Dynamic Pick and Place Trajectory of Delta Parallel Manipulator

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Abstract. Based on the high-speed and stable demand of the dynamic pick-and-place of a Delta parallel manipulator in industrial production, a 5-3-5° multi-segment polynomial is used to design the speed laws of the joints of the manipulator, combined with the constraint of motion, the shortest period, and vibration control to construct a multi-target and multi-constrain. The nonlinear motion trajectory planning model is obtained, and the optimal solution of trajectory planning is obtained by using the optimized gravitational search algorithm. The results show that the speed and acceleration of the motion trajectory reach extreme values, and the motion trajectory is continuously smooth, meeting the expected planning requirements. The effectiveness of the motion trajectory model in shortening the operation cycle and the vibration of the control mechanism is verified, and the effectiveness of the optimized gravity search algorithm in the convergence control and global optimization is verified.

Keywords: Parallel manipulator · Trajectory planning · Multi-stage polynomial · Gravitational search algorithm

1 Preface

The development of the robot industry has played an important role in promoting the third industrial revolution, and the proposal of "industry 4.0" has even prompted many countries to carry out research on emerging technologies in the field of intelligent robot manufacturing [1]. Delta parallel manipulator is one of the modern production equipment which widely used in the industrial production. It has compact and simple structure, flexible and fast operation. It can be seen in food, medicine, logistics, life science, chip manufacturing and other industries.

At present, the study of the Delta manipulator mainly concentrated in the end of the actuator motion trajectory model design and processing algorithm. It has smooth dynamic trajectory which can improve the working efficiency and stability of the Delta manipulator, further stimulate their working performance in the industrial manufacturing, it has important practical significance and value of engineering application on the promotion of advanced manufacturing production. Costantiesu D and Croft E A [2] have studied the relationship between the velocity variation law of the manipulator and the

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vibration of the mechanism, and found that when the velocity function is continuous for at least two times, the acceleration is continuous to ensure the smoothness of the motion trajectory, and the vibration of the mechanism can be suppressed by controlling the change range of acceleration. In the literature [3, 4], polynomial was used to plan the motion law of the actuator for the impact, vibration and other problems that tend to occur when the trajectory of the Delta manipulator is in right-angle transition. The simulation results show that the polynomial speed design can smooth the transition part in a reasonable period of motion. In literature [5], 4-3-4, 3-5-3 and 5-5-5 piecewise polynomials are respectively selected to interpolate the trajectories in joint space, and the continuity, maximum and whether there is a limit of multi-order derivatives of different polynomials are analyzed. The results show that 4-3-4 piecewise polynomials have certain advantages in motion period and acceleration control.

In this paper, the dynamic picking and dropping trajectory planning problem of the manipulator will be transformed into a nonlinear mathematical model according to the optimization needs of Delta manipulator in operating time and mechanical vibration. Based on the characteristics of Gravitational Search Algorithm (GSA), which is easy to realize and it has strong global Search ability, a Fuzzy Parameter gravitation search Algorithm (FPGSA) designed by Fuzzy control parameters is proposed to balance the convergence speed and global Search ability of the Algorithm. The nonlinear mathematical model is solved by gravity search algorithm before and after optimization, and the optimal solution of trajectory planning problem is obtained respectively.

2 Kinematic Analysis of the Delta Manipulator

2.1 Analysis of Configuration

The positive and negative solutions of Delta manipulator position are to obtain the specific mapping relationship between joint Angle and actuator displacement. The specific position of the actuator is the positive solution of the mechanism. On the contrary, joint Angle is obtained based on the position of the end-effector, which is the inverse solution of the mechanism [3]. Figure 1 is a simplified schematic diagram of the structure of the common Delta manipulator, which consists of a moving platform with end-effector, a static platform with fixed robot position, three active rods and the corresponding three groups of follower rods.

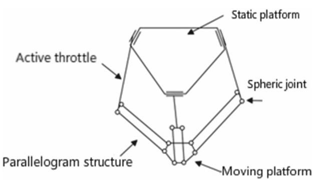

Fig. 1. Structure diagram of Delta parallel manipulator

2.2 Workspace Analysis

The workspace of the Delta manipulator actuator is the intersection of the activity space of each moving branch chain, which is an important indicator of robot mechanism design [7]. In the workspace, a reasonable motion region is divided for dynamic pick up and drop, so as to provide a basic environment for actuator trajectory planning. Analysis formula (1), if there is a solution to this equation, then:

$$(2a)^2 - 4(c-b)(b+c) \geq 0 \tag{1}$$

$$c^2 - \left(a^2 + b^2\right) \leq 0 \tag{2}$$

Relevant parameters in Eq. (3) are substituted into Eq. (5) to obtain:

$$\begin{aligned} K_i(x,y,z) = {} & [(x_p\cos\alpha_i + y_p\sin\alpha_i - \triangle r)^2 + (x_p\sin\alpha_i - y_p\cos\alpha_i)^2 + z_p^2 + l^2 - m^2]^2 \\ & - 4l^2\left[(\triangle r - x_p\cos\alpha_i - y_p\sin\alpha_i)^2 + z_p^2\right] \leq 0 \end{aligned} \tag{3}$$

When inequality (3) is 0, it represents the boundary of the workspace. Because of the uniform Angle distribution of the three moving branch chains of the Delta manipulator, the rotating coordinate system $Ti(x_i, y_i, z_i)$ is established. The position of point P in the coordinate system *Ti* is:

$$\begin{cases} x_p^i = x\cos\alpha_i + y\sin\alpha_i \\ y_p^i = -x\sin\alpha_i + y\cos\alpha_i \\ z_p^i = z \end{cases} \tag{4}$$

The $\alpha_i = \frac{2i-2}{3}\pi$ (i = 1,2,3), in the coordinate system *Ti*, space boundary $K_i(x,y,z) = 0$, after finishing can be simplified as:

$$\left[l^2 - \sqrt{\left(x_p^i - \triangle r\right)^2 + z_p^{i2}}\right]^2 + y_p^{i2} = m^2 \tag{5}$$

Equation (4) is the intersection of three standard toris equations. A calculation example is selected to draw the workspace of the Delta manipulator in MATLAB. The structure of the Delta manipulator and the parameters of joint rotation Angle are shown in Table 1.

The parameters of the Delta manipulator in Table 1 are imported into the space solution program to obtain the 3d space scope of the working area, as shown in Fig. 2.

Table 1. Basic parameters of the Delta manipulator

Parameter	Figure
Radius of static platform (mm)	290
Length of driving rod (mm)	260
Length of follower (mm)	850
Radius of Moving platform (mm)	50
Range of joint angles (°)	2.9–112.6

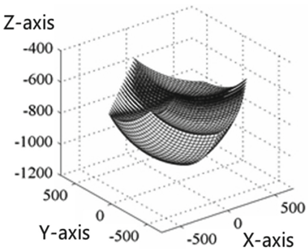

Fig. 2. Schematic diagram of Delta manipulator operating area

3 Gravity Search Algorithm Based on Fuzzy Control

3.1 GSA

GSA is a swarm intelligence optimization search algorithm proposed by Rashedi et al. [10]. Based on the law of universal gravitation and Newton's second law of motion, which USES particle motion to represent the solution process. It is widely used in communication systems, digital image processing and energy analysis [11]. The position of particles in the gravitational search algorithm corresponds to the solution of the optimization problem. Under the action of gravity, particles with a large mass attract other particles, which gradually gather from the disordered state to the point with a large mass, and finally gather to the optimal solution region [12]. Select an optimization model of d-dimensional space and update the position, velocity and acceleration of particle I in the d-dimensional by using Eqs. (6)–(8):

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \tag{6}$$

$$x_i^d(t+1)= x_i^d(t)+v_i^d(t+1) \tag{7}$$

$$a_i^d(t)= F_i^d(t)/M_{pi}(t) \tag{8}$$

$F_i^d(t)$ is the magnitude of the force exerted on particle i in d dimension, $M_{pi}(t)$ is the inertial mass of particle i.

$$F_i^d(t) = \sum\nolimits_{j\in kbest, j\neq i}^{N} rand_j F_{ij}^d(t) \tag{9}$$

$$F_{ij}^{d}(t) = G(t)\frac{M_{pi}(t) \times M_{ai}(t)}{R_{ij}(t) + \varepsilon}(x_j^d(t) - x_i^d(t)) \quad (10)$$

$F_{ij}^{d}(t)$ is the gravitational attraction of particle j on particle i. $G(t) = G_0 e^{-\alpha t/T}(\alpha = 20 G_0 = 100), R_{ij}(t)$, is the Euclidean distance between individual i and individual j, is a small value constant. The inertial mass of particle i is solved as follows:

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (11)$$

$$M_i(t) = m_i(t) / \sum_{i=1}^{N} m_i(t) \quad (12)$$

fiti(t) is the fitness function of particle i at time t, and *best(t)* and *worst(t)* are the optimal fitness value and the worst fitness value. The fitness function can be set as:

$$best(t) = \min_{i=1,2,\ldots,N} fit_j(t) \quad (13)$$

$$worst(t) = \max_{i=1,2,\ldots,N} fit_j(t) \quad (14)$$

Information between GSA particles is transmitted by the law of universal gravitation, which has strong global search ability. But the local search ability is poor, the convergence is not ideal, through the optimization of the algorithm flow design, to make it more suitable for the problem.

3.2 FPGSA

The gravitational constant G can be regarded as the search step of the algorithm, and its change has an impact on the convergence speed of the algorithm. The selection of G value is related to the location of the optimal solution and the range of the solution set, which cannot be obtained based on the qualitative index, otherwise the algorithm cannot effectively deal with the fuzzy problem. Due to the uncertainty of the value of parameter G, fuzzy control is carried out. Fuzzy control is a nonlinear control strategy commonly used in automatic control systems, which mainly includes input fuzzy, deductive reasoning and fuzzy decision [13]. The corresponding specific steps are as follows:

(1) The input is determined by the number of iterations *it*. Last iteration parameter *α(it-1),* richness R_N and development level A_N, the output is the value of this iteration α. Richness R_N represents the position distribution of the population within the solution range. A higher population richness can prevent the algorithm from falling into the local optimal solution in the iterative process, which can be obtained according to Eq. (15):

$$R_N = (\sum_{i=1}^{N} \sqrt{\sum_{j=1}^{D} (X_{ij}^{it} - \overline{X}_j^{it})^2}) / (N \times R_L) \quad (15)$$

Where N is the number of individuals in a population, D is the dimension of the particle, the $\bar{X}$ said individual distribution center, the R_L is the distance between two most remote particle in a population. The value range of R_N is (0,1). The larger the value of R_N is, the more abundant the population is. Design development level A_N by fitness function:

$$A_N = (f_a(it-1) - f_a(it))/f_a(it) \tag{16}$$

$f_a(it\text{-}1)$, $f_a(it)$ is the average value of the *it-1, it* iteration adaptation value. In the minimum value problem, when the value of A_N is positive, the population development is high and the algorithm tends to the optimal solution gradually. When the value of A_N is negative, the direction of the algorithm deviates from the optimal solution.

(2) Deductive reasoning, the subset characteristics of fuzzy control are not obvious. In order to accurately describe the characteristics of group changes, membership degrees of up, medium and low are set.

Table 2 shows the corresponding relationship between the value range and membership of R_N, A_N, *it* and the value range of matrix *(t-1)*.

Table 2. Values and grades of various parameters

Level	R_N	A_N	*it*	$\alpha(t\text{-}1)$
Low	(0, 0.5)	$(-\infty, 0)$	(0, 15)	(10, 15)
Medium	–	–	[15, 25]	[15, 20]
Up	(0.5, 1)	$[0, +\infty)$	(25, 30)	(20, 25)

(3) Fuzzy decision, parametric fuzzy processing rules (Table 3).

Table 3. Values and grades of various parameters

Rules		*a*	*b*	*c*	*d*
Condition	R_N	Low	Low	Up	Up
	A_N	Up	Low	Up	Low
	it	Low	Medium	Up	Up
Result	$\alpha(t)$	Low	Medium	Medium	Up

The interpretation of fuzzy control rules is as follows:

Rule a: In the early stage of the algorithm, if the population development level is high but the richness is low, and the local optimal solution may appear, then the value of the parameter decreases to reduce the convergence speed and improve the global search ability of the algorithm.

Rule b: If the population richness is low and the development level is low in the middle of the algorithm, then the value of parameter order decreases to increase the population richness and ensure the global search ability of the algorithm;

Rule c: If the population richness is high and the development trend is good at the later stage of the algorithm, then the value of parameter order should be further increased to promote the algorithm solution and improve the efficiency of the algorithm.

Rule d: If the population richness is high but the development level is low and the algorithm convergence rate is low at the later stage of the algorithm, then the value of parameter order is increased to speed up the algorithm convergence rate.

4 Trajectory Optimization Simulation

4.1 Parameter Settings

Set Delta manipulator dynamic up path for 25 mm, 305 mm long class door font path, combined with Fig. 4 describes the Delta manipulator workspace, set actuator center point P on the pick up point coordinates of P_A, placed the coordinates of the point of P_D, on the motion path to select two points P_1, P_2, the unit is mm, end get cartesian space location discrete sequence. The coordinates are pick points (140, −90, −850) intermediate points (100, −60, −825) intermediate points (−64, 63, −825) placement points (−104, 93, −850). The size parameter and the position of the actuator were substituted into the position inverse solution model to solve the rotation Angle of the driving joint corresponding to each trajectory point, as shown in Table 4.

Table 4. Joint space Angle discrete virtual sequence

Diversion (degree)	θ_1	θ_2	θ_3
Picking point	0.3109	0.9017	0.5979
Intermediate point	0.2808	0.7125	0.4976
Intermediate point	0.6234	0.2984	0.5372
Placement point	0.8049	0.3087	0.6547

4.2 Analysis of Simulation Results

In this paper, MatlabR2012a was used for simulation. GSA and FPGSA were used to solve the motion trajectory planning model respectively, and the single operation duration t (half movement cycle) and acceleration range were obtained. The single operation time was processed to obtain the optimal and average single operation time and standard beat time (CPM) in the optimal solution. The movement trajectory results are shown in Table 5.

Table 5. Trajectory planning results

Algorithm	tmin (S)	CPMmax	tavg (S)	CPMavg	Jmin/105 (rad/s3)
GSA	0.1795	167	0.1853	162	0.2411
FGSA	0.1726	174	0.1786	168	0.2845

The minimum time of a single operation for GAS and FGSA was 0.1795 s and 0.1726 s, respectively, and the corresponding standard time beats were 167CPM and 174CPM, respectively. The mean standard time of FGSA was 3.7% higher than GSA. Under the 5-3-5 multi-stage polynomial velocity rule design, the Angle, angular velocity and angular acceleration curves of the motion trajectory under the optimal solution obtained based on FGSA are shown in Figs. 3, 4, 5 and 6.

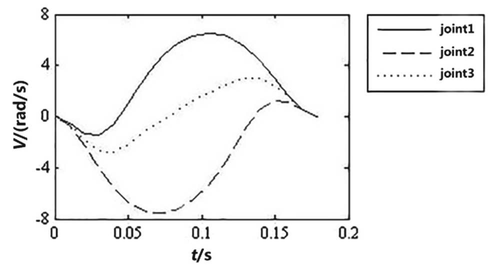

Fig. 3. Joint Angle variation curve based on FGSA

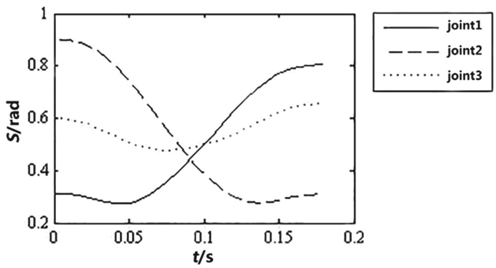

Fig. 4. The variation curve of joint velocity based on FGSA

The kinematic trajectories obtained based on FGSA are smooth and continuous, with no mutation point in velocity transformation and the range of acceleration variation is effectively controlled. Through the change of the acceleration curve of the three joints, the change amplitude of the acceleration is obtained. The smaller the amplitude of

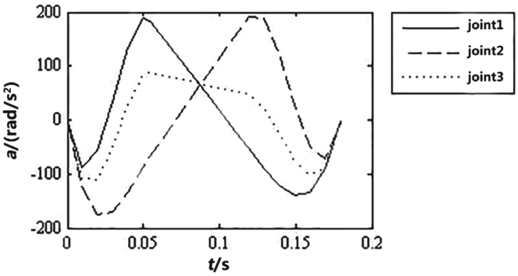

Fig. 5. Curve of joint acceleration based on FGSA

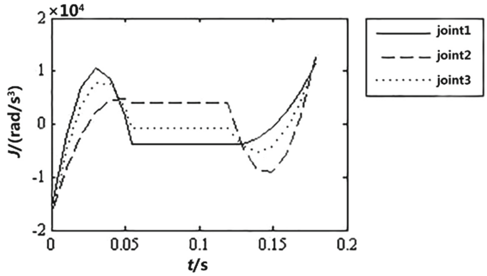

Fig. 6. Curve of joint acceleration based on FGSA

acceleration change, the more obvious the effect of the optimized motion trajectory on the vibration suppression of the mechanism, the better the stability of the motion planning, which is more conducive to the picking and lifting operation of the Delta manipulator. The objectives of operational planning include motion cycle length control and mechanism vibration suppression, adjust the weight coefficient of planning objectives, and analyze the influence between motion cycle reduction and vibration suppression effect. The changes of *k1* and *k2* values are shown in Table 6.

Table 6. The values of *k1, k2*

Group	1	2	3	4	5
k_1	0.85	0.8	0.75	0.7	0.65
k_2	0.15	0.2	0.25	0.3	0.35

The weight coefficients of each group were substituted into the objective function of the algorithm to obtain the change curves of single operation time and acceleration under different weight coefficient value groups, as shown in Fig. 7.

From Fig. 7, it can be found that there is a dual relationship between motion period reduction and vibration suppression. When the weight coefficient of the motion period is higher, the amplitude of acceleration change is larger, indicating that the vibration suppression effect is normal. When the weight coefficient of vibration suppression is

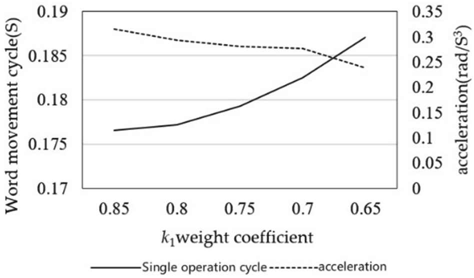

Fig. 7. Curve of single operation time and acceleration change

high, the single operation time increases, the velocity of motion trajectory planning decreases and the operation efficiency decreases. Therefore, there are high requirements for the movement cycle of the Delta manipulator, and when the requirements for the pick and drop smoothness are low, *k1* value in the target planning is large. The stability of the picking and lifting operation of the Delta manipulator is high. When the operation time is loose, *k2* value in the target program is large.

5 Conclusion

The design which based on the 5-3-5 multi-stage polynomial in the Delta manipulator joint angular velocity and angular acceleration can achieve the performance constraints of the manipulator extreme value, and at the same time, the displacement, velocity curve is continuous smooth, it ensure the stability of the manipulator in the picking up operation. The motion cycle of FGSA is shorter and the vibration suppression effect is better than that of GSA, which proves the validity of FGSA. By analyzing the relationship between motion cycle reduction and vibration suppression effect in object programming, the motion trajectory model can meet the demand of dynamic pick up and drop trajectory of the Delta manipulator under various working conditions.

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