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Trajectory Control of Robotic Manipulator using Metaheuristic Algorithms

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Abstract
Robotic manipulators are extremely nonlinear complex and, uncertain systems. They have multi-input multi-output (MIMO) dynamics, which makes controlling manipulators difficult. Robotic manipulators have wide applications in many industries like processes, medicine, and space. Effective control of these manipulators is extremely important to perform these industrial tasks. Researchers are working on the control of robotic manipulators using conventional and intelligent control methods. Conventional control methods are proportional integral and derivative (PID), Fractional order proportional integral and derivative (FOPID), sliding mode control (SMC), and optimal & robust control while intelligent control method includes Artificial Neural network (ANN), Fuzzy logic control (FLC) and metaheuristic optimization algorithms based control schemes. This paper presents the trajectory control of a robotic manipulator using a PID controller. Four different meta-heuristic algorithms namely Sooty tern optimization (STO), Spotted Hyena optimizer (SHO), Atom Search optimization (ASO), and Arithmetic Optimization algorithm (AOA) are used to optimize the gains of PID controller for trajectory control of a two-link robotic manipulator and a novel hybrid sooty tern and particle swarm optimization (STOPSO) has been designed. These optimization techniques are nature-inspired algorithms that give the optimal gain values while minimizing the performance indices. A performance index comprising Integral time absolute error (ITAE) having weights for both links has been considered to achieve the desired trajectory. These optimization techniques are stochastic in nature so statistical analysis and Freidman's ranking test has been performed to evaluate the effectiveness of these algorithms. The proposed hybrid STOPSO provided a fitness value of 0.04541 and showed a standard deviation of 0.0002. A comparative study of these optimization techniques is presented and as a result, hybrid STOPSO provides the best results with minimum fitness value followed by STO, AOA, ASO, and SHO algorithms.

Keywords- Two-link robotic manipulator, Optimization techniques, PID, STO, SHO, ASO, AOA.

1. Introduction

Robotic manipulators are highly nonlinear and uncertain systems. These systems find various applications in industries for pick and place, sorting and dispensing, etc. While performing such tasks manipulators interact with the real world so position or trajectory control becomes very important in such applications. These complexities and inherent nonlinearities make the control of robotic manipulators challenging. Researchers have been developing effective control of manipulators using conventional and intelligent control methods. Conventional control methods are PID, FOPID (Chhabra et al., 2016; Mohan et el., 2018), SMC, and adaptive control (Zhang and Wei, 2017). With the advancements in artificial intelligence techniques like FLC, ANN, and metaheuristic algorithms, improved and effective control can be achieved by incorporating conventional control with such techniques. Considering the complex structure of robotic manipulators, tracking the trajectory is much more complicated. Lopez-Franco et al. (2022) demonstrated trajectory control using different metaheuristic optimization approaches. The objective function for the optimization problem includes the position and joint objectives. Metaheuristic algorithms (Sharma et al., 2022a) have been implemented in conventional controls to find the controllers' optimal gain settings. Yadav et al. (2022) designed a hybrid controller for motion control of a robotic manipulator using the conventional method Zigler Nichols and optimization algorithms such as genetic algorithm (GA), PSO, and ant colony optimization (ACO). The GA outperforms the others including the conventional Zigler-Nichols method. Ayala and dos Santos (2012) designed the PID controllers and tuned them using non dominated sorting genetic algorithm (NSGA) for trajectory control of a two-link robotic manipulator. The proposed controller has been able to handle the nonlinearity and complexity of the system and provides effective trajectory tracking. Minimization of position error and control forces variation has been considered the performance indices. Sharma et al. (2014b) presented the statistical analysis of the GA-based PID optimization for trajectory tracking of two-link robotic manipulators. Being MIMO in nature, two separate PID controllers for different links are designed and tuned by GA. Integral square error (ISE) and integral square of the change in controller output (ISCCO) having equal weightage have been considered as a performance index. The authors provided a range of controller gains to design specifications for hardware implementation. Chhabra et al. (2016) used multi-objective PSO for the design of PID and FOPID for the trajectory tracking problem of a two-link robotic manipulator. FOPID showed superior performance as compared to the conventional PID. Many other metaheuristic algorithms like ACO (Singh and Prasad, 2018; Yadav et al., 2022), whale optimization (Loucif et al., 2020), cuckoo search (Sharma et al., 2015; Sharma et al., 2021) and chicken swarm optimization (Mu et al., 2016) have been implemented to tune the PID controllers for trajectory control of robotic manipulators. Grey wolf optimization (GWO) has been implemented on PID and FOPID controllers in the trajectory control problem. In this paper, four new meta-heuristic algorithms, namely STO, SHO, ASO, and AOA, have been implemented to optimize the gains of PID controller for trajectory control of a two-link robotic manipulator and a novel hybrid STOPSO has been designed to improve the exploitation capability of STO algorithm. Table 1 presents the literature review of metaheuristic algorithm for the control of robotic manipulators.

Table 1. Literature review of metaheuristic algorithms for robotic manipulator.

S. No.	Algorithm	Implementation to robotic systems	References
1.	Genetic Algorithm (GA)	Multi-objective PID, Hybrid control, SMC, and statistical analysis.	(Ayala and dos Santos, 2012; Sharma et al., 2014b; Vijay and Jena, 2014; Yadav et al., 2022)
2.	Particle swarm optimization (PSO)	Fractional PID, Fuzzy PID	(Chhabra et al., 2016; Lopez-Franco et al., 2020; Yadav et al., 2022; Mohan et al., 2019; Liu et al., 2022)
3.	Ant colony optimization (ACO)	Optimal trajectory, Hybrid control methods for joints and positions.	(Singh and Prasad, 2018; Yadav et al. 2022)
4.	Whale optimization Algorithm (WOA)	PID controller-based trajectory tracking	(Loucif et al., 2022)
5.	Chicken swarm optimization (CSO)	Optimal trajectory tracking using PID	(Mu et al., 2016)
6.	Cuckoo search algorithm (CSA)	FOPID controller for trajectory tracking	(Sharma et al., 2015; Sharma et al., 2021)
7.	Grey Wolf Optimization (GWO)	PID controller. Hybrid GWO-ABC tuned FOPID. Hybrid GWO- WOA tunes FLC.	(Gaidhane and Nigam, 2018; Tripathi et al., 2020; Obadina et al., 2022)

Such algorithms show a high affinity towards the control of robotic systems. With the advancements in the field of optimization, there is a large scope for implementing these algorithms on robotic systems to improve performance. In recent years, metaheuristic algorithms have grown as a popular choice by researchers

because robotic systems need to provide accurate and precise solutions for industrial tasks. Metaheuristic algorithms has also been explored by researchers to improves the performance of conventional control by designing the optimal control laws. Therefore, the implementation of recently developed metaheuristic algorithms on the robotic manipulators for the trajectory control is an important research problem.
The main highlights of the paper are as follows:

- Trajectory control of a robotic manipulator using the PID control technique.
- Implementation of four different metaheuristic algorithms, AOA, ASO, SHO, and STO for tuning the controller gains.
- Design of a novel hybrid STOPSO algorithm.
- Evaluation of performance of implemented metaheuristic algorithms based on Friedman ranking test.

The remaining paper has been structured as follows: Section 2 describes the mathematical model of a two-link robotic manipulator. Section 3 describes the control algorithms. Section 4 presents a brief overview of optimization techniques implemented on the PID controller. Section 5 presents the results and discussion. Finally, section 6 presents the conclusion and scope of future work.

2. Robotic Manipulator

Over the last decade, robotic manipulators' use has been increased tremendously. Robotic manipulator is highly nonlinear in nature and in this study two links robotic manipulator as shown in Figure 1 has been considered. Using the Lagrangian function $L=K-P$ where K is kinetic energy, and P is the system's potential energy, the following mathematical model is obtained for the robotic manipulator (Niku, 2020).

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\theta + G(\dot{\theta}) = \tau \quad (1)$$

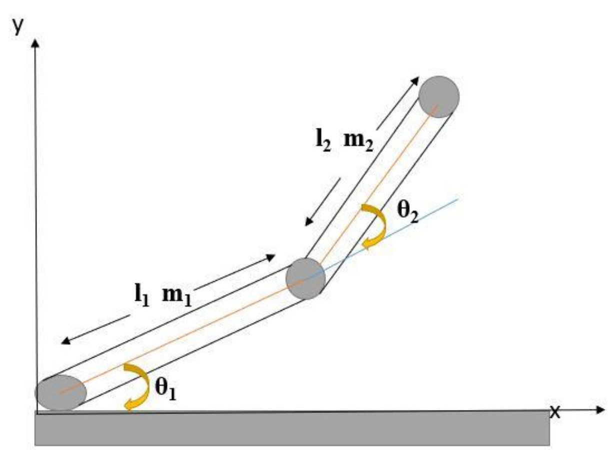

Figure 1. Two link robotic manipulator.

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} (m_1+m_2)l_1^{\,2} + m_2 l_2^{\,2} + 2m_2 l_1 l_2 C_2 & m_2 l_2^{\,2} + m_2 l_1 l_2 C_2 \\ (m_2 l_2^{\,2} + m_2 l_1 l_2 C_2) & m_2 l_2^{\,2} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} \begin{bmatrix} 0 & -m_2 l_1 l_2 S_2 \\ m_2 l_1 l_2 S_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^{\,2} \\ \dot{\theta}_2^{\,2} \end{bmatrix}$$
$$+ \begin{bmatrix} -m_2 l_1 l_2 S_2 & -m_2 l_1 l_2 S_2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_2 \dot{\theta}_1 \end{bmatrix} + \begin{bmatrix} (m_1+m_2) g l_1 S_1 + m_2 g l_2 S_{12} \\ m_2 g l_2 S_{12} \end{bmatrix} \quad (2)$$

where, m_1 , m_2 is the mass of the first and second link, l_1 and l_2 is the length of the first and second links, θ_1, θ_2 is the angular positions of the first and second link respectively. $T_1$is the torque on joint 1 and T_2 is the torque on joint 2. C_2, S_2, and S_{12} are the terms $cos\,\theta_2$, $\sin\theta_2$, and $sin(\theta_1+\theta_2)$. Table 2 presents the parameters considered for the simulation studies.

Table 2. Parameters considered for a two-link robotic manipulator.

Parameters	Link 1	Link 2
Mass of the links	0.1 Kg	0.1 Kg
Length of the links	0.8 m	0.4 m
Gravitational Acceleration	9.81 m/s^2	

3. Control Methodology

PID controller is the most widely used industrial controller, because of its robustness, more than 95 % of industrial controllers are found to be PID in nature. PID controller design requires the implementation of three parameters for the given process: proportional gain K_p (output proportional to error), integral gain Ki (output proportional to integral of error), and derivative gain K_d (output proportional to the derivative of error) (Yadav et al., 2022). The proportional controller gives offset error; integral control removes that error but makes the system slower. Derivative control reduces the sluggishness of the system. The PID controller's equations including proportional, integral, and derivative gain along with the transfer function are as follows:

$$Y(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad (3)$$

$$Y(s) = \left(K_P + \frac{K_I}{s} + sK_D\right)E(s) \quad (4)$$

$$G(s) = \left(K_P + \frac{K_I}{s} + sK_D\right) \quad (5)$$

Finding optimum values of Kp, K_I, and K_D is referred to as tuning of the controller. Various methods like Ziegler- Nichol, and Tyreus - Luven are available for tuning the controller, but they are complex and require the knowledge of transients and desired time response specifications which are challenging. Therefore, metaheuristic algorithms have been widely implemented in tuning of these controllers thus providing an opportunity to use such an algorithm in conjunction with conventional methods. Yadav et al. (2022) presented a comparison of classic tuning methods and advanced optimization algorithm-based tuning and concluded that optimization method-based tuning is much more effective. This motivates researchers to implement various optimization techniques in designing effective PID-based controllers. Vijay and Jena (2014) designed PD and PID controllers with good dynamic properties, global stability, improved disturbance rejection, and low tracking error using GA. Mu et al. (2016) implemented the CSO for trajectory tracking of manipulators where B-spline is used to formulate the trajectory and minimum traveling time is considered as an objective function to obtain optimal trajectory. Experimental results validate the proposed algorithm. Singh & Prasad, (2018) implemented the optimal tracking of the trajectory of a robotic manipulator using ACO tuned with PID controller. The authors considered the external disturbances and tuned the controller gains using ACO for both cases, i.e., with and without external disturbances. Simulation results have proved the fast convergence rate of error. Sharma et al. (2014a) presented a comparison of various optimization techniques for controlling robotic manipulators and tuned the conventional PID controller using GA, PSO, and simulated annealing (SA). Simulation results demonstrate the better performance of PSO over GA and SA. In this paper, trajectory control has been achieved using four recent metaheuristic algorithms and a novel hybrid STOPSO algorithm has been designed and implemented on the robotic manipulator. Figure 2 presents a schematic diagram of the design of the PID control using metaheuristic algorithms. In this paper the methodology for achieving trajectory tracking for a robotic manipulator includes the following steps:

(i) Determining the reference trajectory for each link of the robotic manipulator.
(ii) Control of trajectory by designing a MIMO PID controller.
(iii) Tuning the designed controller using recent metaheuristic algorithms.
(iv) Obtaining the optimal gain with minimum fitness value.
(v) Improve the performance of designed controller tuned with novel hybrid metaheuristic algorithm.

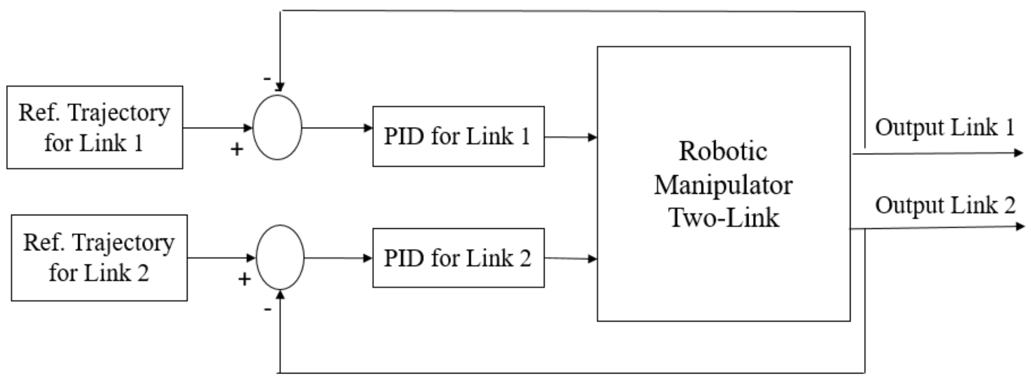

Figure 2. Schematic diagram of the implementation of the control for two link robotic manipulator.

4. Optimization Techniques
This section presents a brief outline of four different metaheuristic algorithms namely AOA, ASO, SHO, and STO which have been implemented to find the optimal solution of the controller gains, providing the minimum value of fitness function of a two-link robotic manipulator. Further a novel hybrid STOPSO algorithm has been discussed which effectively control the trajectory of robotic manipulator.

4.1 Arithmetic Optimization Algorithm (AOA)
Abualigah et al. (2021) proposed a novel mathematics-inspired optimization algorithm named as Arithmetic optimization algorithm (AOA). It makes use of the distributional properties of the four basic mathematical arithmetic operators like addition or summation, subtraction, multiplication, and division.

The Main inspiration of AOA is the use of different arithmetic operators in resolving arithmetic problems. AOA is implemented in three phases: **Initialization phase-** It begins with a set of solutions generated randomly and each iteration gives the optimum solution. Math optimizer function (MOA) is calculated, which denotes the fitness value at t^{th} iteration. **Exploration phase-** during this phase the mathematical operators' division (D) and multiplication (M) explore the optimal solutions. Math optimizer probability (MOP) calculates the fitness value. **Exploitation phase-** in this phase, the mathematical operators' subtraction (S) and addition (A) exploits the candidate solutions. The function MOA supports the exploitation. Flow chart of AOA has been presented in Figure 3.

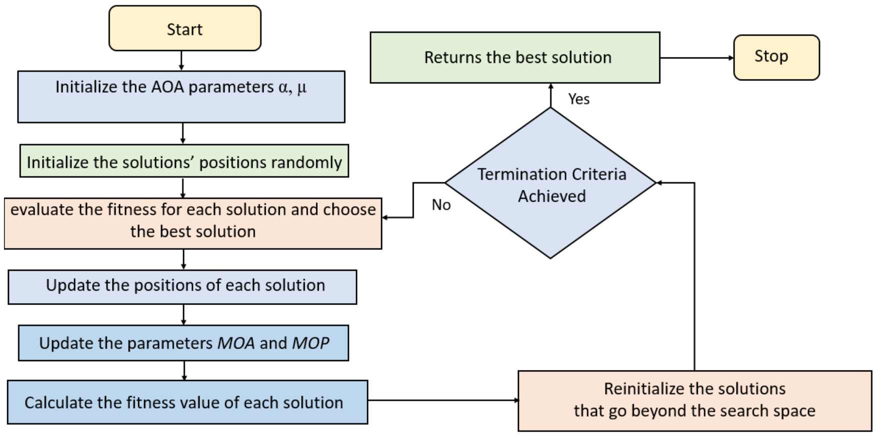

Figure 3. Flow chart of AOA.

4.2 Atom Search Optimization (ASO)

Zhao et al. (2019) proposed a novel physics-inspired metaheuristic algorithm motivated by basic molecular dynamics, known as ASO. It creates a collection of random solutions to begin the optimization process. In every iteration, the atoms apprise their locations and velocities, and in every iteration, the position of the best atom thus far is likewise updated. Atomic acceleration is also caused by two factors. One is the L-J potential's interaction force, which is the vector sum of the attraction and repulsion that other atoms are exerting. Another is the constraint force brought on by the weighted positional difference between each atom and the best atom, or bond-length potential. The positions of atoms are updated interactively till it satisfies the stopping criterion. Finally, as a close approximation to the global optimum, the location and fitness value of the best atom is returned. ASO begins with a randomly generated set of atoms X (solutions) and their velocity v. Each atom's position inside the search space indicates a solution as measured by its mass. According to their distance from one another, every atom in the population will either attract or repel one another, causing the lighter atoms to settle toward the heavier ones. Figure 4 presents the flow chart of ASO algorithm.

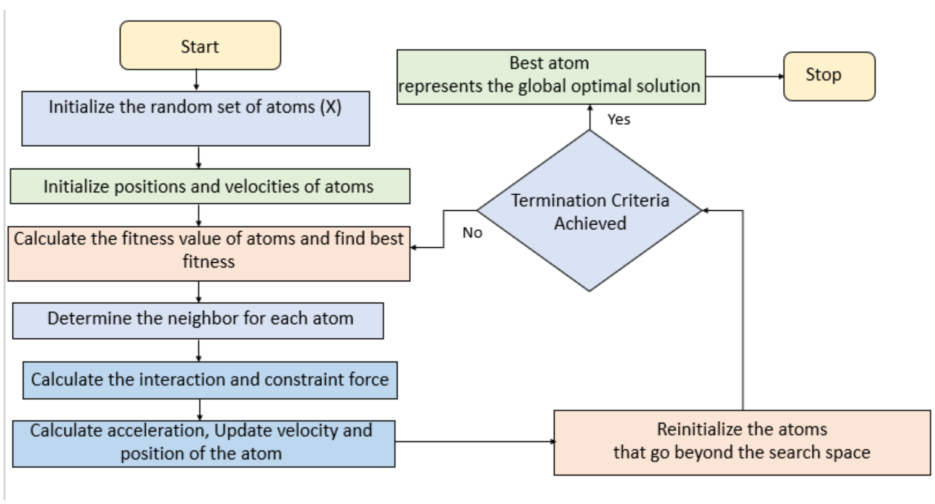

Figure 4. Flow chart of ASO algorithm.

4.3 Spotted Hyena Optimizer (SHO)

Dhiman and Kumar (2017) proposed Spotted Hyena Optimizer (SHO) a metaheuristic algorithm that mimics the behavior of spotted hyenas. The algorithm mimics the social interactions and cooperative behaviour of spotted hyenas. Finding prey, surrounding, and attacking prey are the three fundamental actions of SHO, and each of these actions is mathematically described and carried out.

Encircling Behavior-The best solution is the goal behavior or objective, and the other search agents can update their locations in relation to the found best solution. Spotted hyenas can detect their prey's location and encircle it. Spotted hyena nearest to the target or prey is the current best solution.

Hunting-In hunting strategy, the spotted hyenas create a cluster of optimum hunting strategies against the best search agent, and they also modify the placements of other search agents.
Figure 5 presents the flow chart of SHO algorithm.

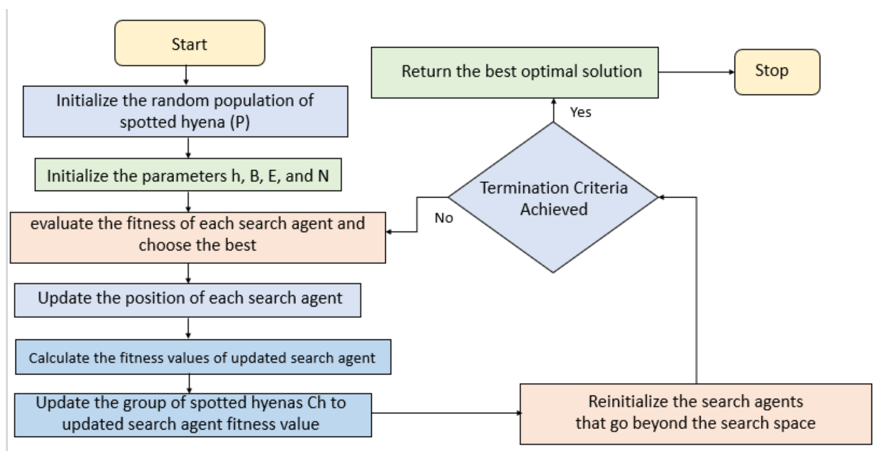

Figure 5. Flow chart of SHO algorithm.

4.4 Sooty Tern Optimization (STO)

Dhiman and Kaur (2019) proposed a unique bio-inspired stochastic optimization method that emulates the migratory and attacking of sooty tern- a sea bird. The behavior of sooty tern is summarized below:

(i) Sooty terns travel in flocks during migration. To avoid a collision between sooty terns, their starting positions are different.
(ii) Sooty terns in a group might go near the direction of the best survival fittest sooty tern, i.e., a sooty tern with a low fitness rating in comparison to others.
(iii) Other sooty terns can modify their starting locations in accordance with the best sooty tern.

The two main components of the STO algorithm are migration behavior (exploration) and attacking behavior (exploitation). In the migration behavior (exploration) sooty tern satisfies the following three conditions:

(i) Collision avoidance with the help of a function S_A.
(ii) Converge toward your best neighbor's.
(iii) Update the positions of sooty terns according to the best search agent.

In the attacking behavior (exploitation), sooty terns create the spiral behavior in the air that has been mathematically modeled. The flow chart of STO algorithm has been presented in Figure 6.

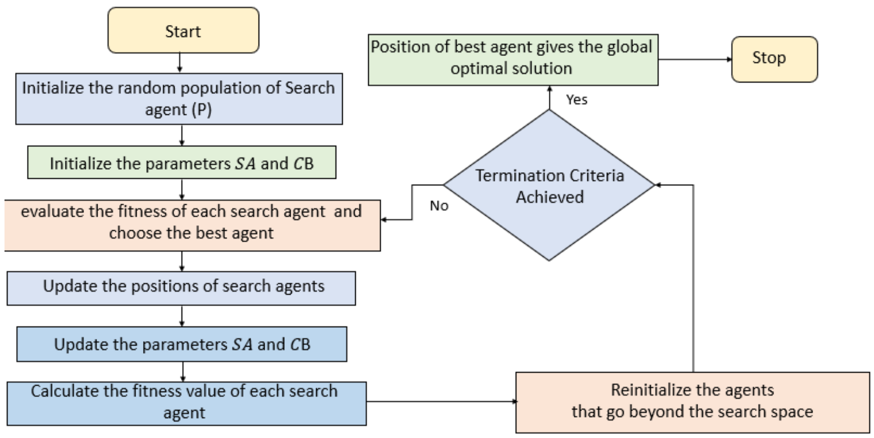

Figure 6. Flow chart of STO algorithm.

4.5 Novel Hybrid STOPSO Algorithm

In this work, a hybrid version of STOPSO algorithm has been proposed for tracking the trajectory of a robotic manipulator. The exploitation capability of STO algorithm is significantly improved by incorporating the exploitation capability of PSO algorithm. As a result, controller parameters converged equally well to the true values with minimum error. The performance of the proposed STOPSO algorithm is measured based on convergence analysis, robustness, reliability, and statistics analysis while trajectory of a robotic manipulator is tracked, and the results are compared with the previous algorithms exist in the literature. Any metaheuristic algorithm's performance is based on how well it searches the search space for an overall optimal solution. According to the NFL theorem, all metaheuristic algorithms don't provide the optimal solution for all sets of complex NP-hard problems. Some of the algorithms have a tendency to trap in the local optimal solution while some algorithms have a slow rate of convergence. It is very difficult to have a proper balance between two strategies exploration and exploitation for most of the optimization algorithms. STO algorithm has good exploration capability where sooty tern explores the search space by updating their position with respect to the position of the best bird by avoiding collisions. In the exploitation phase, sooty terns form a spiral path in the air to attack their prey and if the distance between sooty tern and prey is large then the algorithm has a tendency to get trapped in the local optimal solution. PSO algorithm have good exploitation capability have weak exploration capability. Therefore, in the proposed hybrid STOPSO algorithm the exploitation capability of the STO algorithm is improved by embedding it with PSO algorithm. In the initial stage, the STO algorithm is utilized to find the optimal solution, and thereafter the exploitation capability of the PSO algorithm is used to further optimize the results and obtain the global optimal solution. Figure 7 presents the flow chart of the proposed STOPSO algorithm. The mathematical model of the proposed hybrid STOSPO algorithm is outlined as follows:

Step 1: Randomly initialize the position of sooty tern (search agents) in the search space:

$$\vec{X}_s = (\vec{x}_1, \vec{x}_2, \dots \dots \dots \dots \dots \dots \dots \vec{x}_n) \tag{6}$$

where, n signifies the space dimension.

Step 2: Initialize search agents' velocity in the search space at random.

$$\vec{V}_s = (\vec{v}_1, \vec{v}_2, \dots \dots \dots \dots \dots \dots \dots \vec{v}_n) \quad (7)$$

Step 3: Estimate the fitness of all search agents and based on the minimization or maximization problem the position of the best sooty tern ($\vec{x}_{bs}$) represents the best search agent.

Step 4: The dynamic parameters S_A, C_B, w are initialized which allows search agents to move in the search space. These parameters are defined as

$$S_A = C_f - \left(z * \left({C_f}/{Max_{iterations}}\right)\right) \quad (8)$$

$$w = w_{min} - (w_{max} - w_{min}) * \frac{iter}{Max_{iterations}} \quad (9)$$

where, w_{min}, w_{max} are the minimum and maximum values of inertia weight, C_f is the controlling variable whose value is linearly decreased from C_f to zero, $iter$ is the current iteration and $Max_{iterations}$ is the maximum number of iterations. z= 0, 1, 2, 3, ………………………., $Max_{iterations}$.

$$C_B = 0.5 * R_{and} \quad (10)$$

where, R_{and} is the random number in the range [0,1].

Step 5: The position of search agents is updated based on the following equations:

$$x' = R_{adious} * \sin(i) \quad (11)$$

$$y' = R_{adious} * \cos(i) \quad (12)$$

$$z' = R_{adious} * i \quad (13)$$

$$r = u * e^{kv} \quad (14)$$

where, R_{adious} represents the radius of the spiral movement, i is the variable in the range $[0 \leq k \leq 2\pi]$, u and v are the constant parameters.

$$\vec{C}_s = S_A * x_S \quad (15)$$

$$\vec{M}_s = C_B * (\vec{x}_{bs} - \vec{x}_s) \quad (16)$$

$$\vec{D}_s = \vec{C}_S + \vec{M}_s \quad (17)$$

$$\vec{x}_s = \left(\vec{D}_s * (x' + y' + z')\right) * \vec{x}_{bs} \quad (18)$$

Step 6: The following equations are used to update the search agent velocity depending on the optimal search agent's position:

$$\vec{V}_s(iter + 1) = w * \vec{V}_s(iter) + c_1 * r_1 * \left(\vec{x}_{bs} - \vec{X}_s(iter)\right) \quad (19)$$

where, c_1 is the acceleration parameter and r_1 is the random number in the range [0, 1].

Step 7: Update the position of search agents as follows:

$$\vec{X}_s(iter + 1) = \vec{X}_s(iter) + \vec{V}_s(iter + 1) \quad (20)$$

Step 8: The dynamic parameters S_A and C_B are updated.

Step 9: The position of the search agent are reinitialized if it go beyond the search space.

Step 10: The algorithm is terminated if a minimum error or a maximum number of iterations is reached. Otherwise repeat steps (3) to (9).

Step 11: The position of the best search agent ($\vec{x}_{bs}$) represents the global optimal solution.

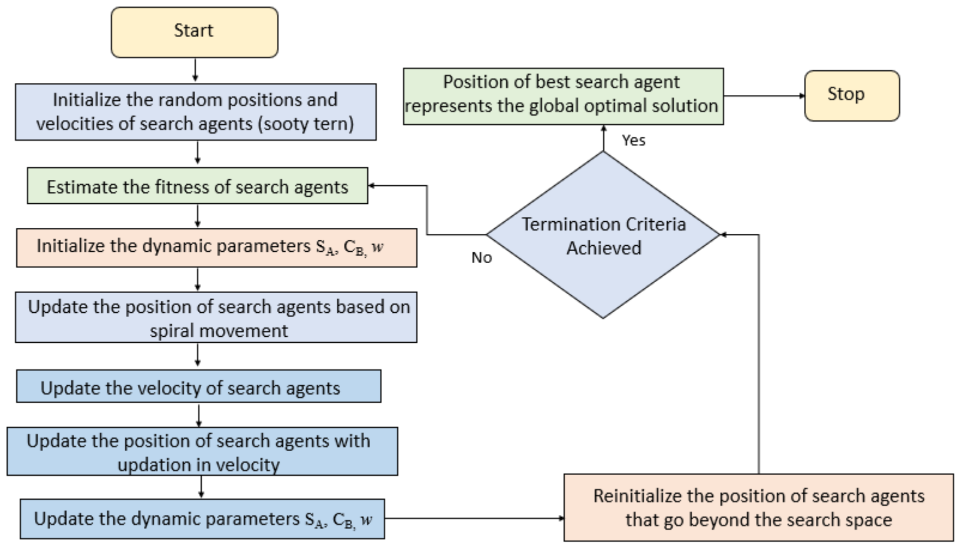

Figure 7. Flow chart of hybrid STOPSO algorithm.

5. Results and Discussion

In this section, simulation results of trajectory tracking have been presented and discussed. The MATLAB/Simulink has been used for the simulation work. The metaheuristic optimization algorithms (ASO, AOA, STO, SHO, and Hybrid STOPSO) have been implemented on a nonlinear two-link robotic manipulator for tuning the PID controller gains to track the reference trajectory. Two separate PID controllers have been designed because of the MIMO dynamics of the robotic manipulator. Each of these techniques can track the reference trajectory under the presence of a cost function. The weighted sum of integral time absolute error (ITAE) has been considered as the performance index and is mathematically represented as:

$$f = w_1 * \int e_1(t)tdt + w_2 * \int e_2(t)tdt \tag{21}$$

where, w_1 and w_2 are the weights assigned to the ITAE of both the links and their values are 0.5. The objective is to track the reference trajectory by tuning the PID control using these recent metaheuristic algorithms. These metaheuristic algorithms provided the optimum value of controller gains while minimizing the error in terms of the fitness value. For trajectory tracking a reference trajectory is required. A cubic polynomial trajectory as shown in eq. (22) has been used as the reference for tracking the trajectory.

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{22}$$

Figure 8 shows the reference trajectories of link 1 and link 2 of a two-link robotic manipulator and Figure 9 is the simulink representation of reference trajectory generation.

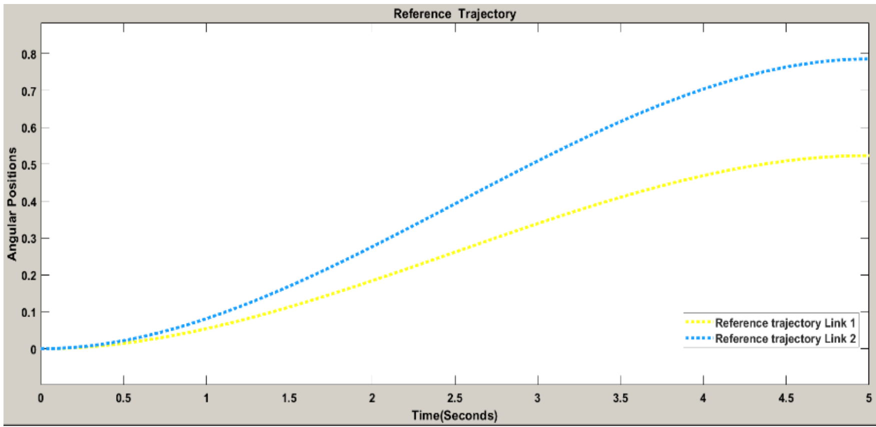

Figure 8. Polynomial reference trajectory.

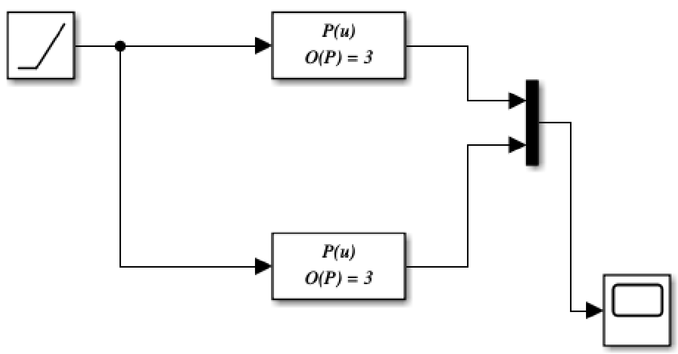

Figure 9. Simulink- reference trajectory generation.

For implementation of these optimization techniques in the PID controller, the parameters considered are given in Table 3. Total 30 search agents, 100 iterations, and 10 runs have been considered for designing the control law. Each of the controller variables has been assigned upper and lower bounds. Two different PID controllers has haven designed for two different links of the manipulators so the dimension in the algorithms has been considered as six. Each of these algorithms has returned the controller gains with minimum cost function ITAE value. Table 4 presents the controller gains of link 1, link 2, and fitness function value.

Table 3. Parameters considered for simulation.

S. No.	Algorithm parameters	PID Values
1.	Dimensions	6
2.	Upper Bounds	[200,100,50,100,100,10]
3.	Lower Bounds	[2, 2, 2, 2, 2, 2]
4.	No of search agent	30
5.	No of iterations	100
6.	Number of Runs	10

Table 4. Controller gains and objective function values for metaheuristic algorithms.

S. No.	Algorithm	Link 1 PID controller gains	Link 2 PID controller gains	Objective function value
1.	ASO	[197.08264,99.8055, 3.3841]	[95.4870,92.845, 4.636]	0.04970
2.	AOA	[200, 100, 2]	[100, 100, 8.74633118938909]	0.04607
3.	STO	[200, 100, 2]	[99.9750, 90.9847, 8.8450]	0.04573
4.	SHO	[186.648660502925, 100, 2]	[100, 100, 2]	0.04944
5.	HYBRID STOPSO	[200, 100, 2]	[100, 100, 8.80909]	0.04541

These metaheuristic algorithms are stochastic in nature; they may yield different results on each run. Therefore, a statistical analysis has been performed by running each algorithm 10 times. Statistical parameters like minimum, maximum, mean, median, and standard deviation of the fitness value have been observed. Table 5 presents this statistical analysis expressing the values of these parameters. It is clear from the statistical analysis that hybrid STOPSO provides the minimum fitness function value. The algorithm SHO has shown the maximum value of the fitness function and a high standard deviation. As per this analysis, the performance of the designed hybrid STOPSO has been found superior as compared to other optimization algorithms.

Table 5. Statistical Analysis of the fitness function in 10 runs.

S. No.	Algorithm	Minimum	Maximum	Mean	Median	Standard Deviation
1.	ASO	0.04970	0.05264	0.05126	0.05105	0.09732
2.	AOA	0.04607	0.04821	0.04800	0.04822	0.06423
3.	STO	0.04573	0.04822	0.04659	0.04629	0.08570
4.	SHO	0.04944	0.05930	0.05439	0.05435	0.28495
5.	HYBRID STOPSO	0.04541	0.04610	0.04601	0.04600	0.00020

To access the performance of these metaheuristic optimization algorithms, a non-parametric statistical test called Friedman's test (Sharma et al., 2022b) has been performed. Each of these techniques has been assigned a Friedman ranking based on that final ranking has been given. Table 6 shows the Friedman ranking and final ranking of every algorithm implemented on PID controllers. According to this test, the hybrid STOPSO algorithm attains a rank of 1 followed by STO, AOA, ASO, and SHO algorithm. The proposed hybrid STOPSO algorithm performs the best and SHO performs the worst. SHO algorithm performs the worst in the trajectory control of robotic manipulators, it attains the rank of 5 and in statistical analysis, it shows the maximum deviation and considerably high fitness value. Figure 10 shows the rankings obtained by Friedman's test and the final ranking calculated accordingly.

Table 6. Ranking of the metaheuristic algorithms on PID controller designed according to the Friedman test.

Algorithm	Friedman's Ranking	Final Ranking
ASO	4.3	4
AOA	2.8	3
SHO	4.7	5
STO	2	2
Hybrid STOPSO	1.1	1

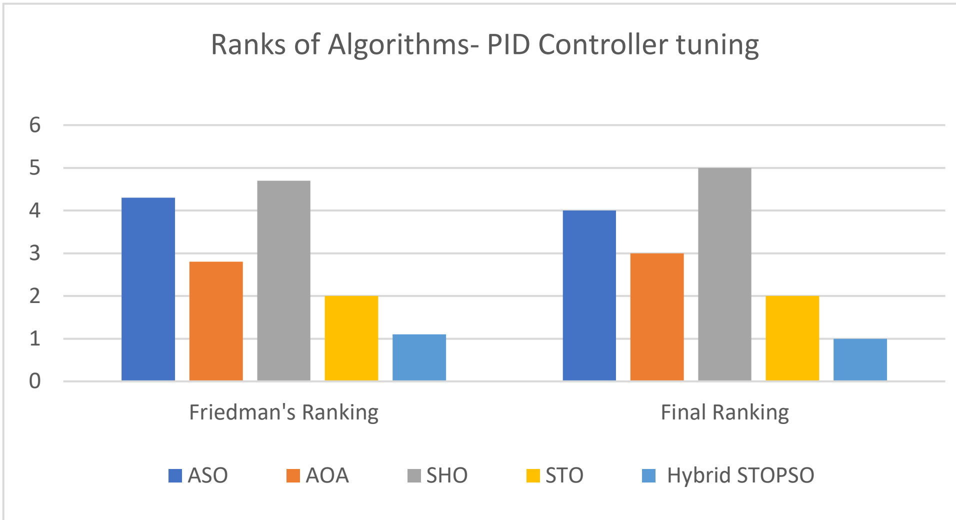

Figure 10. Friedman's Ranking of the metaheuristic algorithms on PID controller.

Figure 11 shows the trajectory tracking using an ASO-tuned PID controller with a fitness value of 0.04970. Initially, the trajectory showed deviation from the reference but later it achieved the trajectory. Figure 12 shows the trajectory tracking using AOA-tuned PID with the 0.04607 value of the objective function.

In this case, link 1 has shown some overshoots while tracking the reference trajectory while link 2 has no overshoots. Figure 13 presents the trajectory tracking using SHO-tuned PID with a 0.04944 value of the objective function. This has overshoots in the trajectory of both links. The performance of SHO algorithm has been found the worst as evaluated from its statistical analysis.

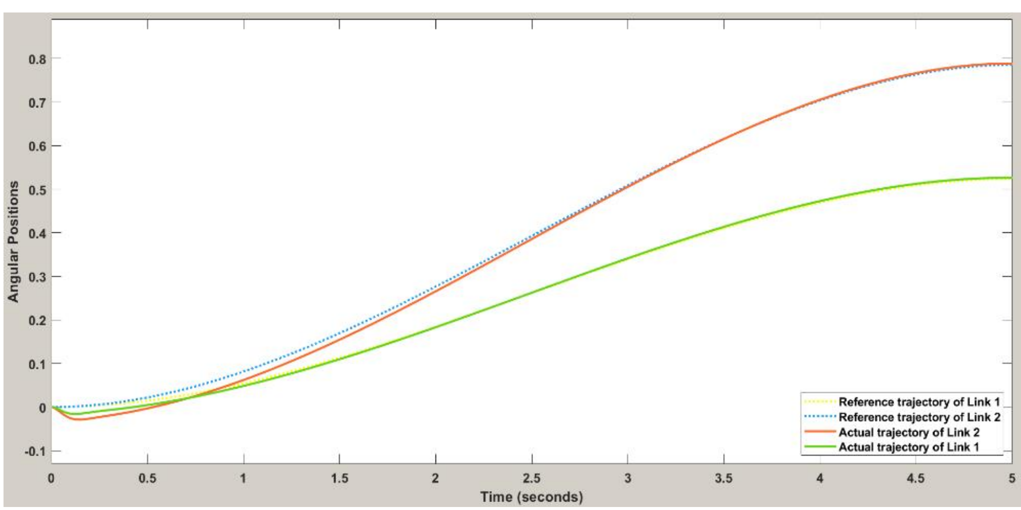

Figure 11. Trajectory tracking using ASO-tuned PID.

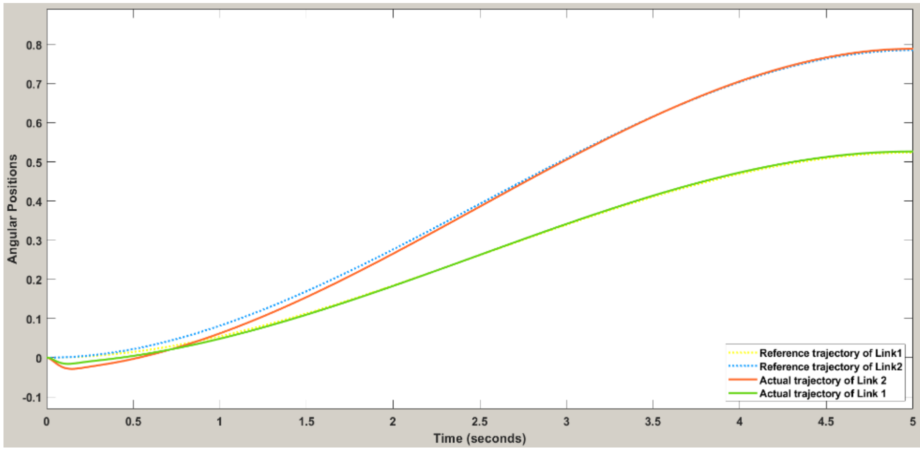

Figure 12. Trajectory tracking using AOA-tuned PID.

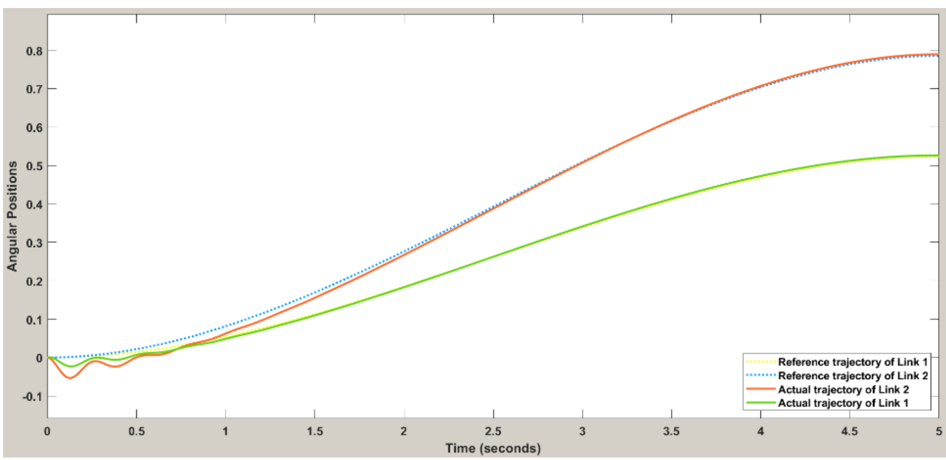

Figure 13. Trajectory tracking using SHO-tuned PID.

Figure 14 presents the trajectory tracking using STO-tuned PID with a 0.04573 value of the objective function.

STO algorithm has significantly improved the fitness value and shown good trajectory tracking as compared to the previous ones. Further, the hybrid STOPSO algorithm has improved the fitness function and shown improved statistical performance as shown in Figure 15.

Convergence analysis is another criterion to evaluate the effectiveness of any algorithm. Convergence to a minimum value of fitness and how fast it converges determines the performance of any algorithm. Figure 16 presents the combined convergence of all these algorithms implemented on the PID controller for trajectory tracking of a two-link robotic manipulator. It is evident from Figure 15 that the algorithms ASO and SHO converge to larger values of error, while AOA, STO, and hybrid STOPSO converge to lower error values out of which hybrid STOPSO algorithm converges to the minimum error value.

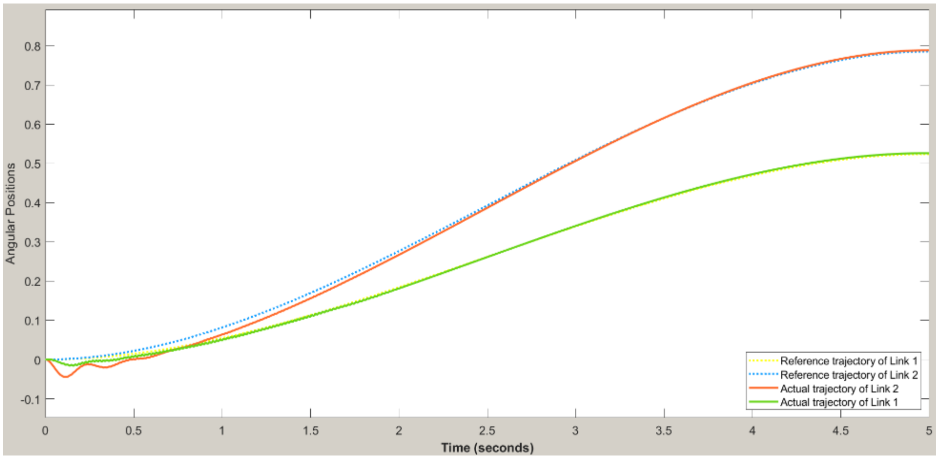

Figure 14. Trajectory tracking using STO-tuned PID.

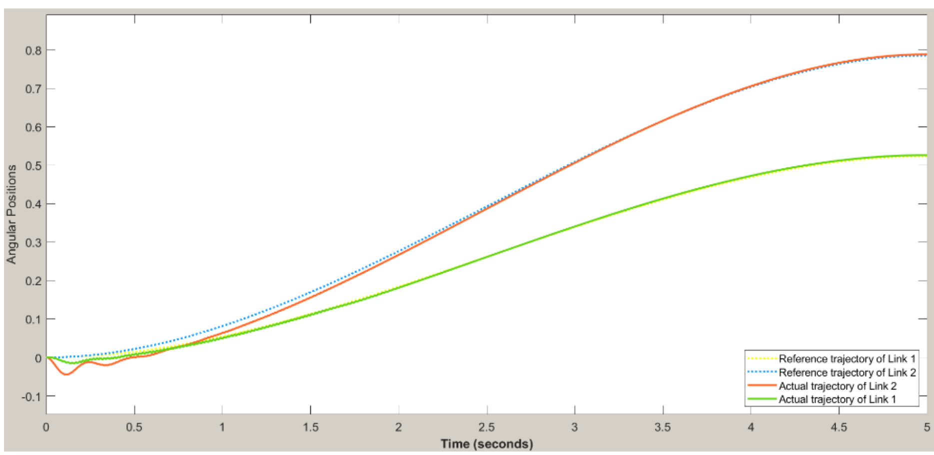

Figure 15. Trajectory tracking using Hybrid STOPSO-tuned PID.

Singh and Prasad (2018) and Loucif et al. (2020) have implemented ACO and WOA for trajectory tracking on a two-link robotic manipulator using a PID controller. The controller's performance has been evaluated for IATE error and obtained the fitness value of 0.1648 and 3.102 respectively. The fitness value obtained using AOA, ASO, SHO, STO, and hybrid STOPSO algorithm is much lower as compared to ACO and WOA as shown in Table 7.

Table 7. Comparative study of the proposed algorithm.

S. No.	Technique Implemented	Fitness function value	Technique Implemented	Fitness function value
1.	Ant Colony Optimization (ACO) (Singh and Prasad, 2018)	0.1648	ASO	0.04970
2.	Whale Optimization (WAO) (Loucif et al., 2020)	3.102	AOA	0.04607
			STO	0.04573
			SHO	0.04944
			HYBRID STOPSO	0.0454 1

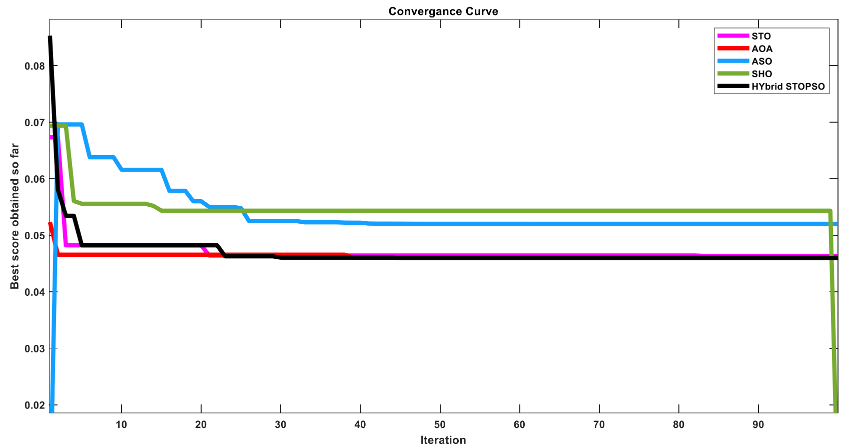

Figure 16. Convergence curve of all the metaheuristic algorithms.

6. Conclusions

Robotic manipulators have many applications in the household, industry, and medical fields. These systems are complex, and uncertain from a control point of view. Researchers are exploring many ways to control such systems so that they can perform the intended tasks with utmost efficiency. Various methods, including conventional and intelligent, have been implemented on robotic systems for such applications. Conventional methods include adaptive control, optimal control, proportional-derivative and integral control while intelligent control is the use of artificial intelligence methods like metaheuristic optimization algorithms. In this work, the problem of trajectory tracking has been addressed for a two-link robotic manipulator using various metaheuristic algorithms (ASO, AOA, SHO, and STO) tuned PID controller. The weighted sum of an integral time absolute error (ITAE) has been taken as the performance index for the implementation of such metaheuristic algorithms. Considering the stochastic nature of these algorithms, a statistical analysis has been carried out by running each algorithm for 10 runs. Afterward, to enhance the exploitation capability of the implemented STO algorithm a novel hybrid algorithm STOPSO has been designed and implemented for the trajectory tracking of the robotic manipulator. It has attained promising trajectory tracking by significantly improving the exploitation capability of STO algorithm with the help of PSO algorithm. To evaluate the effectiveness of the proposed algorithms, a nonparametric statistical test known as the Friedman test has been performed and each algorithm has been assigned a rank, hybrid STOPSO attains a rank of 1 followed by STO and SHO algorithm attains the lowest rank. Thus, the proposed hybrid STOPSO algorithm performs the best and SHO algorithm performs the worst. These metaheuristic algorithms provide the optimum gains of the controller parameters, thus providing optimal trajectory tracking for robotic manipulators. The proposed STOPSO algorithm is a proficient and robust technique to track the trajectory of a robotic manipulator. Various other hybrid algorithm-based tuning may further improve the tracking performance of the robotic manipulators. As the future scope, the implementation of STOPSO algorithm in various other applications like path planning, joint angle orientation, and tuning of other conventional controllers may also be fascinating for researchers and scientists across the globe.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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