

Research Article

Research on a LADRC Strategy for Trajectory Tracking Control of Delta High-Speed Parallel Robots

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In order to better track the planned trajectory of Delta high-speed parallel robot, this paper proposes a dynamics control strategy for Delta high-speed parallel robots based on the linear active disturbance rejection control (LADRC) strategy which realizes decoupling control through observing and compensating the coupling and internal and external disturbances between the three joints. Firstly, the structure and dynamics model of the Delta high-speed parallel robot are analyzed, respectively. Secondly, the control scheme of the Delta high-speed parallel robot dynamic LADRC strategy is constructed, and then, the system stability is analyzed. Taking a representative 8-shaped space helical variance trajectory as a given input of the system and a triangular wave as an external disturbance as given disturbance input of the system, simulations are carried out to demonstrate the effectiveness of the proposed LADRC strategy; results indicate that the system with the LADRC strategy has a good quick and precise real-time trajectory tracking and strong robustness.

1. Introduction

The parallel robot has the advantages of high speed, light-weight, and strong flexibility, which is complementary to the serial robot. Thereby, an increasing number of researches were carried out by numerous research institutions at home and abroad [1, 2]. At present, the parallel robot has not been widely used inasmuch as it has a difficult design of the parallel mechanism, difficult kinematics solution, complex trajectory planning, difficult trajectory tracking control, and other problems [2–6]. In this paper, Delta parallel robot is chosen as a study object; the control of Delta parallel robot can be divided into two types: one is kinematics control, which ignores the centripetal force, Coriolis force, and all kinds of disturbances of the robot. It directly controls the rotation angle of the servo motor through the given rotation angle of trajectory planning, which is mainly used in the low-speed parallel robot; the other is dynamics control. Under the condition of high-speed motion, if the centripetal force, Coriolis force, and all kinds of disturbances are ignored, the

operation accuracy of the robot will decrease, and the joints of the robot will vibrate. Therefore, the dynamics control method is designed to improve the dynamic response of the robot system and effectively control all kinds of forces and disturbances in high-speed motion, which realize that the control of the robot in high-speed motion accuracy is of great importance. The controls of three joints of Delta parallel robot are coupled with each other, and the control object has nonlinear characteristics. Therefore, its control has always been a difficult issue in the field of parallel robots; the quality of control strategy directly affects the quality of trajectory tracking, the speed, and operation accuracy of the parallel robot.

The existing control strategies that have been applied to the parallel robot include PID control [7–11], calculated torque control [12–17], and sliding mode variable structure control [18–20]. These methods have higher requirements on the model of the control object, and the operating conditions and operating environment are deterministic. In order to improve the control performance, some scholars

combined the intelligent control strategy with the traditional control strategy on control of the Delta parallel robot [21–28].

It is generally accepted that classical PID control has good robustness and reliability, and it is easy to be realized. It plays an important role in single input and single output applications. The outputs of three joints of Delta parallel robot are coupled with each other, and the control is nonlinear. The classical PID control is difficult to ensure high-precision and high-speed trajectory tracking and has poor robustness. Therefore, scholars at home and abroad are committed to researching the improved PID control method.

In literature [7–11], starting from the robot joint or joint drive servo system, PD control, PD + speed feed-forward, PD + position feed-forward, a nonlinear combination of PID parameters, online optimization of PID parameters, fuzzy self-tuning PID, and other controllers as well as various dynamic compensation controllers are used to enable the robot joints to track the given trajectory curve. The method of calculating torque control is to simplify the dynamic model of each joint and carry out decoupling control, which can achieve linear control of each joint. In literature [12–17], the dynamics control of the robot is realized based on the computational torque control method which achieves a good trajectory tracking control. In order to improve the tracking performance of the system, various improvements and compensations are made to predict or calculate the torque in the literature, and the robustness of the system is analyzed. In the nonlinear control system, the sliding mode variable structure control strategy is very popular with researchers, but the controller itself has the problems of chattering and easy to be disturbed. In literature [18–20], a new adaptive variable structure controller, a new smooth sliding mode control algorithm, and a combination of REF neural network and sliding mode control algorithm are used to solve the chattering problem of the traditional sliding mode control, with strong robustness. Since the advent of artificial intelligence control technology in the 1960s, an increasing number of control systems have been added to the elements of artificial intelligence. There are many active figures of artificial intelligence control technology in control of robot trajectory tracking of the robot. Experts and scholars have applied various neural networks, predictive control, fuzzy algorithm, expert system, and other technologies to control of robot trajectory tracking of the robot, which achieve good results. Moreover, the performance of the controller is improved by combining the artificial intelligence method with PID control, calculation torque method, and sliding mode variable structure control, such as the achievements in literature [11, 20, 27–29]. However, the aforementioned methods excessively depend on the model and are difficult to be realized due to the complexity of calculation. Consequently, these methods cannot meet the requirements of high-precision and high-speed control of high-speed parallel robot.

In literature [30], the method of combining the Active Disturbance Rejection Controller (ADRC) with Generalized Proportional Integral (GPI) was adopted. ADRC has

the advantage of being model independent, and Generalized Proportional Integral Observer (GPIO) was used instead of Extended State Observer (ESO), which has a better performance comparing with the calculated torque. However, the entire system has many parameters to be tuned, which can achieve good results at a specific load time. Nevertheless, the performance of the system decreases when the load changes, and the parameters cannot be optimized.

In the last few years, Professor Gao Ziqiang proposed the linear active disturbance rejection control method [31] (LADRC) which mainly deals with the linearization of the Extended State Observer and the error feedback combined controller, which is convenient for stability analysis and parameter tuning by using the frequency domain method. The LADRC has been widely used in a wider range owing to its advantages of simple parameter tuning and strong anti-interference ability, and more achievements have been achieved in some literature [32–38]. Motivated by the aforementioned analysis, this paper proposes an LADRC strategy to apply to the dynamic stability control of Delta high-speed parallel robot for the first time. Simulation results demonstrate that the system with LADRC strategy has the performance of a good trajectory tracking and strong robustness.

2. Structure and Dynamics Modeling of Delta High-Speed Parallel Robots

2.1. Structure of Delta High-Speed Parallel Robots. In this paper, the structure sketch of Delta high-speed parallel robot is depicted in Figure 1. A1A2A3 is a fixed platform, B1B2B3 is a mobile platform, Ai is a rotating joint, Bi and Ci are spherical joints, AiCi is an active arm, and CiBi is a driven arm, $i = 1, 2, 3$. O is the center of the fixed platform, and P is the center of the mobile platform. R is the outer circle radius of the fixed platform, and r is the outer circle radius of the mobile platform. Both A1A2A3 and B1B2B3 are regular triangles.

2.2. Dynamics Modeling of Delta High-Speed Parallel Robots. According to the literature [30], the dynamics equation of delta high-speed parallel robot can be expressed by

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

Add friction force and disturbance to formula (1), and formula (2) can be obtained as

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) + F(\dot{\theta}) + \tau_d = \tau, \quad (2)$$

where $\theta \in R^n$ is the rotation angle of the three joints of Delta high-speed parallel robot; $M(\theta) \in R^{n \times n}$ is inertia matrix of the three joints of Delta high-speed parallel robot; $C(\theta, \dot{\theta})$ is centripetal force and Coriolis force; $G(\theta) \in R^n$ is the gravity term; $F(\dot{\theta}) \in R^n$ is friction; τ_d is disturbance term; and τ is servo input.

Formula (2) is transformed into formula (3), as

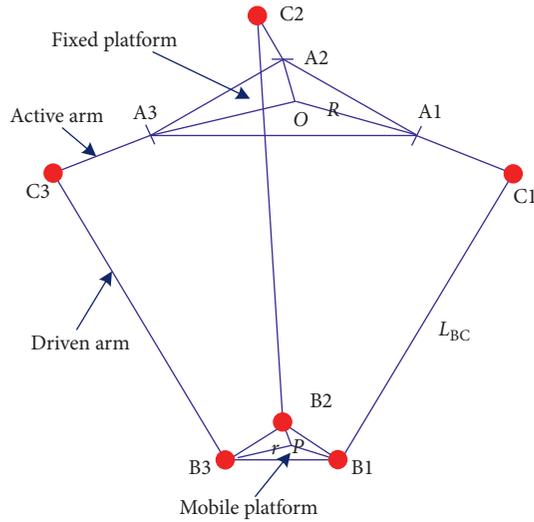


FIGURE 1: Mechanism sketch of three-degree-of-freedom Delta high-speed parallel robots.

$$\ddot{\theta} = -M^{-1}C(\theta, \dot{\theta})\dot{\theta} - M^{-1}G(\theta) - M^{-1}F(\dot{\theta}) - M^{-1}(\theta)\tau_d + M^{-1}\tau. \quad (3)$$

3. Study on LADRC Strategy

3.1. Scheme of LADRC. The mechanical structure of the Delta high-speed parallel robot is complex, and the three joints are coupled with each other. The control structure is shown in Figure 2. $X_1(s)$, $X_2(s)$, and $X_3(s)$ are inputs of Delta high-speed parallel robot. $Y_1(s)$, $Y_2(s)$, and $Y_3(s)$ are outputs of the Delta high-speed parallel robot. When one $X_i(s)$ is changed, at the same time, the other two $X_i(s)$ will follow it, and three $Y_i(s)$ will change. Thereby, in order to realize the trajectory tracking control of Delta high-speed parallel robot, three joints need to be input at the same time and decoupled each other.

When the parallel robot is running, the decomposed load on each joint changes nonlinearly with the change of pose and angular acceleration, which cannot be expressed linearly. Therefore, PID control cannot meet the requirements of the high-speed and high-precision control system of Delta high-speed parallel robot. According to the motion requirements and nonlinear characteristics of Delta high-speed parallel robot, this paper adopts the LADRC strategy to control Delta high-speed parallel robot. An 8-shaped space helical variance trajectory as the input signal is used to verify the trajectory tracking of the control strategy.

Figure 3 shows the LADRC strategy. The LADRC strategy has strong robustness, in that many uncertain factors are omitted in dynamics modeling. In practical control, these are uncertain factors of control, while the LADRC strategy does not depend on the establishment of the dynamics model, which circumvents the error problem of the dynamics model of the parallel robot. Control idea is to control each joint separately; the coupling parameters between the joints, the omitted factors in modeling, and the disturbance in actual operation are all treated as the disturbance to compensate.

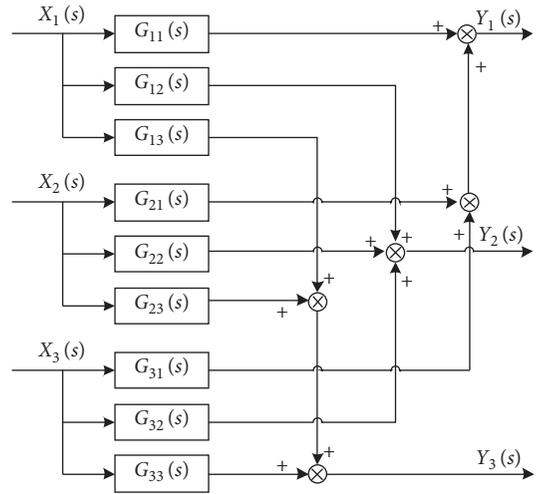


FIGURE 2: Control system structure of Delta high-speed parallel robot.

Finally, the high-precision trajectory tracking control of Delta high-speed parallel robot is realized.

3.2. Design of System Controller. The dynamics of Delta high-speed parallel robot are expressed by formula (3) which can be converted into

$$\ddot{\theta} = -a_1\dot{\theta} - a_2\theta + f_0(\theta, \dot{\theta}, \omega, t) + b\mu, \quad (4)$$

where μ is the input of the system; θ is the output of the system; $-a_1\dot{\theta} - a_2\theta$ is known modeling dynamics of object; $f_0(\theta, \dot{\theta}, \omega, t)$ is unknown modeling dynamics of objects and sum of external disturbances; b is the uncertain control gain; and b_0 is the approximate value of uncertain control gain b ; let $f(\theta, \dot{\theta}, \omega, t) = f(\cdot) - a_1\dot{\theta} - a_2\theta + f_0(\theta, \dot{\theta}, \omega, t) + (b - b_0)\mu$ which is called "total disturbance."

Let $x_1 = \theta$, $x_2 = \dot{\theta}$, and $x_3 = f(\cdot)$. Formula (4) expresses state equation of the second-order objects which can be written as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3 + b_0\mu, \\ \dot{x}_3 &= h + \dot{f}. \end{aligned} \quad (5)$$

The state equation of the LESO (Linear Extended State Observer) designed for formula (3) is expressed as follows:

$$\begin{aligned} e &= z_1 - \theta, \\ \dot{z}_1 &= z_2 - \beta_1 f_1(e), \\ \dot{z}_2 &= z_3 - \beta_2 f_2(e) + b_0\mu, \\ \dot{z}_3 &= -\beta_3 f_3(e), \end{aligned} \quad (6)$$

$$\mu = \frac{-z_3 + \mu_0}{b_0}, \quad (7)$$

where L is the gain of LESO; $L = [\beta_1 \ \beta_2 \ \beta_3]^T$, $f_i(e) = z_i - \theta$ ($i = 1, 2, 3$), and β_1 , β_2 , and β_3 are selected

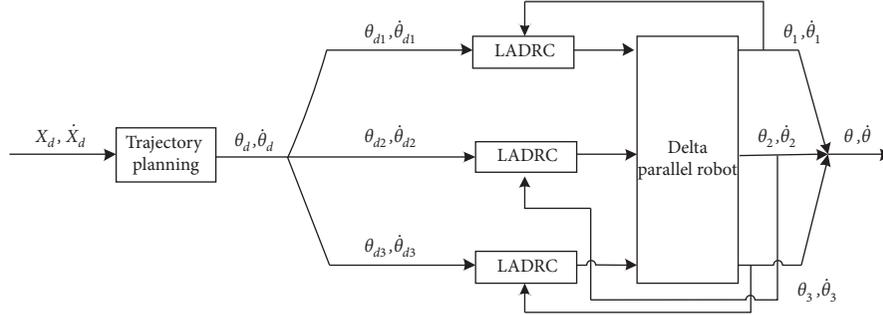


FIGURE 3: Delta high-speed parallel robot based on LADRC.

appropriate gains of LESO, respectively; LESO can track all variables including $z_1 = \theta$, $z_2 = \dot{\theta}$, and $z_3 = f(\cdot)$ in the system expressed through formula (6) in real time.

Linear control law can be expressed by

$$u_0 = k_p(v - z_1) + k_d(\dot{v} - z_2). \quad (8)$$

According to formula (6),

$$\begin{aligned} z_1 &= \frac{\beta_1 s^2 + \beta_2 s + \beta_3}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \theta + \frac{b_0 s}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \mu, \\ z_2 &= \frac{(\beta_2 s + \beta_3)s}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \theta + \frac{b_0(s + \beta_1)s}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \mu, \\ z_3 &= \frac{\beta_3 s^2}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \theta - \frac{b_0 \beta_3}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \mu. \end{aligned} \quad (9)$$

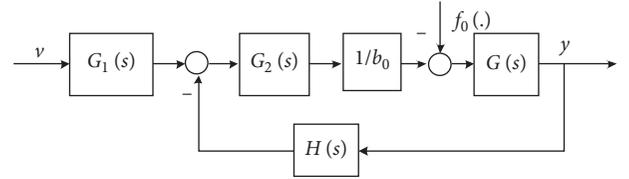


FIGURE 4: The single closed-loop structure diagram.

According to formula (8),

$$\mu_0 = \frac{1}{b_0} [k_p(v - z_1) + k_d(\dot{v} - z_2) - z_3]. \quad (10)$$

Substitute z_1, z_2 , and z_3 into formula (11) as follows:

$$\mu = \frac{1}{b_0} \frac{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3}{s^3 + (\beta_1 + k_d)s^2 + (\beta_2 + k_p + k_d \beta_1)s} \left[(k_p + k_d s) v \frac{(k_p \beta_1 + k_d \beta_2 + \beta_3)s^2 + (k_p \beta_2 + k_d \beta_3)s + k_p \beta_3}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \right]. \quad (11)$$

3.2.1. Stability Analysis. From equation (13), the single closed-loop structure diagram is shown in Figure 4.

One has

$$G_1(s) = k_p + k_d s, \quad (12)$$

$$G_2(s) = \frac{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3}{s^3 + (\beta_1 + k_d)s^2 + (\beta_2 + k_p + k_d \beta_1)s}, \quad (13)$$

$$H(s) = \frac{(k_p \beta_1 + k_d \beta_2 + \beta_3)s^2 + (k_p \beta_2 + k_d \beta_3)s + k_p \beta_3}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3}. \quad (14)$$

From the structure diagram in Figure 4, the closed-loop transfer function can be obtained as

$$G_b(s) = \frac{((G_1(s)G_2(s)G(s))/b_0)}{1 + ((G_2(s)G(s))/b_0)H(s)}. \quad (15)$$

(1) *The Scenario of Precisely Known Controlled Object.* It can be seen from the above analysis that dynamics model formula (3) of the parallel robot is established by omitting the moment of inertia and the friction between joints; thereby, the model is considered to be known.

Theorem 1. *When the model of the controlled object is known accurately, the differential tracker does not affect the stability of the system but only affects the zero point of the system. Reasonable selection of $b_0, k_p, k_d, \beta_1, \beta_2$, and β_3 can make the system stable.*

Proof. If the object model is known precisely, its transfer function is

$$G(s) = \frac{k_0}{s^2 + a_1 s + a_2}. \quad (16)$$

Substituting formulae (14)–(18) into formula (17), one obtains

$$G_b(s) = \frac{(k_p + k_d s)[s^3 + \beta_1 s^2 + \beta_2 s + \beta_3]k_0}{b_0\{[s^3 + (\beta_1 + k_d)s^2 + (\beta_2 + k_p + k_d\beta_1)s][s^2 + a_1 s + a_2]\} + k_0[(k_p\beta_1 + k_d\beta_2 + \beta_3)s^2 + (k_p\beta_2 + k_d\beta_3)s + k_p\beta_3]} \quad (17)$$

Closed-loop characteristic equation is presented as

$$D(s) = b_0 s^5 + b_0(\beta_1 + k_d + a_1)s^4 + b_0(\beta_2 + k_p + k_d\beta_1 + a_1(\beta_1 + k_d) + a_2)s^3 + [b_0 a_1(\beta_2 + k_p + k_d\beta_1) + b_0 a_2(\beta_1 + k_d) + k_0(k_p\beta_1 + k_d\beta_2 + \beta_3)]s^2 + [b_0 a_2(\beta_2 + k_p + k_d\beta_1) + k_0(k_p\beta_2 + k_d\beta_3)]s + k_0 k_p \beta_3. \quad (18)$$

The following constraint can be specified:

$$\begin{aligned} D_0 &= b_0, \\ D_1 &= b_0(\beta_1 + k_d + a_1), \\ D_2 &= b_0(\beta_2 + k_p + k_d\beta_1 + a_1\beta_1 + a_1 k_d + a_2), \\ D_3 &= [b_0 a_1(\beta_2 + k_p + k_d\beta_1) + b_0 a_2(\beta_1 + k_d) + k_0(k_p\beta_1 + k_d\beta_2 + \beta_3)], \\ D_4 &= [b_0 a_2(\beta_2 + k_p + k_d\beta_1) + k_0(k_p\beta_2 + k_d\beta_3)], \\ D_5 &= k_0 k_p \beta_3. \end{aligned} \quad (19)$$

From Routh criterion, the stability of the system can be obtained as

$$\begin{array}{cccc} s^5 & D_0 & D_2 & D_4, \\ s^4 & D_1 & D_3 & D_5, \\ s^3 & B_{31} & B_{32}, \\ s^2 & B_{41} & B_{42}, \\ s^1 & B_{51}, \\ s^0 & B_{61}, \\ B_{31} &= \frac{D_1 D_2 - D_0 D_3}{D_1}, \\ B_{32} &= \frac{D_1 D_4 - D_0 D_5}{D_1}, \\ B_{41} &= \frac{B_{31} D_3 - D_1 B_{32}}{B_{31}}, \\ B_{42} &= D_5, \\ B_{51} &= \frac{B_{41} B_{32} - B_{31} D_5}{B_{41}}, \\ B_{61} &= D_5. \end{array} \quad (20)$$

(2) *The Scenario of Unknown Parameters of the Controlled Object.* When Delta high-speed parallel robot runs at a high speed, the coupling relationships between joints are significantly relevant to the effects of the moment of inertia and friction between joints. They will result in the system chatter in the process of operation and ultimately destroy the stability of the system and decrease trajectory tracking performance if these impact factors were not taken into account. Therefore, in the design of the LADRC strategy, these factors are taken into consideration as unknown model parameters of the system when carrying out modeling.

The stability of the system model is proved as follows. Let the nominal model of the object be G_n , and then the actual object is $G(s) = G_n(1 + \delta G(s))$; δG is the perturbation of nominal model and meets $|\delta G(j\omega)| \leq \overline{\delta(G\omega)}$; $\overline{\delta G(\omega)}$ is bounded the uncertainty of multiplicative norm.

Owing to the closed-loop characteristic equation $1 + G_2(s)(1/b_0)G(s)H(s) = 0$, the following expression is obtained as

$$1 + G_2(s) \frac{1}{b_0} G_n(s) (1 + \delta G) H(s) = 0. \quad (21)$$

According to robust stability criterion, for arbitrary ω , the inequality satisfying formula (21) is as follows:

$$\begin{aligned} b_0 + G_2(s)G_n(s)H(s) + G_2(s)G_n(s)H(s)\delta G(s) &= 0, \\ \overline{\delta G(\omega)} < \Delta G(\omega) &= \left| \frac{b_0 + G_2(s)G_n(s)H(s)}{G_2(s)G_n(s)H(s)} \right|. \end{aligned} \quad (22)$$

The conditions given by formula (22) can stabilize the system.

It can be seen that selecting b_0 , k_p , k_d , β_1 , β_2 , and β_3 properly can make the system stable, which can guarantee that the system has the stability and certain robustness.

It can be concluded from the above stability proof that the LADRC strategy not only realizes the dynamics control of the trajectory tracking of Delta high-speed parallel robot but also guarantees that the uncertain factors of the model will not affect the stability of the system at high-speed operation. \square

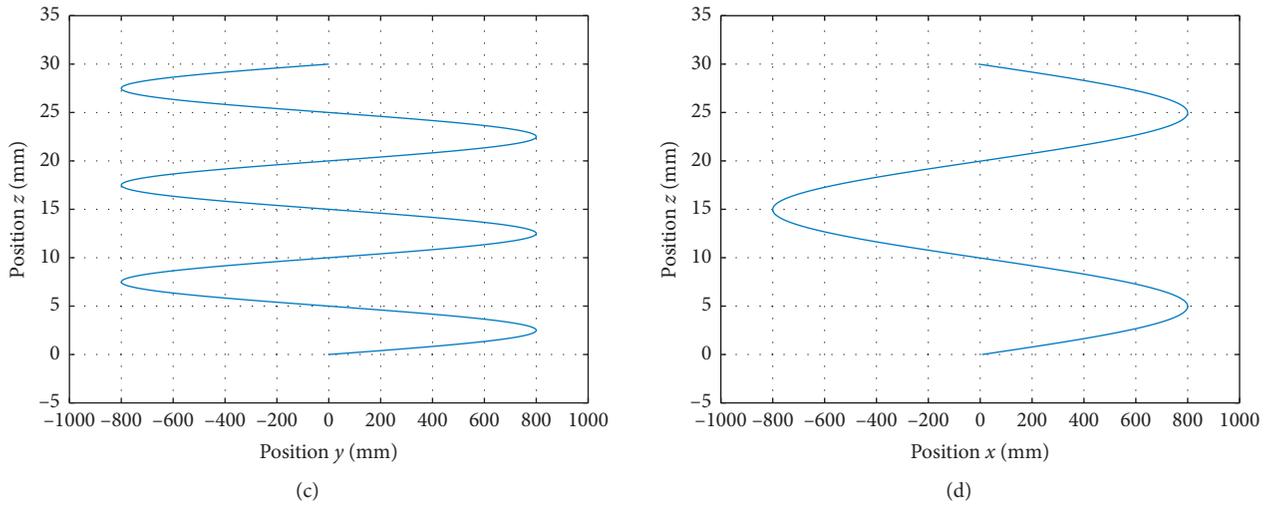


FIGURE 7: 8-shaped trajectory. (a) The space trajectory in 3D coordination system. (b) The projection on the x-y plane. (c) The projection on the y-z plane. (d) The projection on the x-z plane.

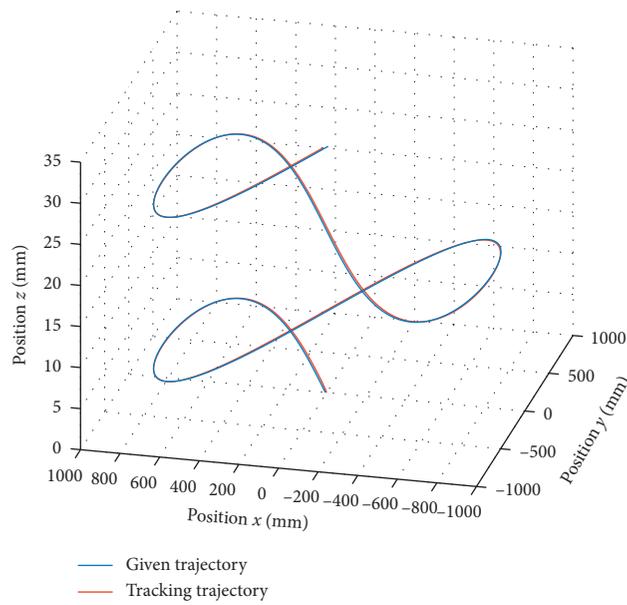


FIGURE 8: Trajectories without disturbance.

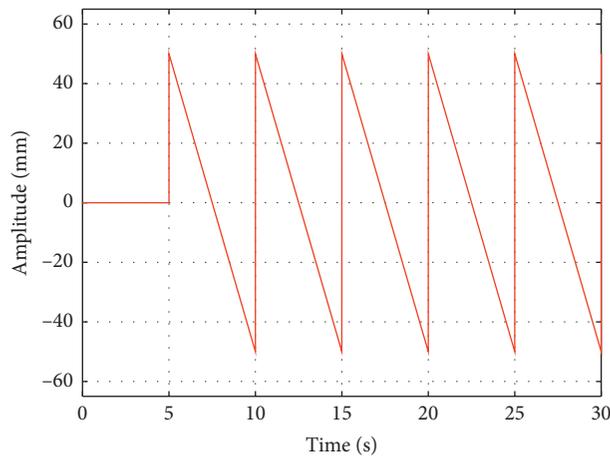


FIGURE 9: Disturbance signal.

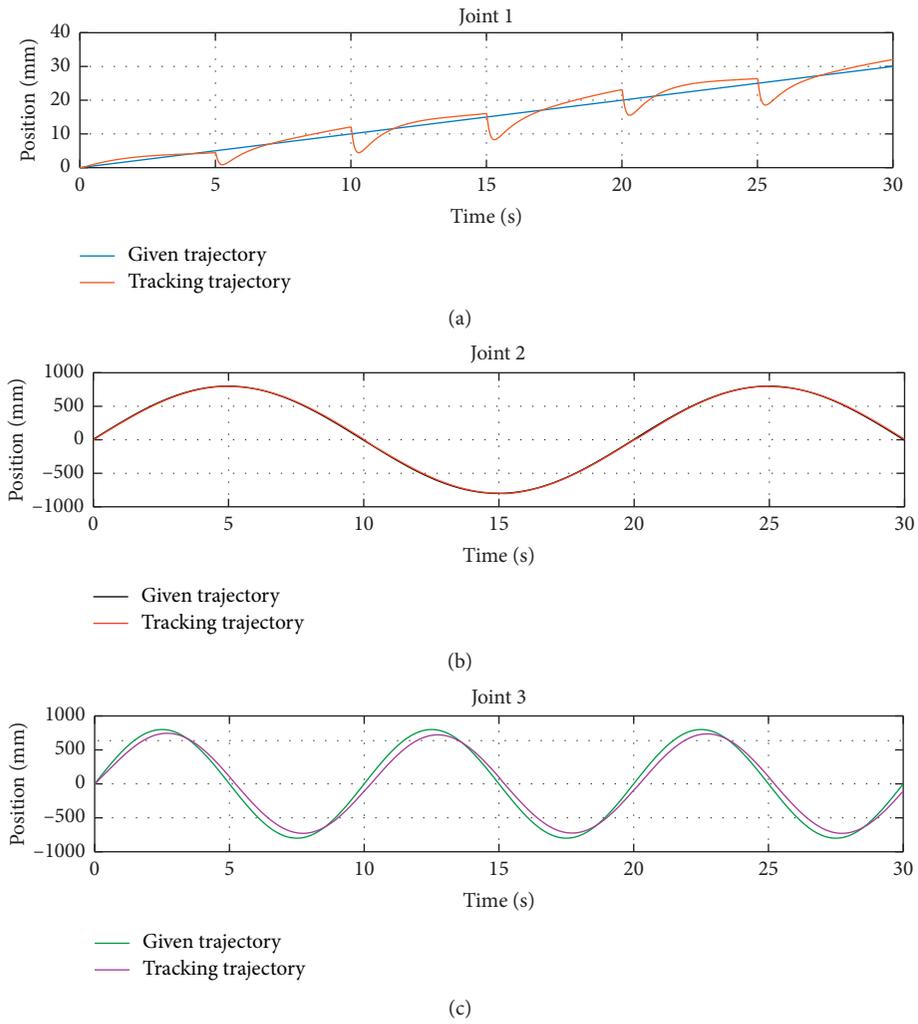


FIGURE 10: Trajectories of 3 joints without the LADRC strategy. (a) Trajectories of joint 1. (b) Trajectories of joint 2. (c) Trajectories of joint 3.

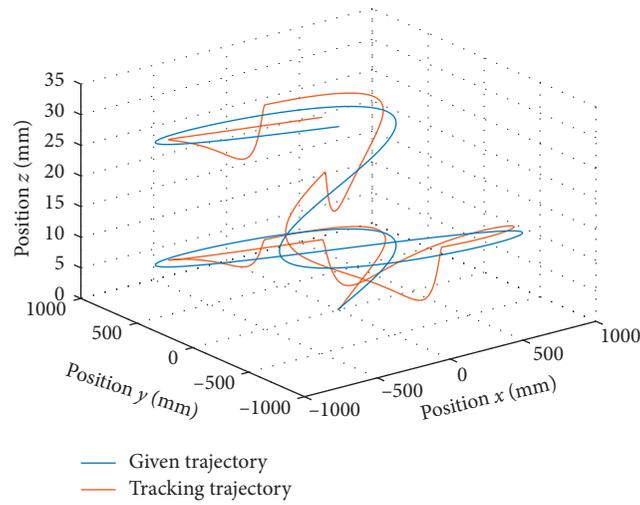


FIGURE 11: The tracking trajectory of without the LADRC strategy.

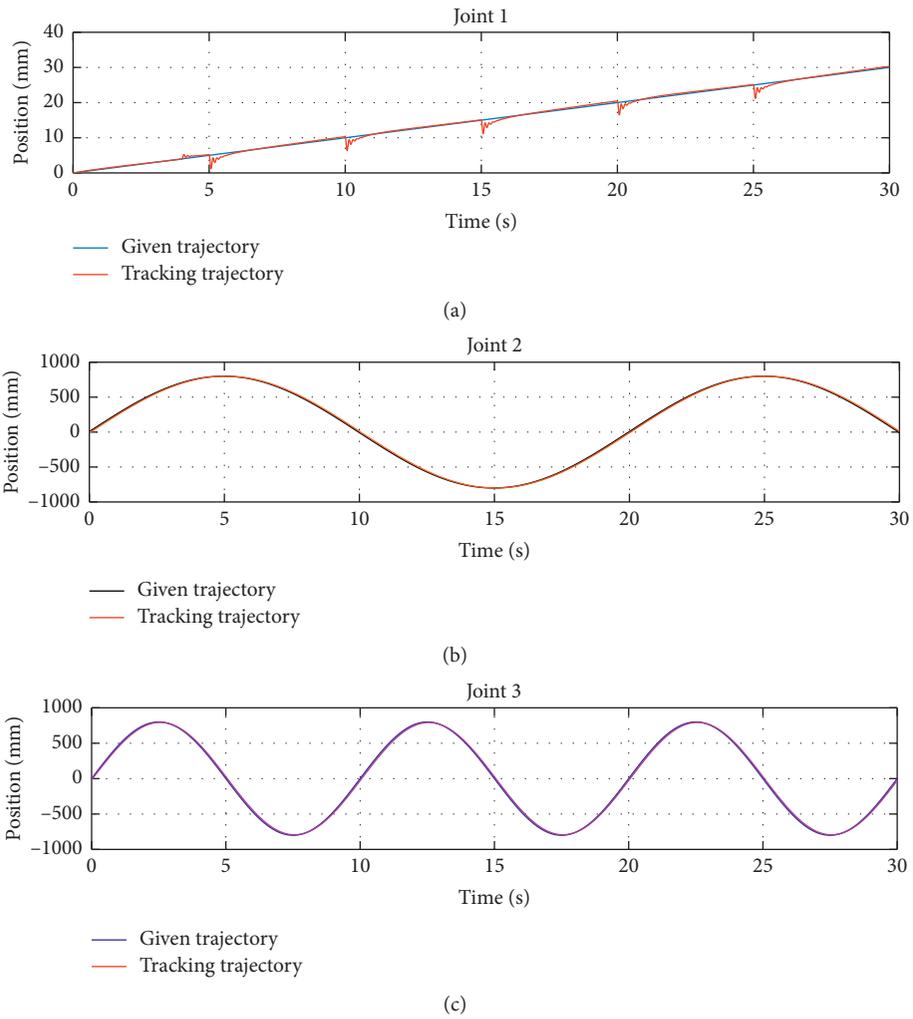


FIGURE 12: Trajectories of 3 joints with the LADRC strategy. (a) Trajectories of joint 1. (b) Trajectories of joint 2. (c) Trajectories of joint 3.

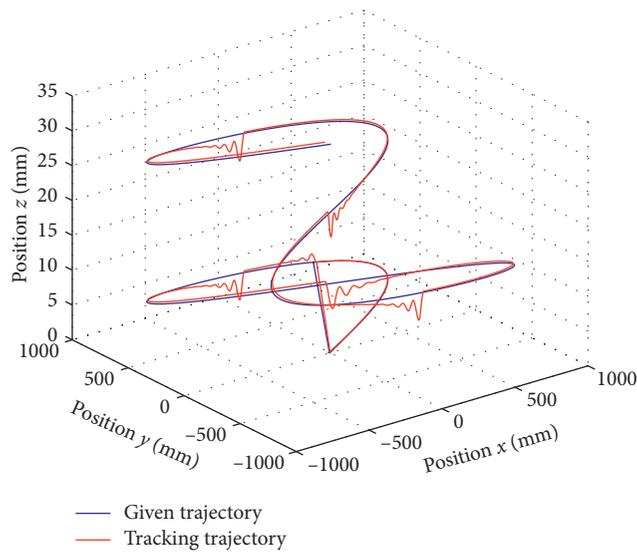


FIGURE 13: The tracking trajectory with the LADRC strategy.

5. Conclusion

Aiming at the motion requirements, nonlinear characteristics, and the omission of the relevant factors for modeling Delta high-speed parallel robot, this paper proposes an LADRC strategy to be applied to the dynamic control of Delta high-speed parallel robot. Through the stability analysis, the LADRC strategy can realize the dynamic control of the trajectory tracking of Delta high-speed parallel robot, and when the robot is running at high speed, the stability of the model will not be affected by the uncertain factors of the system.

In order to verify the proposed LADRC strategy, the circular trajectory, a representative 8-shaped space helical variance trajectory, and a triangular wave external disturbance with large amplitude are input, respectively. The PID method and the linear ADRC control strategy are used to simulate, respectively. The simulation and comparative analysis show that the LADRC strategy is applied to the Delta high-speed parallel robot control which has a good quick and precise real-time trajectory tracking and strong robustness.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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