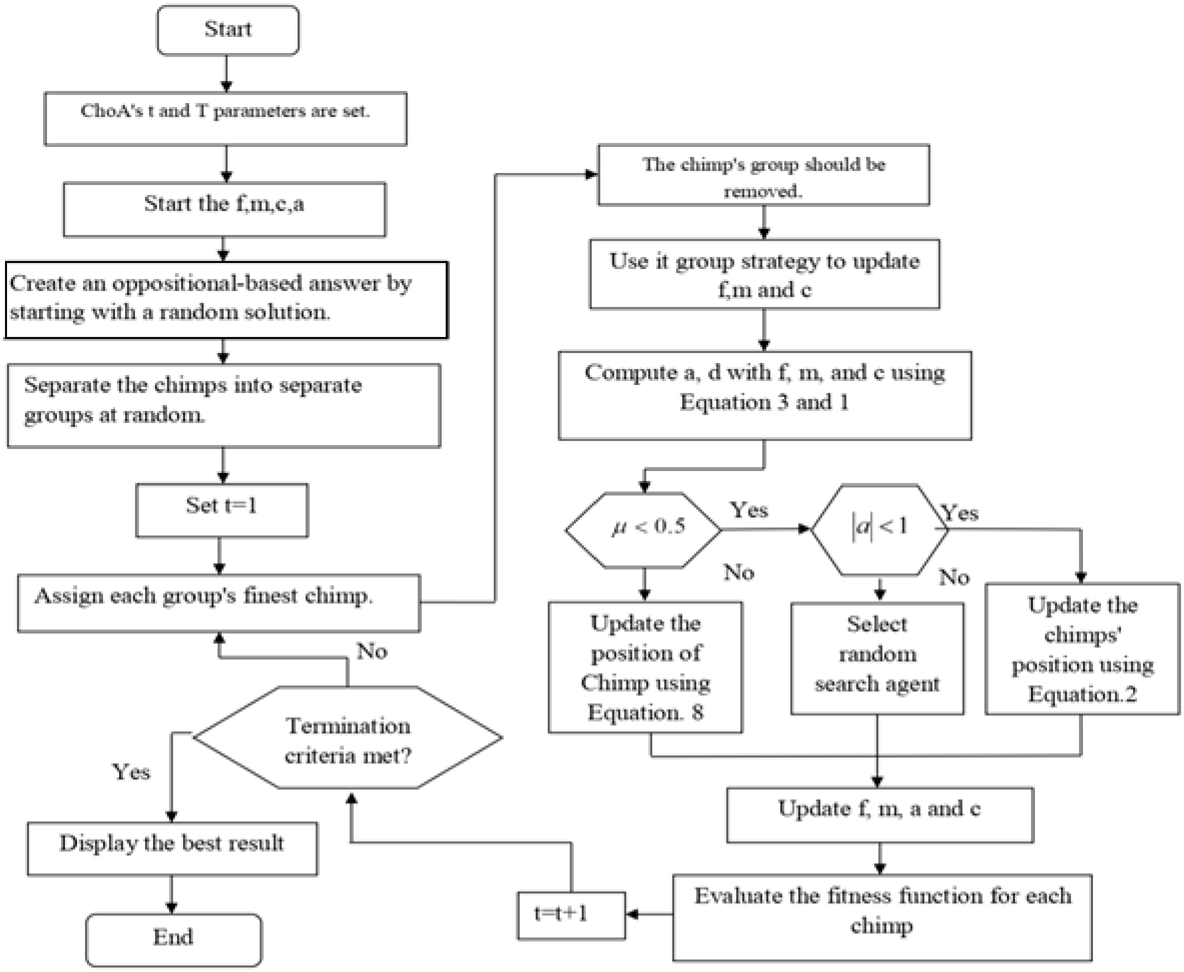


Figure 2: Oppositional-based Chimp Optimization Algorithm flowchart

IV. EXPERIMENTAL RESULTS

This section evaluates the proposed method-based PID controller's efficacy to reduce tracking error and solar tracking system energy consumption. The suggested technique is implemented in MATLAB/ Simulink 7.10.0 on a system with an Intel(R) Core(TM) i5 CPU and 4GB RAM (R2015a). The proposed method-based controller is compared to current approaches such as the GPI controller, CT controller, and PID controller to see how successful it is in reducing solar tracking system error and energy consumption.

A. *Performance Analysis*

On April 3, 2018, a simulation was held in Madrid, Spain. For a total of 12.8063 hours of sunshine, the sun rose at 06:54:05, set at 19:42:28, and rose again at 13:18:16. The overall azimuthal angle displacement β_{tot}=196.94°, and the total elevation angle γ_{tot} =108.34°,

TS	ε_β			ε_γ			ε_{tot}
	Min	Max	Avg	Min	Max	Avg	
CT controller [18]	-0.05	0.11	0.08	1.6	1.82	1.71	1.1719
GPI controller [32]	-0.06	0.06	0.06	-0.05	0.07	0.06	0.0849
PID controller [31]	-0.8	0.8	0.8	0.20	0.40	0.3	0.8544
Proposed controller	-0.01	0.01	0.01	-0.02	0.07	0.045	0.0541

Table 3: A list of simulation tracking errors

If the acceptance angles $\alpha_\beta=\alpha_\gamma$=0.25°. The solar route is divided into 788 and total=108.34 steps for azimuthal and elevation motions, respectively, using expression (1). The number of points in the trajectory is set to n=n=788 for simplicity during the implementation process. Figure 3 displays the segmentation of the trajectory's azimuthal and elevation angles in n-points. Figures 4a and 4b shows tracking system simulations using the three TS approaches.

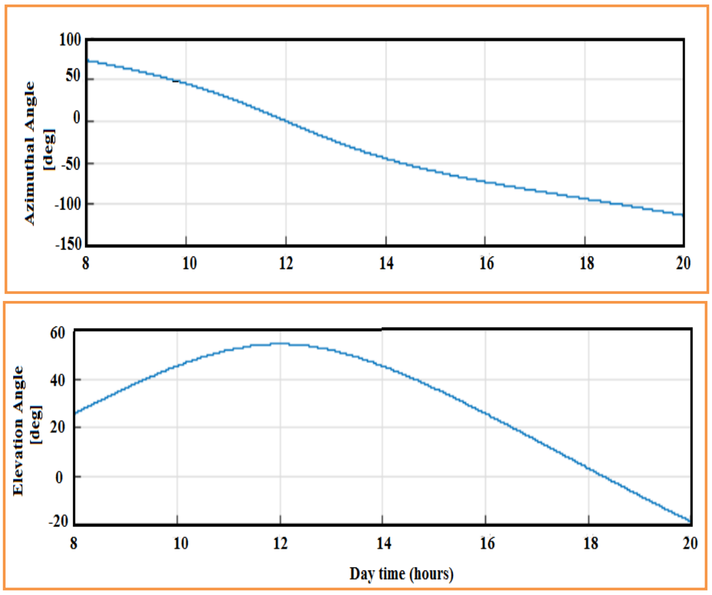
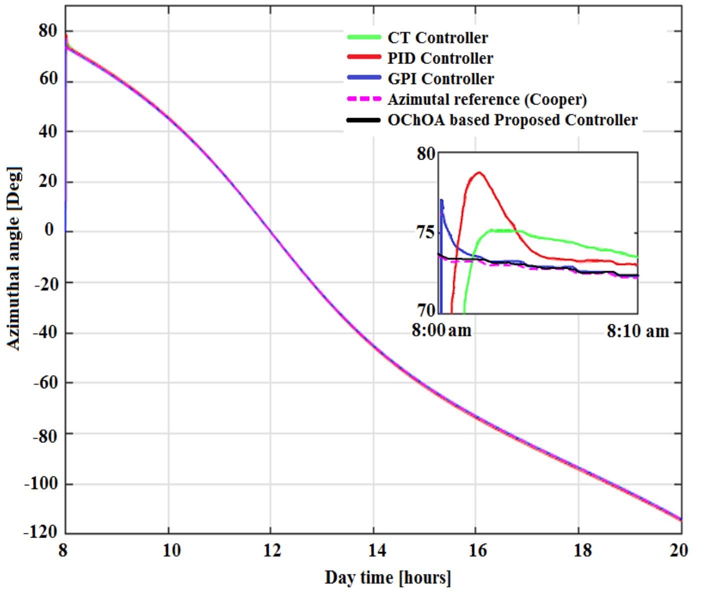
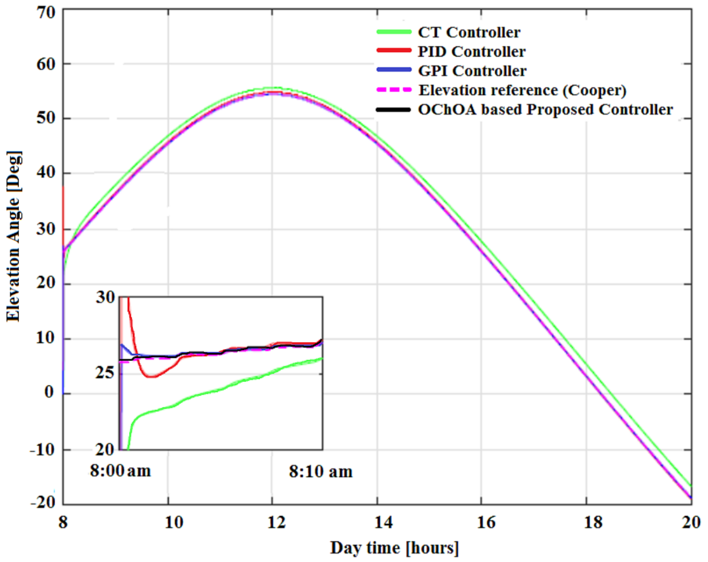


Figure 3: Solar path segmentation simulation for $\varepsilon_\beta=\varepsilon_\gamma$=0.25°, and $n_\beta=n_\gamma$ =788.

Figures 4a and 4b shows azimuthal and elevation tracking trajectory calculations for suggested and alternative controllers, respectively. The azimuthal and elevation angle tracking errors for each TS are shown in figure 5.



(a)



(b)

Figure 4: TS strategy simulations (a) tracing the azimuthal movement's trajectory and (b) The elevation movement's trajectory was tracked. An enlarged view of trajectories is shown in both.

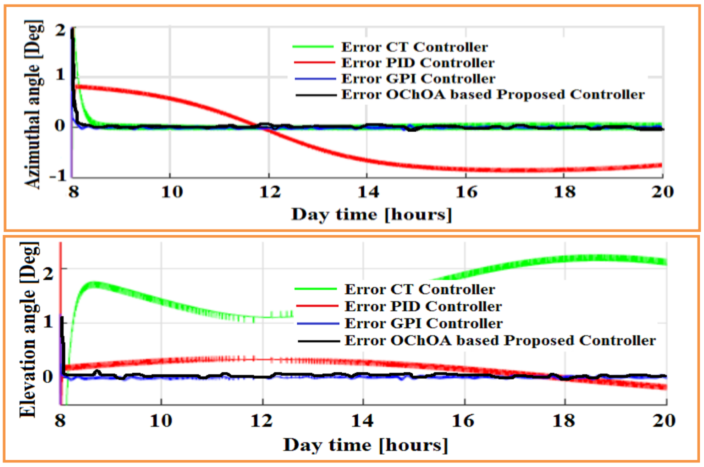


Figure 5: The trajectory's tracking accuracy

As shown in Figure 5a, the proposed controller based TS effectively accomplished the reference azimuthal angle with extraordinarily low tracking error when compared to prior controllers based TS such as the GPI controller [32], PID controller [33], and CT controller [18].

Similarly, the suggested controller achieved the reference elevation angle with minimal tracking error (see Figure 5b), beating other controllers as the GPI controller [32], PID controller [33], and CT controller [18]. Table 1 summarizes the findings in Figure 6. The total tracking error is calculated using an expression (4). With a value of 0.0541°, the suggested controller-based system has a smaller tracking error.

The tracking errors are calculated using mathematical computations, the mixed error is calculated using equation (3), and the overall tracking error was calculated using equation (4).

The ESS4 is the best energy-saving strategy determined by the OChOA-based suggested PID controller, and the utility function has a minimum value of 1.4584. The entire energy consumption is 3.56879Wh, and the total tracking inaccuracy is 0.0541°.

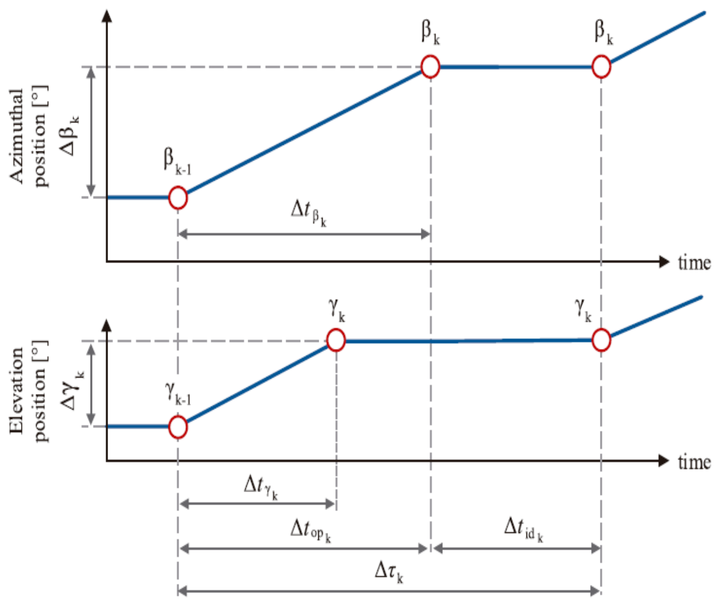


Figure 6: Time intervals for tracking movement from point

V. CONCLUSION

An OChOA-based PID controller was developed in this work to reduce mechanical device tracking error and energy consumption while improving the solar tracking system's performance. The major goal of this project is to reduce energy usage while improving the tracking system's accuracy. An OChOA has been used to tune the PID controller's performance. The proposed system's tracking error and energy consumption are compared to existing controllers such the GPI, PID, and CT controllers. Finally, a new solution developed to overcome the demerits of previous methods in terms of tracking error reduction and system energy consumption while tracking.

Conflict of interest

On behalf of all authors, the corresponding author declares (states) that there is no conflict of interest and no funding is there for this research.

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