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Optimal TID Tracking Control for Industrial Delta Robot Based on Harmony Search

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***Abstract*—This paper seeks to enhance the delta robot accuracy using the Tilt-Integral-Derivative (TID) technique. A CAD model for a real delta robot was developed on SolidWorks®. Then a Simscape model was generated using MATLAB® to apply the proposed control technique. The proposed TID technique was compared with the Proportional integral derivative (PID) control to ensure robustness. The harmony search (HS) optimization was used to find the optimal parameters of the PID and the TID controllers based on an effective objective function. Several operating points of robot angles were applied to investigate the accuracy of each control technique. The results show that the TID based on harmony search had the best settling time, rise time, minimum overshoot, and minimum steady-state error.**

***Keywords*—PID Control; Delta Robot; Harmony Search (HS); TID Control.**

I. INTRODUCTION

In recent technological development, robots have gained great popularity and interest of the researchers' consideration. Robots are those programmable machines that can perform multiple tasks at the same time with no need for all time human supervision with speed and accuracy. Robots can be classified into serial and parallel manipulation robots, each with a specific type of tasks and application. Generally, they can perform tasks in different conditions such as repetitive motion tasks [1][2] with different payload [3] at variable speed [4].

Delta robot is one of the typical parallel robot manipulators with flexible closed-loop mechanism that gives it the advantage of speed, force, motion accuracy and rigidity [5]-[7] so it is used in industrial field such as packaging and pick-and-place tasks and also in pharmaceutical and surgical fields that requires accuracy and high speed [8][9]. So, delta robot can be considered as one of the most important and successful parallel robot which makes it a hot research topic for continuous performance enhancement.

The delta robot is known as a complex structure electromechanical system that has a parallel closed-loop articulated design with nonlinear characteristics so optimizing its performance has been a major challenge since 1980 [10]. Over the past few decades, many studies have been presented regarding delta robot performance in the aspect of structure kinematics and motion control. However, delta robot's end effector can perform in a small and limited workspace area and needs kinematics and dynamic motion control [11]-[13].

Several control techniques were applied and simulated on the delta robot mechanism to control and optimize the end effector motion by analyzing its workspace [14]-[20]. The robot's manipulator kinematics, inverse kinematics, and dynamics were used to achieve good accuracy for the end effector motion [21]-[25].

Parameter Varying Model Predictive Control (LPV-MPC) was used for manipulator robots by incorporating Dynamic Confined Space of Velocities (DCSV) as a recursive polytopic constraint. By optimizing constraint adjustments based on DCSV dynamics, it effectively manages dynamic uncertainties and improves trajectory tracking performance under flexibility challenges [14].

The PID control is the simplest and the most common controller that is used in many systems: industrial process [21]-[30], position and speed control [19][20], automotive cruise [21][22] , drone and aircraft [23][24], 3D printers, liquid level control, robotic systems [25][26], temperature control in HVAC systems [27] and biomedical [28].

For example, the PID control was used to reduce the steady-state error of conveyor system from 47.16% to 1.015% (unloaded) and 2.202% (loaded) [29]. Also, the PID control was developed as an integral state feedback algorithm for tracking the speed of the DC motor using Simulink Matlab and Arduino hardware implementation [30]. A dual real-time PID controllers design was presented to enhance trajectory tracing for delta robot by reducing settling time, rise time, overshoot and error values which effectively achieves stability and energy saving [31]. In [32], an Active Disturbance Rejection Control (ADRC) was implemented on 2-DoF robot. The results show the superiority of ADRC in estimating each link speed and position by root mean square error less than 0.1343 degrees. In [8], Computed Torque Controller (CTC) was presented and applied on the 4-DoF SCARA robot. The proposed control technique achieves RMSE 0.1003 compared to tuned PD and PID controllers.

The proposed Torque Feedforward Fuzzy PD Controller Bat algorithm based (BA-TFFPD) was developed for pick-and-place parallel robot and the simulations showed lower computational costs than Computed Torque Controller (CTC) and faster transient responses compared to TFPD [33]. Integration between the Nonlinear PD (NPD) control with the Sliding Mode Control (SMC) was developed to show the effectiveness and the robustness of the proposed control compared to the NPD [34]. In [35], a switching control between the PID and Fuzzy Sliding Mode Controller (FSMC) is presented where PID is switched when the robot is far from the target otherwise FSMC is activated as it deals with nonlinearities and disturbances. Three control schemes (PID, adaptive control and SMC) for 3-DoF delta robot were presented in [36], The comparison showed that best performance was the SMC with RMSE 0.4188. SMC with Active Disturbance Rejection Control (ADRC) was used to improve position trajectory of delta robot. Simulation results showed that (SMC-ADRC) achieves better results than both PD and SMC in feed-forward, offering better disturbance rejection and overall system performance [37].

However, classical control methods show inability to deal with complex and nonlinear robotic systems, so machines learning and advanced control schemes can be integrated to enhance the control response and optimize the gains values. Many studies have been performed to treat the traditional controllers' limitations and enhance overall efficiency. For example, the PD controller-based feedforward technique showed 50% error reduction compared to conventional auto-tuning and Ziegler-Nichol's methods [38]. A fuzzy logic control system for a 4-degree-of-freedom (4-DOF) manipulator was developed in [39]. It achieved successful path planning with an average error 1.8%. A fuzzy-PID controller was used to enhance the efficiency of a line-following [40]. The proposed control was showed a great result in terms of rise and settling times and the overshoot compared to fuzzy and P controllers [41][42]. By adding second-order integral control to the fuzzy control system, steady-state errors for ramps path were 0.78, 0.68, and 0.689 m [43]. A fuzzy logic control system enhanced with second-order integral control was presented for improved rocket tracking. The proposed control had minimal steady-state error and good performance [44]. In [45], A bat algorithm-optimized fuzzy PD controller (BA-TFFPD) was designed. It achieved faster transient response and lower tracking error compared to torque feedforward-based PD (TFPD) and control system and computed torque method control (CTC).

Particle Swarm Optimization (PSO) method had showed its effectiveness in improving controller's performance comparing to traditional controllers such as PID controller in terms of tracking performance [46]-[49]. Flower Pollination Algorithm (FPA) was used to enhance the performance of the PID control in case of linear and nonlinear systems, where the simulation results showed superiority of FPA-PID controller over the traditional (PID) [50].

Other machine learning algorithms have been used to optimize the different gains of traditional and classical controllers such as Reinforcement Learning (RL) approach [51], Ant Colony (ACO) Algorithm [52] which was used to minimize the robot's manipulator tracking error by determining the PID controller's gains. Artificial Neural Network (ANN) had been used in collision avoidance dual-arm robot by online detection approach [53]. Also, Support Vector Machine (SVM) algorithm that had enhanced to improve the trajectory tracking [54]. Moreover, the Grey Wolf Optimizer (GWO) approach that had been used in [55] to tune the different parameters of SMC, PDSMC and NSMC.

A comparative analysis study between (PID, FOPID, NPID) compensators based on the Covid-19 optimization algorithm was presented in [56]-[58]. The simulations results showed that the superiority of NPID in reducing rise and settling time and overshoot compared to the other methods. Also, an inverse dynamic model for a delta robot using deep neural networks optimized by the COVID-19 algorithm was introduced to improve the trajectory accuracy. A PD compensator was added to handle system uncertainty and nonlinearity, the root mean square errors are 0.00258m for a spiral path and 0.00152m for a parabola path [57]-[59].

A finite-time adaptive neural network backstepping control is developed in [59]. It was applied for uncertain rigid feedback systems with unknown disturbances and asymmetric dead zones. Simulations showed that tracking errors for quadrotor UAVs converge near the origin using a radial basis function neural network (RBFNN) and a Lyapunov function. In [60], MIMO vector backstepping was used to ensure system stability, while Moore-Penrose pseudo-inverse was used to solve static control allocation.

However, PID and PD controllers have some limitations despite their simplicity and quick response, they are not suitable for nonlinear systems because of complexity of parameters tuning which is time-consuming, especially in time-varying dynamics applications, and poor robustness due to uncertainty and disturbance.

Also, the PID controller is sensitive to noise and external disturbances. As a result of PID disadvantages, Tilt-Integral-Derivative (TID) control has been presented due to its tuning simplicity, its ability to eliminate steady-state error as the integral (I) term reduce the error signal before integration. TID also has limited effect on closed loop response and a great disturbance rejection ratio [61]. PID or TID parameters tuning is a complex process that can be determined by trial-and-error method which is a time consuming and a non-professional technique that has limitations according to each application.

So, an optimization algorithm is required to find the optimum parameters actional such as Gradient Descent, Newton's method, PSO, Simulated Annealing, ACO, Genetic Algorithm (GA) and finally Harmony Search (HS). HS is characterized by its simplicity in tuning parameters compared to other algorithms, efficiency in finding the best real-time parameters quickly and accurately and its robustness compared to other algorithms [62].

From the previous literature review the TID control showed its superiority over the PID control, and it hasn't been applied on delta robot before. In this study, the TID control will be applied on the delta robot. The Harmony Search (HS) optimization method is used to determine the best settings for the proposed controllers (PID and TID) based on the behavior of the output response and the required performance. A comparative study between PID and TID will be presented in this paper.

In the paper, the system modelling is presented in section II. While section III describes the proposed control techniques. The results are explained in section IV. Finally, section V includes the discussion of the conclusion.

II. System Modeling and Simulation

This section shows the delta robot mechanism, and robot assembly. Each platform is connected to the other by three independent and identical kinematic chains that are distributed at an angle of 120° as shown in Fig. 1. Every drive has two connections that form a parallelogram connecting it to the platform. A parallelogram assists an output link to keep it in a fixed orientation with relative to an input link. This kind of architecture performs very well in terms of rapid speed, low inertia, and precision.

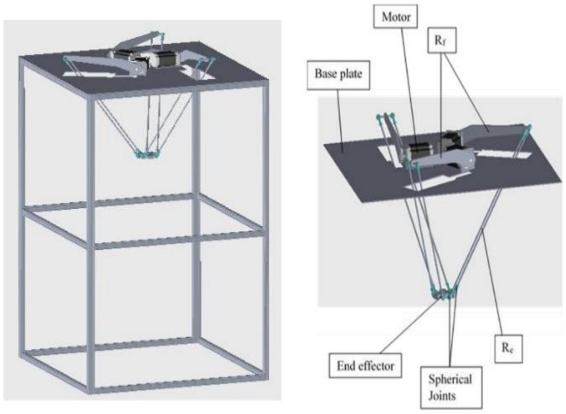


Fig. 1. CAD model for delta robot assembly

The Lagrangian formulation is used to determine the dynamic equations of the Delta robot which is expressed below:

$$\begin{aligned}\boldsymbol{\tau}_1 = \left(\psi^2 I_m + I_1 + m_2 r_f^2\right)\ddot{\theta}_1 &- \left(m_1 r_{fc} + m_2 r_f\right) g cos\theta_1 \\ &- 2 r_f \Upsilon_1[(x_0 cos\beta_1 + y_0 sin\beta_1 \\ &+ b - a) sin\theta_1 - z_0 cos\theta_1]\end{aligned} \quad (1)$$

$$\begin{aligned}\boldsymbol{\tau}_2 = \left(\psi^2 I_m + I_1 + m_2 r_f^2\right)\ddot{\theta}_2 &- \left(m_1 r_{fc} + m_2 r_f\right) g cos\theta_2 \\ &- 2 r_f \Upsilon_2[(x_0 cos\beta_2 + y_0 sin\beta_2 \\ &+ b - a) sin\theta_2 - z_0 cos\theta_2]\end{aligned} \quad (2)$$

$$\begin{aligned}\boldsymbol{\tau}_3 = \left(\psi^2 I_m + I_1 + m_2 r_f^2\right)\ddot{\theta}_3 &- \left(m_1 r_{fc} + m_2 r_f\right) g cos\theta_3 \\ &- 2 r_f \Upsilon_3[(x_0 cos\beta_3 + y_0 sin\beta_3 \\ &+ b - a) sin\theta_3 - z_0 cos\theta_3]\end{aligned} \quad (3)$$

The following Table I shows the delta robot parameters.

TABLE I. Values of Delta Robot Parameters

Parameter	Value	Parameter	value
Υ_1	-15.1458	r_f	366 mm
Υ_2	-13.238	r_{fc}	183 mm
Υ_3	-16.4696	ψ	5:1
$\ddot{\theta}_1$	15.02 rad/s^2	I_m	0.5x10^{-4} kgm^2
$\ddot{\theta}_2$	12.02 rad/s^2	I_1	80x10^{-4} kgm^2
$\ddot{\theta}_3$	17.36 rad/s^2	m_1	200 g
G	9.81 m/s^2	m_2	400 g
X_0	70.45 mm	m_p	200 g
Y_0	-116.6 mm	a	370 mm
Z_0	-819 mm	b	40 mm
θ_1	Variable	β_1	60°
θ_2	Variable	β_2	180°
θ_3	Variable	β_3	-60°

Fig. 2 shows the delta robot system on SolidWorks® after applying reverse engineering on the actual model.

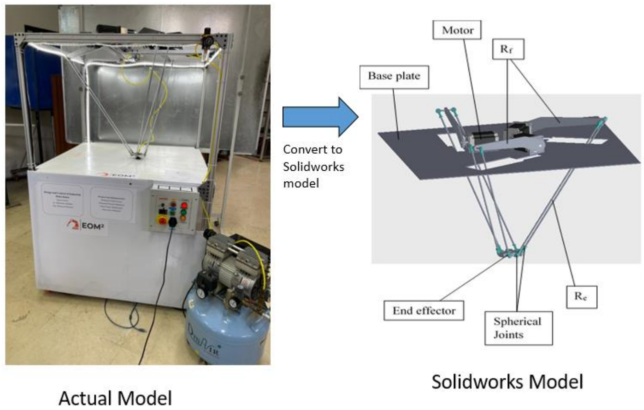


Fig. 2. Delta robot CAD model

The SolidWorks® model was converted to MATLAB® and Simscape model as shown in Fig. 3 to apply and compare between the response of different controllers. Also, selection the optimal control parameters by using HS optimization. Additionally, the choice of the suitable control technique will depend on the best performance of the Delta robot.

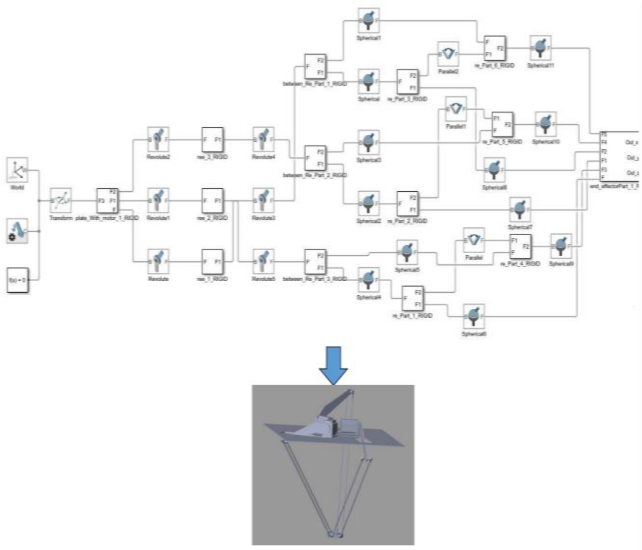


Fig. 3. Simscape model for delta robot

The obtained simscape model was validated with the actual delta robot by applying several angles on the robot joints and estimate the end effector position for both the simscape model and the actual system. The result of validation shows that the simscap model can simulate significantly the actual system.

III. Control Techniques and Optimization

This section is divided to three parts the first presents the PID control and the second describes the TID control and shows their equations. While the third part explains the used optimization method.

A. Propotional Integral Derivative (PID) Control

The PID controllers had been used to control a wide range of several systems in industrial processes. The PID controller transfer function was presented in equation (4). Where K_p is proportional gain, K_i is integral gain and k_d is differential gain [63].

$$K(s) = K_P + \frac{K_i}{s} + K_d s \tag{4}$$

Linear controllers, such as the PI and the PID, are designed to achieve control objectives such as low steady-state error and fast transient response [64].

B. Tilt Integrative Dervative (TID) Control

It is an enhancement that builds upon the classic PID controller by focusing on reducing overshoot, minimizing oscillations, responding more effectively and dealing with nonlinear systems.

Tilt integrative derivative (TID) controllers are commonly used since they are easy to tune, offer higher disturbance rejection, and are less sensitive to changes in plant parameters. The TID controller's structural layout is shown in Fig. 4.

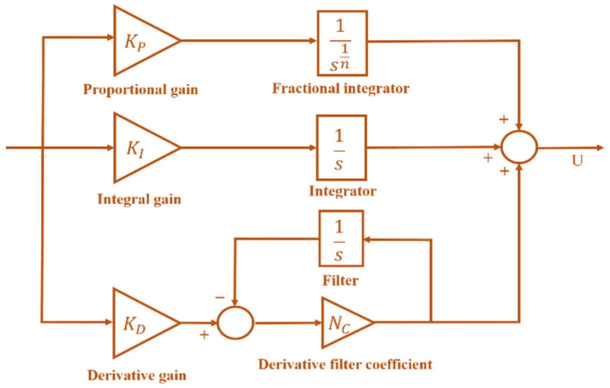


Fig. 4. Structure of TID controller

The proportional component of the controller is replaced with tilted component having a transfer function $s^{\frac{-1}{n}}$. K_P, K_D, K_I are proportional, derivative, integral gains and n is a nonzero real number respectively. The parameter NC is the derivative filter coefficient. The mathematical model of the TID controller is given by:

$$TF_{TID} = \frac{K_t}{s^{\frac{1}{n}}} + \frac{K_I}{s} + K_D\left(\frac{N_C s}{s + N_C}\right) \tag{5}$$

C. Hamony Search (HS Optimization

Try-and-error and Ziegler-Nichol’s methods are two of the various ways to specify the PID and TID parameters, although most of these approaches are unreliable [65]. However, The Harmony Search (HS) optimization method, is used to determine the best settings for the proposed controllers (PID and TID) based on the behavior of the output response and the required performance [66]-[82].

Geem et al. introduced Harmony Search (HS) in 2001. HS focuses on aesthetic quality, which can be enhanced by modifying each musical instrument's pitch. Additionally, the quality of selecting variables is determined by the objective function value [66]. In the process of improvising music, each player sounds all notes in the range in order to create one harmony. When all pitches reach a harmonious pitch, every player retains that experience in his mind, increasing the chance of achieving a harmonious pitch during the next iteration. Like this, in optimization, the first solution is produced at random using decision variables that fall inside a range. In case that the objective function values of these choice variables yield a promising respond there is a greater chance of reaching a good solution in the next set of trials as shown in Fig. 5 [67].

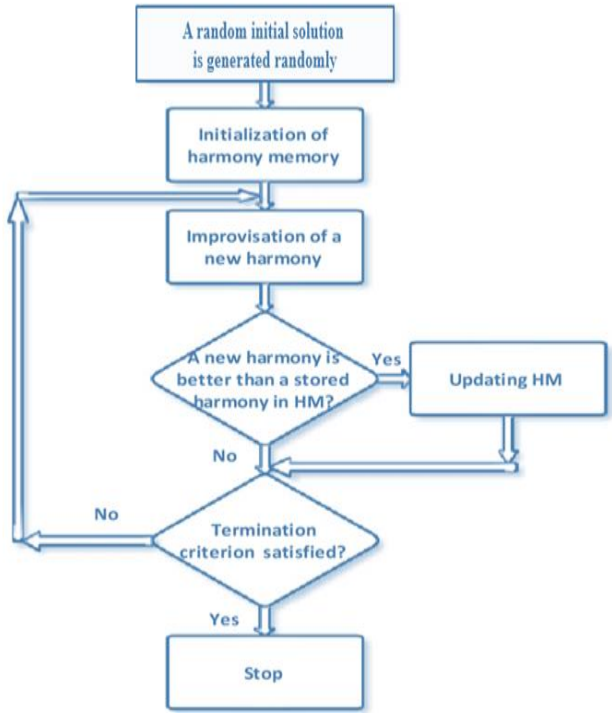


Fig. 5. Harmony search flow chart

In this paper, the harmony search optimization technique will be used to obtain the optimal parameters of the TID control and the PID control according to the objective function as shown in equation (6).

$$f = \frac{1}{(1 - e^{-\beta})(M_p + e_{ss}) + e^{-\beta}(t_s - t_r)} \tag{6}$$

Where M_p is the system response overshoot, e_{ss} is the steady state error, t_s is the settling time and t_r is the rise time. Further, this objective function can compromise the designer demand based on the weighting parameter value (β). To reduce overshoot and steady-state errors, the parameter is set higher than 0.7. If this parameter is set smaller than 0.7 the rise time and settling time will be reduced.

The analogy between improvisation and optimization is likely as follows:

a) Each musician corresponds to each decision variable (controller parameters).

b) Musical instrument’s pitch range corresponds to the decision variable’s value range.

c) Musical harmony at a certain time corresponds to the solution vector at certain iteration.

d) Audience’s aesthetics corresponds to the objective function to be minimized or maximized.

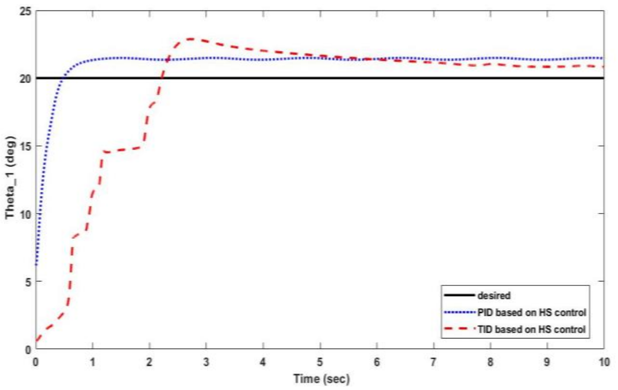
The following Table II shows the obtained PID controller for each motor.

TABLE II. PID & TID PARAMETERS FOR THE 3 MOTORS

PID Control	k_p	k_i	k_d
Motor 1	43.0713	2.9593	9.8256
Motor 2	44.531	18.3684	1.5641
Motor 3	49.531	15.3684	9.8256

IV. RESULTS AND DISCUSSION

This section shows the performance of the delta robot using the proposed control techniques through several operating points. The first test is a step input for the three joints of the delta robot as illustrated in Fig. 6.



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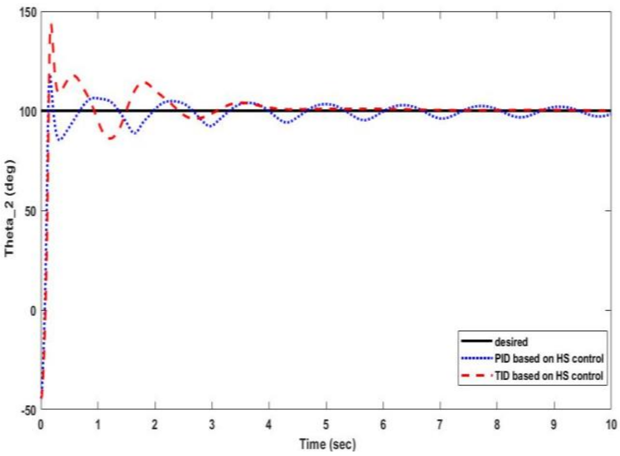

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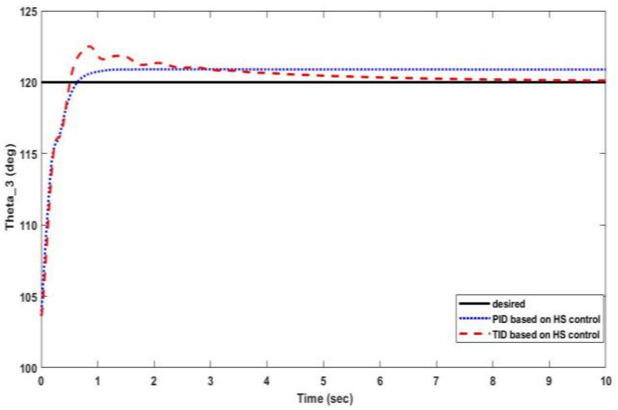

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Fig. 6. Comparison between PID & TID controllers based on HS for step desired angle Input for: (a) Theta_1 (b) Theta_2 and (c) Theta_3

It can be noted that the TID control based on HS can reach to the desired angle before the PID control based on HS. Also, it achieved minimum error and high accuracy compared to the PID control based on HS. Moreover, the TID control based on HS has low fluctuation which makes the robot move smoothly without high vibration.

It is obvious that the TID control achieves minimum rise time and minimum overshoot percentage. Also, it gives minimum overshoot except only theta_3. Overall, the TID control based on HS improves the dynamic response of the delta robot in case of the step angle input.

The following Table III and Table IV show in detail the rise time, settling time and overshoot percentage for each control technique.

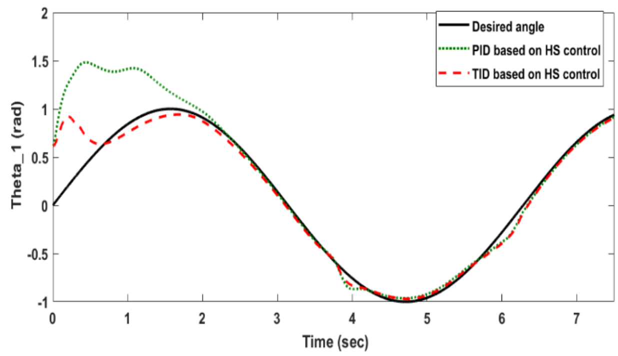
TABLE III. THE PERFORMANCE PARAMETERS OF THE PID CONTROL

PID Control	Rise time	Settling time	Overshoot %	Steady state error
Theta_1	1.3491	2.2281	0.1424	1.4656
Theta_2	0.2053	0.2053	20.1532	3.3359
Theta_3	1.5285	2.2186	0.0114	0.8974

TABLE IV. THE PERFORMANCE PARAMETERS OF THE TID CONTROL

TID Control	Rise time	Settling time	Overshoot %	Steady state error
Theta_1	2.2792	5.6006	9.8558	0.9982
Theta_2	0.1700	3.2654	43.5227	0.0911
Theta_3	1.0582	6.8420	1.9936	0.1152

The second test investigates a sin function input for the delta robot using the proposed control techniques to ensure the control robustness. Fig. 7 shows the dynamic response for each control technique through the test. It can be illustrated that the TID control based on HS can track the desired path with high accuracy compared to the PID control based on HS. Also, it has low steady state error specially in theta_1 and theta_3. Moreover, the TID control based on HS can follow the desired track smoothly and without high fluctuations.



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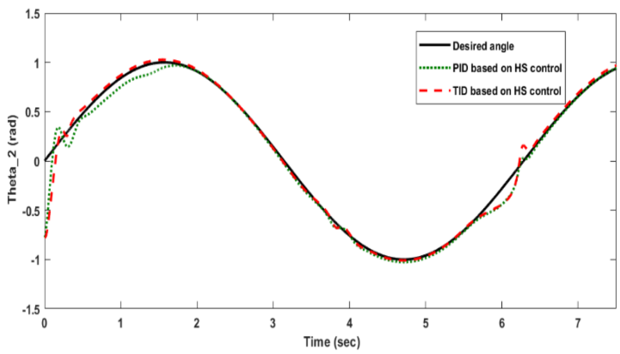

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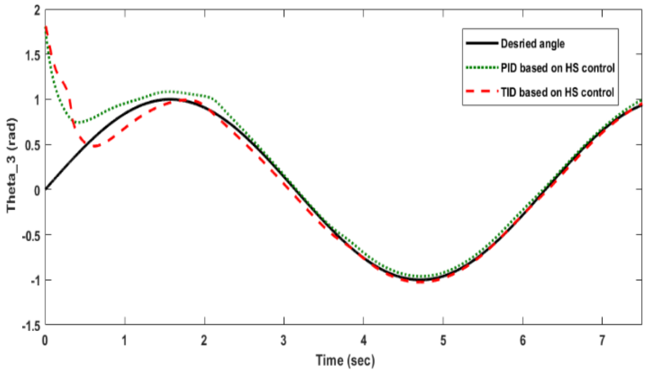

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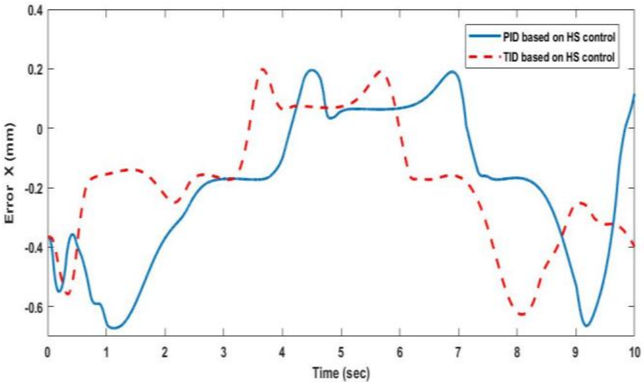
Fig. 7. Comparison between PID & TID controllers based on HS for Sine Wave Input for: **(a)** Theta_1 **(b)** Theta_2 and **(c)** Theta_3

In Fig. 8, the instantaneous error for the PID and the TID controllers was presented through the sin function input angle. It can be noted that the TID controller gives a small error in the x, y, and z coordinates compared to the PID controller. This result provides that the TID can absorb nonlinear behavior of the delta robot mechanism best than the PID controller. Also, it enhances robot performance. It makes the delta robot motion more smooth and more stable. Moreover, it gives a satisfied response, and it can be implemented with low processing and low embedded system memory where the TID controller has the same structure as the PID controller. So, the TID controller achieves a good accuracy track in direction, direction and direction.

Additionally, Table V presents the root mean square error value in each axis with each control.



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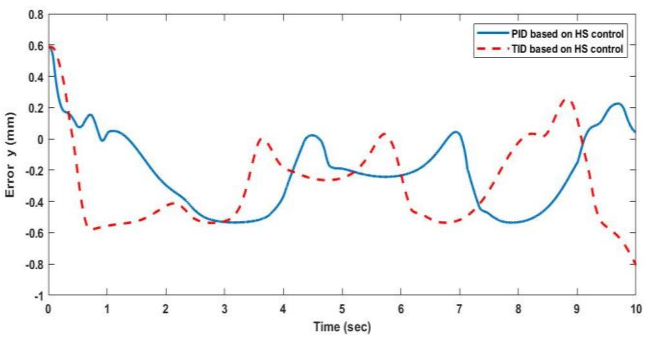

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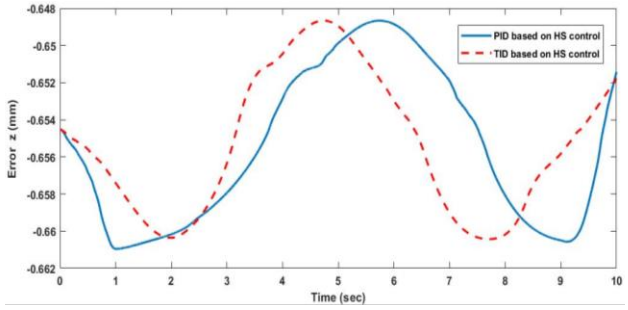

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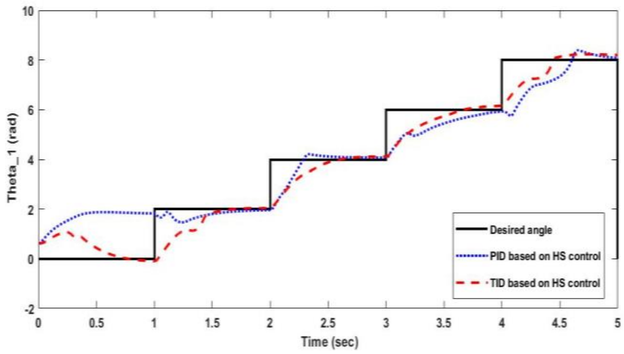
Fig. 8. Instantenous error for PID & TID controllers: **(a)** Erroe_x **(b)** Error_y and **(c)** Error_z

TABLE V. ROOT MEAN SQUARE ERROR FOR PID AND TID CONTROL

RMSE	PID control	TID control
RMSE_x (mm)	0.3197	0.2739
RMSE_y (mm)	0.3190	0.3047
RMSE_z (mm)	0.6555	0.6554

However, the proposed TID controller can eliminate the root mean square error and gives fast and stable response for delta robot simulation. Consequently, the TID has showed its superiority over PID controller in delta robot application.

A comparison between the PID and the TID controllers-based HS optimization for stair reference for the three different angles is shown in Fig. 9. The PID controller gives a poor response compared to the desired input signal while the TID controller has better tracking behavior, settling time and rise time. However, the TID controller tracks each new step in the desired angle faster and smoother than PID controller.



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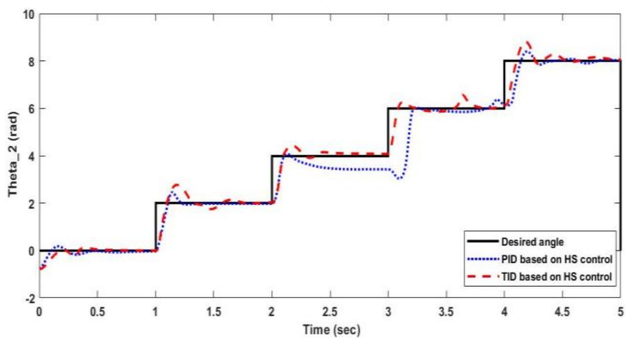

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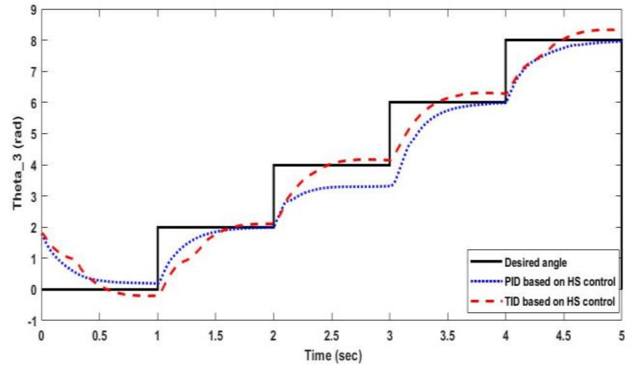

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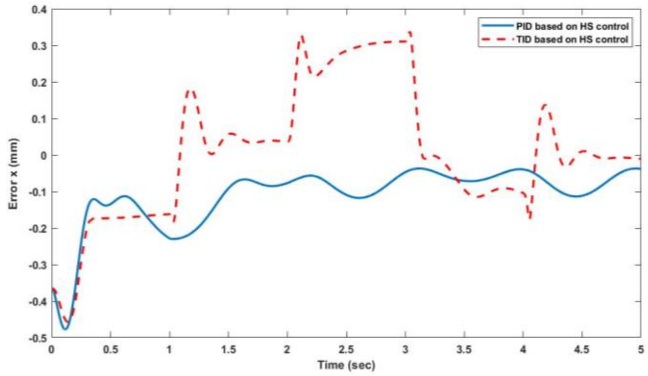
Fig. 9. Comparison between PID & TID controllers based on HS for Stair Input for: **(a)** Theta_1 **(b)** Theta_2 and **(c)** Theta_3

Fig. 10 shows the corresponding instantaneous error in case of the stair input. It can be noted that the TID control can achieve minimum error for each coordinate.



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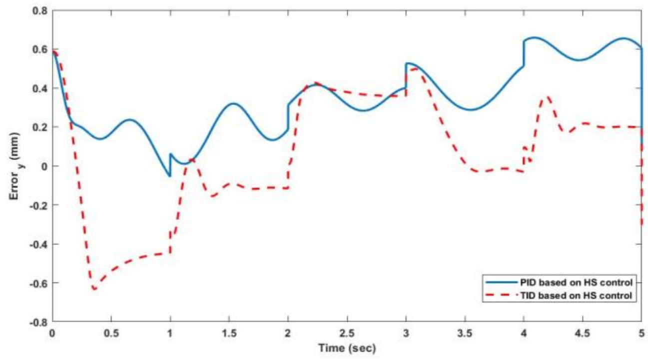

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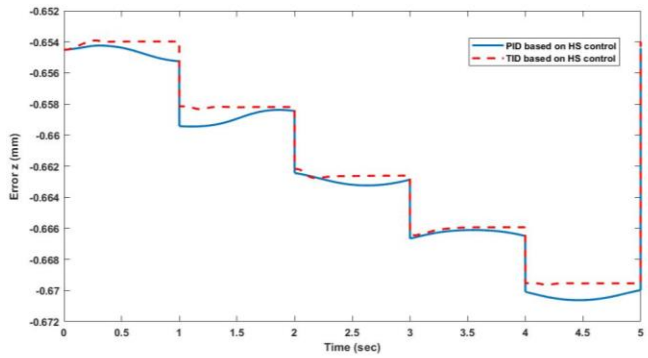

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Fig. 10. Instantaneous error for the PID & TID controllers: **(a)** Error_x **(b)** Error_y and **(c)** Error_z

Table VI demonstrates the root mean square error in case of the PID and TID controllers at the stair input.

TABLE VI. ROOT MEAN SQUARE ERROR FOR PID AND TID CONTROL

RMSE	PID	TID
RMSE_x (mm)	0.1402	0.1613
RMSE_y (mm)	0.3874	0.3099
RMSE_z (mm)	0.6627	0.6621

V. CONCLUSION

The Tilt-Integral-Derivative (TID) has been used to improve the accuracy of the delta robot. To verify robustness, the suggested method has been examined by contrasting it with the PID control. Based on an effective goal function, the harmony search (HS) optimization has been utilized to determine the PID and TID controllers' ideal parameters. A number of robot angle operating points have been used to test the precision of each control method. The harmony search-based TID has the best rise time, settling time, least amount of overshoot, and least amount of steady-state inaccuracy, according to the results.

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