Improved Tracking Accuracy of Par-4 Delta Parallel Robot Using Optimized FOPID Control with PSO Technique

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***Abstract*—The Par-4 Delta parallel robot is an excellent choice for most pick-and-place applications. The parallel robot has complex and high nonlinearities and the choice of control design is one key to improving the tracking performance and accuracy of parallel robots. This study proposes two structures of proportional-derivative-integral (PID) controller. The first scheme utilized Integer-order setting of controller's terms, while the second structure used integral and derivative terms with fractional orders and it is termed as fractional-order PID (FOPID) controller. The terms of FOPID controller are synthesized based on fractional calculus theorem. It has been shown that FOPID controller has high efficacy when applied to complex and nonlinear systems. However, the tuning of its terms is a critical issue in its design. As such, an algorithm-based particle swarm optimization (PSO) has been developed to tune the parameters of FOPID controller such as to achieve global minimum of tracking errors Par-4 Delta parallel robot. The effectiveness of optimized FOPID controller has been verified via numerical simulation and it is compared to integer PID (IPID) controller with the same PSO algorithm. The computer simulations have showed that better tracking errors have been obtained with FOPID controller compared to its counterpart. Using the root mean square of error (RMSE) as the metric of evaluation, the numerical results showed that PSO-FOPID achieved 60% and 62.9% improvement in terms of tracking accuracy along both the x-axis and the z-axis, respectively, as compared to IOPID applied controller techniques.**

Keywords*—Par-4 Delta Parallel Robot; Integer PID Controller; Fractional PID Controller; Tracking Accuracy; Particle Swarm Optimization.

I. Introduction

Parallel robot manipulators have several benefits compared to serial robots. They are stiffer, more accurate, faster, and can accelerate quickly, allowing them to carry heavier loads. However, they do have limitations in workspace and movement [1], [2]. One well-known type of parallel robot is the delta robot, established by Reymond Clavel and his team in the early 1980s. In recent years, high-speed pick-and-place delta robots have been generally used in many industriousness, such as electronics, foodstuffs, medications, packaging, and light manufacturing [3], [4].

To effectively track the path of a delta robot, researchers have looked into various advanced control methods [3]. These include sliding mode control, adaptive control, and model-predictive control. Delta robots display complex movements, making determining the best control method challenging. Various strategies have been developed to enhance tracking accuracy and reduce errors. The next sections will briefly describe these control methods.

In 2007, Pei *et al.* [4] developed a control system that improves a hydraulic parallel robot. They used a type of artificial intelligence called a radial basis function (RBF) neural network. This network helps change the settings of the PID controller in real time, making the system more adaptable. In a 2008 study conducted by M.A. Laribi *et al.* [1], extreme configurations were employed to address workspace limitations in the DELTA robot using a genetic algorithm approach. In 2008, Garrido *et al.* [5] developed an image-based PID control system for a redundant planar parallel robot, that used a fixed camera for position tracking. They applied the Lyapunov’s method and the LaSalle invariance to ensure the system's long-term reliability. In 2010, Zhang [2] showed that the average and standard deviation of general compliance matrices can be used to describe how a parallel manipulator, specifically a 5-DOF, behaves magneto statically on a global scale. This approach also aids in designing spatial stiffness optimization.

In Khosravi and Taghirad [6] 2014 analyzed a robust PID control for fully-constrained cable-driven parallel manipulators, addressing both predictable and unpredictable factors. They assessed the closed-loop control system stability using the Lyapunov-directed method, resulting that PID controller reach robustly stable if gains were appropriately chosen. In 2016, Lu and Liu [7] introduced the non-dominated sorting genetic algorithm (NSGA-II) optimization method to design and adjust a PID interval-type-2 fuzzy logic controller to regulate the path of a delta parallel robot. In [8], Angel and Viola has proposed computed torque control (CTC) to the linearized model of delta robot. The CTC is also integrated with fractional and integer-order PID controllers to improve the tracking performance based on different scenarios. In addition, the controllers have been assessed in terms of control efforts and robustness characteristics against variation in applied disturbance. Humaidi *et al.* 2019 [9] developed two controllers: an augmented PD (APD) controller and an augmented nonlinear PD (ANPD) for a Delta/Par4-like parallel robot. Meanwhile, Humaidi *et al.* (2019) [10] enhanced the robot's dynamic performance by optimizing the controllers’ parameters via the particle swarm optimization (PSO) approach. In Zhang and Ming [11] 2019 proposing the grey-wolf optimization

(GWO) method was used to enhance the Par4 parallel robot trajectory tracking, resulting in smoother operation and reduced residual vibration, in addition to asymmetric 5th- and 6th-order polynomial laws of mobility. In Villamizar and Silva [12] 2019, describe the parallel robotic manipulator tracking control employing a FOPID controller with feedback linearization technique. In Al-Mayyahi, *et al.* [13] 2020, managed the 3-RRR planar parallel robot center's path tracking with the use of the FOPID controller, where the controller parameters were tuned with the bat optimization method. In Nguyen-Van *et al.* [14] 2020 proposed a PID control for a spatial cable-driven parallel robot using three evolutionary algorithms (EAs) to adjust the controller parameters such as: genetic-algorithm (GA), particle-swarm optimization (PSO), and differential-evolution (DE). In Humaidi *et al.* [15] 2021 evaluated both the performance and robustness of the robot tracking of the IT2FL controller using two scenarios: one with disturbance and one without. Where the IT2FL controller exceeded the T1FL controller in both cartesian and joint spaces whit no external disturbance.

In Pak, *et al.* [16] (2023), used two methods to find the best settings for a robust PID controller. This controller follows a desired path using a computed torque control (CTC) strategy based on the Delta parallel robot's model. They combined differential evolution (DE) and particle swarm optimization (PSO) into one optimization algorithm. In Yigit and Celik [17] 2023 constructed many scenarios for the Delta robot, which was controlled using both moth swarm algorithm (MSA) optimization and PSO methods for tunning the FOPID controller parameters [18]. Serrano and Cardona [19] 2024 used the Euler-Lagrange mathematical formulation to create the dynamic modelling of the delta parallel robot for trajectory tracking. Then, they minimized the error by applying the robust H-Infinity controller method between the desired and actual positions after synthesizing the control law using the Lyapunov functional. In Blanck-Kahan *et al.* [20] 2024, two approaches have been suggested to optimize cascaded PI controller parameters to minimize the five-bar parallel robot position error trajectory. The first approach uses differential evolution to adjust controller parameters during the process of implementation for the desired trajectory. The second approach uses data created in the first approach to train a deep neural network. In Aghaseyedabdollah, *et al.* [21] 2024 developed a supervisory interval type-2 fuzzy adaptive sliding mode control scheme with the grasshopper optimization algorithm, determining the ideal fuzzy controller's membership functions for cable parallel robots to achieve accurate tracking performance. In Zhu *et al.* [22] 2024 identified an adaptive backstepping fractional-order – nonsingular terminal sliding mode control (ABF-NTSMC) to address the model's fundamental errors and reduce the effect of external disturbances on the delta parallel robot's motion stability.

The control approach used in parallel robots plays a vital role in governing the robot motion. There are two versions of controllers used with parallel robots. The first types are synthesized and developed based on nonlinear control methodologies like sliding mode controller, synergetic controllers, passivity-based controllers and robust adaptive controller [23]-[35]. The best controller is the one which gives better performance in terms of tracking errors and robustness characteristics.

Recently, a fractional-order PID controller has demonstrated enhancements in stability and system performance despite the presence of the Par-4 Delta parallel robot model uncertainties and external disturbances after tuning its parameters with one of the optimization methods. As the present research studies the feasibility of a FOPID controller for a delta parallel robot Par-4 via particle swarm optimization (PSO),

The main contributions of this study can be highlighted as;

- Design of optimized IOPID controller based on PSO algorithm.
- Design of optimized FOPID controller based on PSO algorithm.
- Conducting a comparison study between optimized OPID and FOPID controllers.

The present research contains the dynamic equation of delta parallel robot Par-4 in section 2, then the IOPID and FOPID controllers simplified details in section 3. Section 4 introduces the PSO optimization method with the algorithm. Section 5 shows the simulated results, and finally, conclusions are in section 6.

II. Parallel Robot Structure and Dynamics

The Par4-like delta parallel robot is a parallel manipulator known for its high speed and quick movements. Its lightweight parts make it strong and stable. This robot features four actuators that work together and can move in three directions: x-axis as left and right directions, y-axis as forward and backward directions, and z-axis as up and down directions.

In Fig. 1, you can see the three main parts of the Par-4 robot: (1) the fixed base, which includes the reducer, servo motor, and mounting frame; (2) the movable base that contains one actuator; and (3) the spherical hinge that connects the large and small arms to four chains that are arranged symmetrically [11], [23].

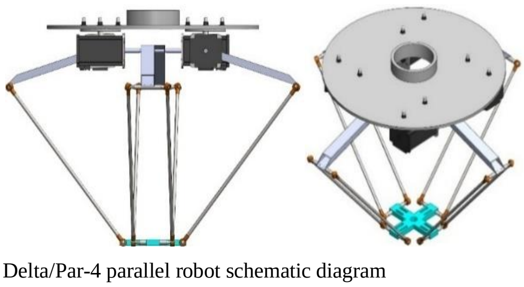

Fig. 1. Delta/Par-4 parallel robot schematic diagram

Delta robots' function in joint and Cartesian spaces. Their end effector is positioned using 3D coordinates (x, y, z), with base arm angles controlling joint space. This enables parallel movement for picking, placing, and path-following tasks.

There are two main types of motion analysis: forward and inverse for both types' kinematics and dynamics. In forward kinematics the end effector's Cartesian location from joint angles, while inverse kinematics finds the required joint angles for desired position. Delta robots require efficient and precise mapping between these regions for precision control, especially in high-speed applications. However, in terms of joint space control, the biggest drawback of Cartesian control is the limitation it imposes due to the difficulty in accurately and rapidly observing the end effector's attitude. This problem may be solved by performing the control of the robot dynamic kinematics in Cartesian space and computing the end-effector posture using forward kinematics [9].

The following equation relates the acceleration factor to the q to the actuator torque vector τ_q:

$$\tau_q - J_q^T F = I_{tot} \ddot{q} \tag{1}$$

where J_q^T represents the robot's joint Jacobian, τ_q is the actual joint torques vector, F denotes the forces vector of exerted on robot arm, and I_{tot} is a diagonal matrix.

One can write the motion equation for the moving plate as [9]:

$$J_x^T F = M_{tot} \ddot{X} \tag{2}$$

where, M_{tot} and J_x^T denote diagonal mass matrix and Cartesian Jacobian matrix of the robot, respectively, and $X = [x \quad y \quad z]$. The Delta/Par4, similar to the robot dynamic model can be noted in Cartesian space as [9]:

$$\begin{aligned} M_{tot} \ddot{X} &= J_x^T J_q^{-T} \left(\tau_q - I_{tot} \ddot{q}\right) \\ &= J_m^T \left(\tau_q - I_{tot} \ddot{q}\right) \end{aligned} \tag{3}$$

The dynamic model is developed based on the Lagrange formulation of the inverse dynamic model of a robot, which is given in the joint space using the following equation [9], [36], [37]:

$$M\ddot{X} + C X = J_m^T \tau_q = F \tag{4}$$

where, the inertial matrix is $M = M_{tot} + J_m^T I_{tot} J_m$, and the centrifugal and Coriolis forces is defined as $C = J_m^T I_{tot} \dot{J}_m$.

III. Controller Design

Over the years, control feedback has been proven to be a good mechanism for improving system performance [38]-[40]. The integer order proportional, integral, and derivative (IOPID) controller is commonly used in industries. Yet, it may not always perform effectively to nonlinear systems seen in manufacturing processes. Also, IOPID controllers frequently experience a decision between performance and robustness, making it difficult to obtain both while maintaining stability and speed. The IOPID controller is sometimes not successful in controlling nonlinear, unpredictable, and attributed systems. As a result, despite its numerous advantages, it failed to provide disturbance rejection and robustness features [41], [42]. The PID controller is expressed as:

$$G_{IOPID}(s) = u(s)/e(s) = K_p + K_I s^{-1} + K_D s \tag{5}$$

where $u(s)$ symbolizes the control action, e(s) symbolizes the error and K_p symbolizes the proportional gain, K_I symbolizes the integral gain, and K_D symbolizes the derivative gain.

In order to improve the PID controller performance, a fractional order PID (FOPID) controller was built [42] for situations where the derivative and integral values are not integers. FOPID has many practical uses, including Fractional-Order controller design, progress control of manipulators, heat distribution systems, electric control systems, and time-varying delay operations.

In comparison with IOPID controllers, FOPID has five parameters $(K_p, K_d, K_i, \lambda, \mu)$ where λ and μ are the controller fractional orders of both the integral and derivative parts, respectively, must be adjusted according to particular standards of design [13], [41], [43]-[50]. It is known that FOPID controllers often provide greater flexibility than IOPID controllers. This increased flexibility has shown to be particularly useful for a variety of applications, including vibration suppression in structural engineering [31]-[33]. Fig. 2 shows the closed loop control system with the configuration of a FOPID controller, where FOPID controller $PI^{\lambda} D^{\mu}$ continuous transfer function is defined as [31], [34]-[38]:

$$G_{FOPID}(s) = u(s)/e(s) = K_p + K_I s^{-\lambda} + K_D s^{\mu} \tag{6}$$

where the input signal e_i is multiplied by $K_p, K_I - \lambda$, and $K_D - \mu$ and then the total of the results is used to produce the error signal $u(t)$.

According to control law of (6), the Par4-Delta parallel robot dynamic model can be described by (7):

$$\begin{aligned} M \ddot{X} + C \dot{X} = M \ddot{X}^d + C \dot{X}^d + K_p e + K_I s^{-\lambda} e \\ + K_D s^{\mu} e \end{aligned} \tag{7}$$

The (7) can be rewritten as:

$$M (\ddot{e}) + C (\dot{e}) + K_p e + K_I s^{-\lambda} e + K_D s^{\mu} e = 0 \tag{8}$$

where $\ddot{X}^d$ and $\dot{X}^d$ are the desired travelling plate acceleration and velocity, correspondingly, and $e = [e_x \quad e_y \quad e_z]^T = X^d - X$ represents the position errors in the three channels.

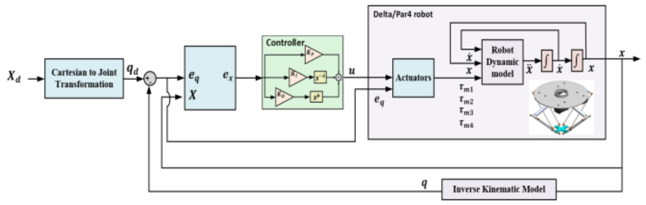

Fig. 2. Delta/ Par-4 parallel robot close-loop system

IV. Particle Swarm Optimization (PSO)

In 1995, Kennedy and Eberhart developed PSO algorithm, which has since become one of the most applied SI-based algorithms [51]. It is an optimization approach modelled by the cooperated actions of birds and fish. It has an effective, evolutionary and probabilistic optimization methods which is considered for addressing complex optimization problems. Many engineers and researchers in control systems prefer PSO algorithm for tunning because of its efficiency, ease of use, and quick convergence without requiring derivatives [52].

The PSO approach investigates the domain of an objective function by altering the paths of a single agents, titled particles, which are piecewise trajectories constructed by vectors of position in a quasi-stochastic manner. The motion of a swarming particle is classified into two main components: stochastic and deterministic. Individually, the particle is involved to g^* which is the current global optimum and x_i^* its historical best position, while also tending to random movement [38]. When particle i finds a site better than all the others, it identifies it as the new best for particle i. The best solution for all n particles is found at any given time t during iterations. Until the objective stops improving or after a certain number of iterations, the objective is to find the best answer out of all available solutions [52]-[61]. The primary PSO phases may be described using the pseudocode provided in Algorithm 1.

Algorithm 1: Particle swarm optimization pseudocode

Objective function $\boldsymbol{f}\ (x), x = (x_1, \dots, x_n)^T$
Set initial locations x_i and velocity v_i of n particles.
Find $\boldsymbol{g}^*$ from $min\{f(x_1), \dots, f(x_n)\}\ (at\ t = 0)$
while (criterion)
  for the cycle over all n particles and all D dimensions
  New velocity $\boldsymbol{v}_{t+1}$ is generated by applying the following equation:
  $\boldsymbol{v}_i^{t+1} = \boldsymbol{v}_i^t + \boldsymbol{\alpha}\, \epsilon_1 [\boldsymbol{g}^* - \boldsymbol{x}_i^t] + \boldsymbol{\beta}\, \epsilon_2\, [\boldsymbol{x}_i^{*(t)} - \boldsymbol{x}_i^t]$
  Where $\boldsymbol{\epsilon}_1$ and $\boldsymbol{\epsilon}_2$ are two random vectors with values between 0 and 1.
  α and β are considered as acceleration constants or the learning parameters, which are estimated as $\alpha \approx \beta \approx 2$
  Determine the new position locations of the position $\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \boldsymbol{v}_i^{t+1}$
  Measure objective functions in novel locations $\boldsymbol{x}^{t+1}$
  Determining $\boldsymbol{x}_i^{*i}$ as the current optimal value for each particle
end for
  Determine $\boldsymbol{g}^*$ as the current global best value
  Update $t = t + 1$ (iteration counter or pseudo-time)
end while
  The final results $\boldsymbol{x}^{*i}$ and $\boldsymbol{g}^*$ should be output.

Fig. 3 shows the FOPID- PSO controller optimization algorithm. In this configuration, the gains of the FOPID controller are selected with the PSO algorithm. The findings are then reviewed, allowing designers to choose the best-suited controller [45].

V. Simulation Results

The figures represent position, position error time-varying reactions, torque, and control input, respectively. The paper explains the system's performance under various control schemes, with a particular emphasis on the impacts of the IOPID and FOPID controllers, where Table I shows the parameters of each implemented controller type.

Both Fig. 4 and Fig. 5 how the time-varying position tracking for the parallel robot in the x-axis and z-axis, respectively, for both the IOPID controller and FOPID controller without and with PSO algorithm implementation, where the results show significant improvement by applying FOPID as compared to the IOPID before and after PSO applying with setting parameters as in Table II. This is obvious in the root mean square (RMS) error result in Table III, Fig. 6, and Fig. 7 of the robot's errors in both x- and z-axes, while Fig. 8 shows the root mean square error (RMSE) with statistical analysis. The reductions in position error with RMS indicate that the FOPID controller with PSO produces a more stable response with less overshoot and steady-state error. The suggested controller may be more successful at maintaining the necessary positional precision for the defined time.

Based on above results, it has been shown that better accuracy can be obtained with optimal FOPID controller compared to optimal IOPID controller. Fig. 9 depicts the torque sustained with time for both controller types, showing comparable oscillatory activity; however, the FOPID controller responds more consistently with fewer peaks and troughs. This feature promotes improved performance and decreases the probability of mechanical stress on the system. For instance, the IOPID controller exhibits high peaks, indicating rapid torque fluctuations that may increase wear and tear on system components. In terms of control efforts, Fig. 9 showed that FOPID controller delivers higher control signals (torque signal) as compared to IOPID controller. This is the price – paid for the improved performance and accuracy, due to FOPID controller. To quantity this argument, Table IV reports the neumic values of torques for all channel of parallel robot. The evaluation metric is based on root mean square of torque (RMST). Fig. 10 clarified this evaluation using statistic histograms.

TABLE I. Parameters for Both Controllers

Channel of controller's gains	Controller's gains			
	IOPID Controller		FOPID Controller	
	Classical	PSO Algorithm	Classical	PSO Algorithm
K_p	60×10^3	3.0297×10^4	60×10^3	4.1813×10^4
K_i	1×10^{-3}	0.0068	55×10^3	4.5231
K_d	1×10^3	802.4862	1×10^3	443.7630
λ	1	1	0.001	0.013
μ	1	1	0.98	0.96

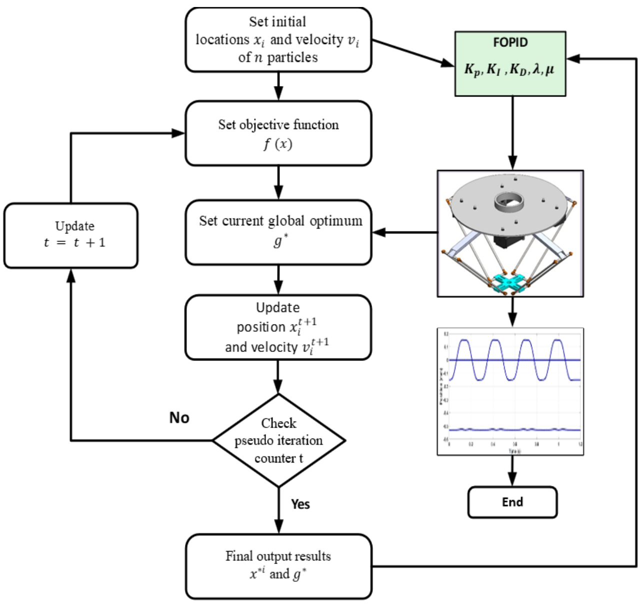

Fig. 3. Tuning FOPID controller via PSO optimization algorithm

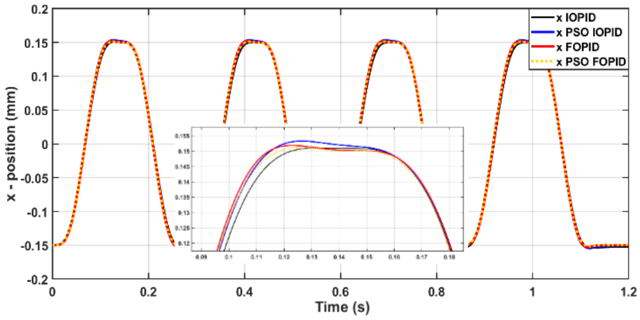

Fig. 4. X – axis position response of controlled 4DOF parallel robot

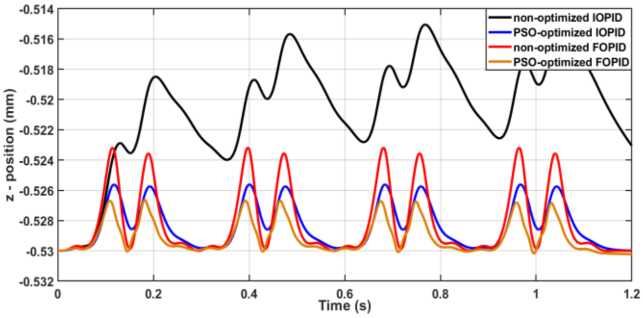

Fig. 5. Z – axis position response of controlled 4DOF parallel robot

TABLE II. SETTING OF PARAMETERS FOR PSO TECHNIQUE

PSO swarm size	50
Maximum iterations	100
Inertia weights	0.7298
Cognitive parameter	1.5
Social parameter	1.5

TABLE III. EVALUATION OF TRACKING ERRORS BASED ON BOTH CONTROLLERS

Channel of controller's gains	Root Mean Square of Errors (RMSE) (mm)			
	IOPID Controller		***FOPID Controller***	
	Classical	***PSO Algorithm***	***Classical***	***PSO Algorithm***
e_x	5.3×10^{-3}	3.5×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
e_y	0	0	0	0
e_z	10.1×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1×10^{-3}

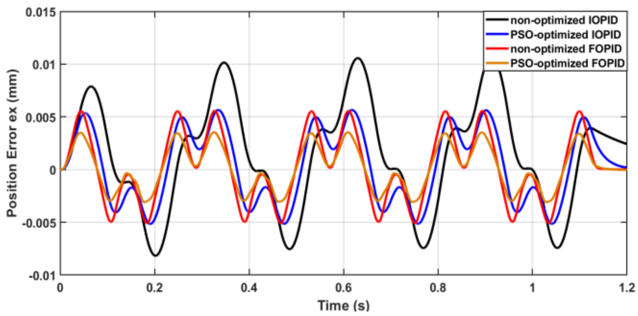

Fig. 6. X – axis position error response of controlled 4DOF parallel robot

The implemented figures show that the FOPID controller system response improves the IOPID controller system response when it comes to decreasing position error and increasing the system's stability. The results presented indicate that FOPID is an enhanced option for situations demanding accurate control in a multidimensional environment.

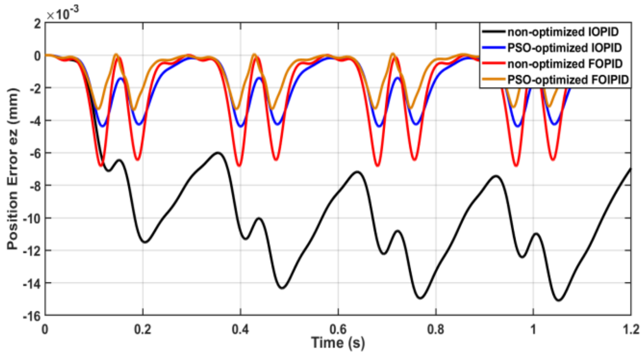

Fig. 7. Z – axis position error response of controlled 4DOF parallel robot

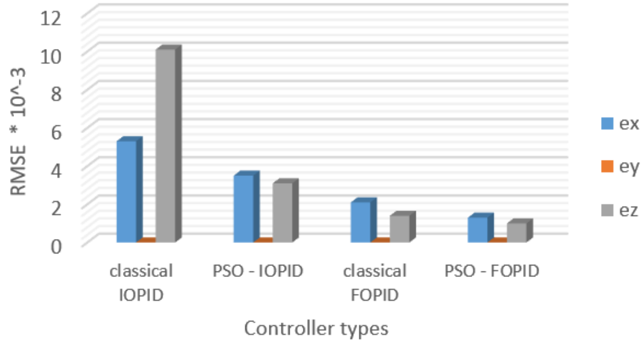

Fig. 8. The root-mean square error (RME) statistical analysis

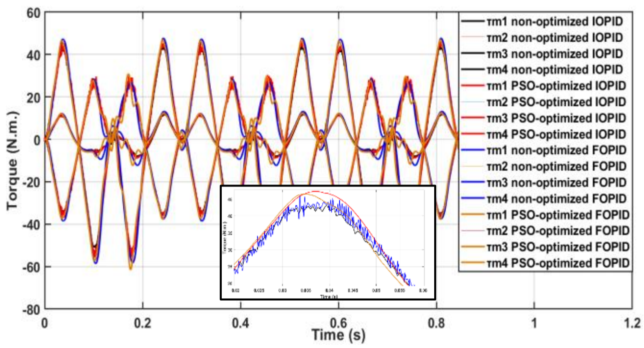

Fig. 9. Torque response of controlled 4DOF parallel robot

TABLE IV. EVALUATION OF ACTUATING TORQUES BASED ON BOTH CONTROLLERS

Channel of controller's gains	Root Mean Square of Torque (RMST) (N.m)			
	IOPID Controller		***FOPID Controller***	
	Classical	***PSO Algorithm***	***Classical***	***PSO Algorithm***
τ_{M1}	28.6199	34.3272	30.0493	43.135
τ_{M2}	5.5626	7.1734	6.0598	21.234
τ_{M3}	18.7908	21.4428	19.1325	41.578
τ_{M4}	5.5626	7.1734	6.0598	21.234

In order to extend this study for future work, one can compare the optimized controller for the suggested parallel robot to other control techniques used in the literature. Intelligent and nonlinear controllers may be used for such comparison to show the effectiveness of proposed controller compared to others [62-75]. In addition, one can use other optimized technique such as genetic algorithms (GA), differential evolution (DE), ant colony algorithm, and bee algorithm and to be compared to PSO algorithm as another extension of this study [76]-[80].

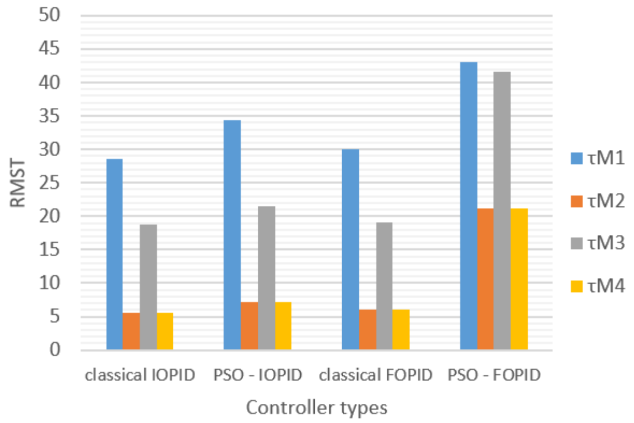

Fig. 10. The root mean square torque (N.m) statistical analysis

VI. Conclusions

The control design for 4 DOF parallel robot is challenging problem due to its high complexity and nonlinearity. In this study, two versions of PID controllers are presented and design for tracking control of parallel robot. The PSO algorithm is used to improve the performances of proposed controllers by tuning of their terms. The numerical results showed that the optimized FOPID controller improved the tracking accuracy by 60% and 62.9% along x-axis and z-axis, respectively, compared to IOPID controller. However, the price paid by this improvement in accuracy is the higher torques delivered by the FOPID controller. The statistic, based on Table IV and Fig. 10, has numerically evaluated and reported this important conclusion.

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