

Structure design and trajectory positioning method of underwater telescopic arm robot based on DE algorithm

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Abstract. In view of the large target location error in underwater environment and the low search accuracy of common underwater robotic arms, an underwater telescopic arm robot based on the DE algorithm is proposed. Firstly, the mechanical structure design and D-H parameter method are used to construct the robot arm, and the feasibility of the underwater telescopic arm robot is verified by the parameters of the kinematic solution of the robot arm combined with 5-5-5 polynomial trajectory planning. Considering the possible collision in the trajectory of the underwater robot arm and the increase in load pressure on the arm, the differential evolution method is introduced to iterate the time of the arm through six stages to plan the optimal value of time for the optimal trajectory of the arm, and finally, the algorithm is applied to the experiment. The end-effector parameters' smooth and non-abrupt graphs of acceleration, velocity, and impact demonstrate the efficiency of the underwater robot design.

Keywords: Underwater telescopic arm robot / 5-5-5 Polynomial trajectory planning / DE algorithm / optimal value of trajectory positioning time

1 Introduction

In recent years, the development of flexible underwater robots has involved several fields, and the application scenarios of flexible robotic arms are concentrated in medical surgery, confined space search and rescue, and industrial equipment overhaul [1,2]. Traditional robotic arms in unknown underwater environment present the disadvantages of redundant degrees of freedom [3], low positioning accuracy, long capture and collection of targets, and complex planning of trajectory routes, which often prompt the robotic arms to fail to produce effective obstacle avoidance.

With the rapid expansion and depth of the industry, in order to improve the efficiency of the underwater robot arm to grasp the target object, it is necessary to complete the time-optimal planning problem under the complex conditions of underwater disturbances. The current solution

path for such complex arithmetic problems mostly introduces optimization algorithms for verification of motion laws, and the common optimization algorithm guidelines are the quadratic planning method [4], the two-level objective optimization method [5], Newton iteration [6], etc. The trajectory planning of robotic arms has the characteristics of multi-level and shallow abruptness [7], and the optimal time planning route cannot be obtained by applying conventional algorithms, so there are many scholars who have conducted in-depth research on finding optimal time planning for robotic arms. Ak et al. [8] applied an improved algorithm based on the differential evolutionary algorithm to solve the inverse solution of the positional pose, which substantially improved the convergence accuracy and speed of the algorithm; Wei et al. [9] introduced the DE algorithm recursive improved DE algorithm to increase the recognition of the unknown target of spatial robot grasping and proved that the improved algorithm applied to solve the spatial recognition accuracy of the robotic arm is higher than other algorithms; Liu et al. [10] used multi-strategy improved differential algorithm for the Delta robotic arm to identify the population target,

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which effectively improves the accuracy and advancement of time-optimal trajectory planning applied to space; Li et al. [11] embedded differential evolution to optimize each parameter of trajectory in order to verify the effectiveness of intelligent optimization algorithm applied to control under-driven robotic arm, which proved the global search capability of DE algorithm. Lou et al. [12] applied the differential evolution algorithm to reduce robotic arm perturbation and control torque to solve the collision problem generated by robotic arm grasping targets and ensure the calming control of robotic arm trajectory planning. In the field of searching and discovering clustered target object groups, the differential evolution algorithm compared to the whale optimization algorithm (WOA) [13], the particle swarm algorithm, and the sky horse swarm algorithm (BSO) [14] found significantly faster and more robust convergence of the optimal trajectory line.

At this stage, most underwater robots are still limited to search and detection of target object functions, mainly due to the practical operation of the embedded algorithms that produce positioning errors and retrieval difficulties. The multifunctional robots that have been developed can be divided into bionic robots [15], tracked robots [16], mobile robots [17], soft robots [18], and pipeline robots [19], each of which has its own advantages in adapting to different environment. Xiao et al. [20] designed a multi-module snake-shaped pipe grinding robot by combining the complex factors of each module of the pipe with comprehensive mechanical analysis. Lu et al. [21] invoked a segmented differential evolutionary algorithm to effectively constrain the measurement direction angle for removing the cavity margin of the aero-engine and ran the optimal robot joint path to promote the motion trajectory to keep it smooth. Gautreau [22] designed and manufactured a 7-DOF robotic arm to measure the positioning error of the trajectory. Several types of robotic arms exist at this stage that serve as tools to capture the target object effectively, such as hydraulic robotic arms [23], space robotic arms [24], and flexible robotic arms [25], which are suitable for practical use and can solve the problems of high precision positioning and effective trajectory tracking of the target object.

In this paper, we design an underwater telescopic arm-type robot based on a complex underwater environment and introduce the 5-5-5 polynomial estimation planning and differential evolution algorithm into the entire motion trajectory planning path of the underwater telescopic arm for the first time. Additionally, we evolve the entire motion travel path of the robot arm to differentially align selection and cross and iterate the optimal time planning route to produce effective obstacle avoidance against other collisions, combining kinematic collision detection and experimental planning comparison. This allows the underwater telescopic arm to efficiently generate the optimal path and complete the time-optimal planning route in the structure and algorithm design environment, demonstrating the effectiveness and advancedness of the differential evolution algorithm applied to the actual trajectory planning.

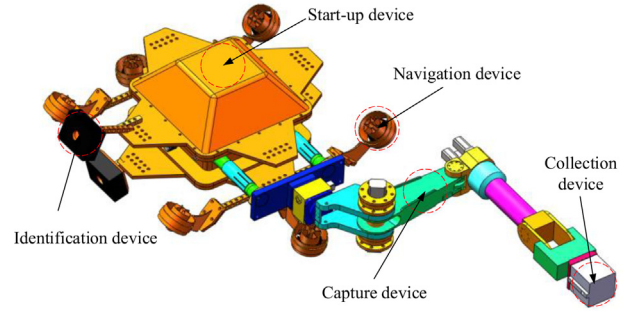


Fig. 1. Overall structure of underwater flexible robot.

2 Underwater telescopic arm robot model design

Given the distinctive characteristics of underwater robots searching for targets, the robot is designed to adapt to the complex environment of underwater, and each parameter is used to build the flexible telescopic arm of the underwater robot by using the kinematic analysis of the D-H algorithm, which is applied to drive the robot arm by kinematic analysis.

2.1 Working principle of telescopic arm

A closed-loop servo control underwater telescopic arm robot is designed and fabricated, and the model structure is shown in Figure 1. The main components of the robot include the starter device with the drive energy, the six-rotor slurry navigational device for underwater cyclic searching, the identification device for cruising and sneaking identification, the grasping device relying on the triboelectric relay drive, and the collection device for capturing the target objects. The robot is more accurate in planning and searching complex target objects, avoiding the disadvantages of the time-consuming, laborious, and poor searching accuracy of traditional underwater vehicles. Compared to traditional underwater vehicles, the telescopic arm robot is able to accurately plan and capture complex targets using effective algorithms, avoiding the drawbacks of traditional underwater vehicles' time-consuming, labor-intensive, and low search accuracy.

The control of the designed three-motor drive includes common load and elimination of backlash in two modes. Three-motor servo-driven joints to eliminate the performance of the backlash lie in the existence of impedance force generated by the traditional effective control. That is, it can increase the fixed torque in advance to the end of the actuator's output shaft in the last transfer. So that the instantaneous torque generated by the drive converter and shaft actuator maintains the engagement with the wheel system. Three drive motors drive the three driving wheels, which together drive the driven wheels. The whole servo system is composed of two processes: starting and steering. Three servo motors output torque linkage control three

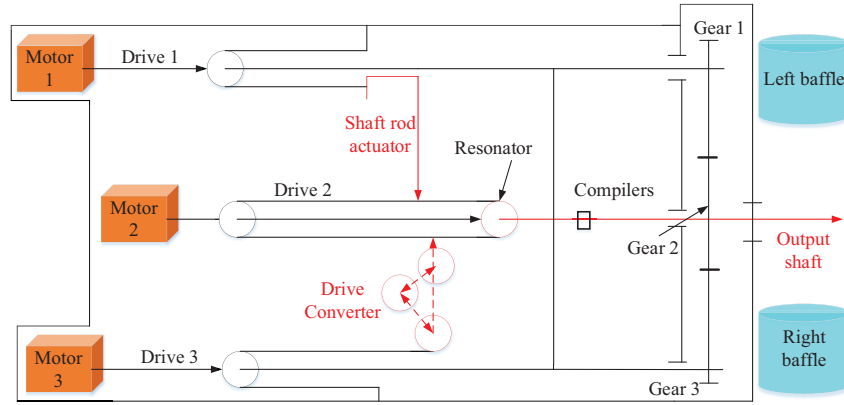


Fig. 2. Principle of three-motor servo-driven telescopic arm.

gears, ensuring that the entire drive process is always in a gap-free control state. The linkage driving principle of the entire telescopic arm movement is shown in Figure 2.

2.2 Kinematic model of the robotic arm

The underwater robot arm in series is composed of six free joints and telescopic joints. The telescopic arm is composed of a large arm, a small arm, and a telescopic rod arm connected to an end actuator. The entire robotic arm can be positioned in three dimensions. The three rotating subsets of the axial rotation axis, the bottom rotation axis and the axial rod rotation axis regulate the joint swing of the big arm, the lower arm, and the telescopic rod arm, respectively.

In the whole process of movement, the telescopic arm must establish its positive and negative solutions by establishing the coordinate system at each joint. Therefore, according to the established D-H model, combined with the robot body structure diagram and the mathematical model of the robot arm connecting rod system, the attitude and angle relationship between the connecting rod and the joint are described. The connecting rod coordinate system of the established underwater robot telescopic arm is shown in Figure 3, with a total of 6 coordinates (X_0, Y_0, Z_0), (X_1, Y_1, Z_1), (X_2, Y_2, Z_2), (X_3, Y_3, Z_3), ($X_{4,5}, Y_{4,5}, Z_{4,5}$), and (X_6, Y_6, Z_6). According to the forward kinematics analysis, the D-H parameters of the underwater robot arm are shown in Table 1.

The essence of the positive solution of the kinematics is based on the input parameters a , parametric α , and d for the given six joint angles. The position of the end actuator of the telescopic arm relative to the base is solved by the Chi-square transformation matrix. According to the coordinate system established in Figure 3, the Chi-square transformation matrix between two adjacent connecting rods is obtained, and the improved expression is as follows:

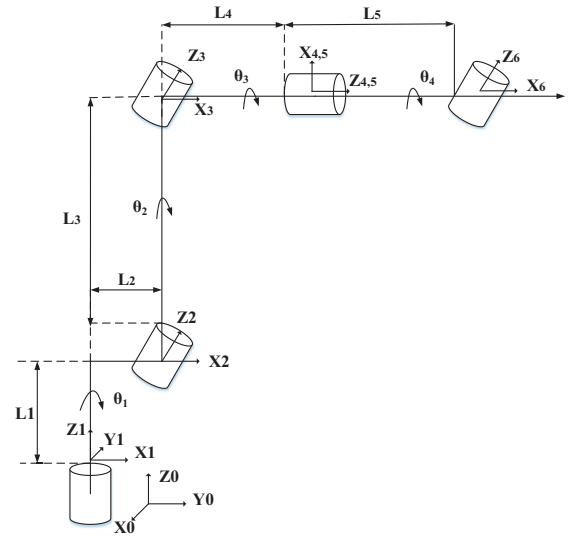


Fig. 3. Linkage coordinate system of underwater robot telescopic arm.

See equation (1) below.

By substituting the D-H parameter values in Table 1 as in equation (1), the end-effector poses can be obtained:

$${}^0T_6 = {}^0T_1 {}^1T_2 {}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2)$$

$${}^{i-1}T_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & \alpha_{i-1} \\ \sin(\theta_i)\cos(\alpha_{i-1}) & \cos(\theta_i)\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})d_i \\ \sin(\theta_i)\sin(\alpha_{i-1}) & \cos(\theta_i)\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

Table 1. D-H parameter table of underwater robot arm.

Connecting rod	$a_i/(\circ)$	$\alpha_i/(\text{mm})$	$d_i/(\text{mm})$	$\theta_i/(\circ)$
1	0	0	0	90
2	-90	150	245	0
3	0	215	0	0
4	-90	220	0	-90
5	0	0	0	0
6	90	0	355	-90

The parameters in the formula are obtained:

$$\begin{cases} n_x = c_5 s_1 s_4 - c_4 c_2 s_3 - c_1 c_2 c_3 - s_5 c_1 c_2 s_3 + c_1 c_3 s_2 \\ n_y = -c_5 c_1 s_4 + c_4 s_1 s_2 s_3 - c_2 c_3 s_1 - s_5 c_2 s_1 s_3 + c_3 s_1 s_2 \\ n_z = -c_{23} s_5 - s_{23} c_4 c_5 \end{cases} \quad (3)$$

$$\begin{cases} o_x = -s_5 s_1 s_4 - c_4 c_1 s_2 s_3 - c_1 c_2 c_3 - c_5 c_1 c_2 s_3 + c_1 c_3 s_2 \\ o_y = s_5 c_1 s_4 + c_4 s_1 s_2 s_3 - c_2 c_3 s_1 - c_5 c_2 s_1 s_3 + c_3 s_1 s_2 \\ o_z = s_{23} c_4 s_5 - c_{23} c_5 \end{cases} \quad (4)$$

$$\begin{cases} a_x = -c_4 s_1 - s_4 c_1 s_2 s_3 - c_1 c_2 c_3 \\ a_y = c_1 c_4 - s_4 s_1 s_2 s_3 - c_2 c_3 s_1 \\ a_z = -s_{23} s_4 \end{cases} \quad (5)$$

$$\begin{cases} p_x = 150c_1 + 215c_1 c_2 - c_4 s_1 + s_4 c_1 s_2 c_3 - c_1 c_2 c_3 \\ \quad + 500c_1 s_2 s_3 + 500c_1 c_2 c_3 \\ p_y = 150s_1 + 215c_2 s_1 + c_1 c_4 - s_4 s_1 s_2 c_3 - c_2 c_3 s_1 \\ \quad - 500s_1 s_2 s_3 + 500c_2 c_3 s_1 \\ p_z = -500s_{23} - 215s_2 - s_{23} s_4 \end{cases} \quad (6)$$

3 Telescopic arm differential time trajectory planning

In view of the particularity of the operating trajectory of the underwater telescopic arm, 5-5-5 polynomial trajectory planning is introduced to ensure the accuracy of the actuator to grasp and find the target object at the end of the entire operating trajectory. This ensures the high-order continuity of the underwater robot, the improved search range of the underwater robot arm, and the global push-away strategy. The differential evolution algorithm is used to optimize the global search of the underwater telescopic arm, which enhances the convergence ability of the original search object and improves the robustness of the optimal evolutionary search trajectory from low level to high level.

3.1 5-5-5 Polynomial trajectory planning

Considering the particularity of 5-5-5 polynomial trajectory planning, it is necessary to ensure that the impact of the underwater telescopic arm at the beginning and end of the movement is zero. This will reduce unnecessary collision interference and ensure that the end effector first moves from the initial position in the entire motion trajectory of the underwater telescopic arm, and finally successfully reaches the designated position to complete the task of capturing the underwater target object. It is necessary to ensure continuous and uninterrupted movement of the underwater telescopic arm during the whole movement process to improve search efficiency. The underwater telescopic arm can be divided into three stages: the target discovery stage, the end effector slowly touching the target stage, and the underwater telescopic arm position adjustment stage. The starting point of the underwater telescopic arm in Cartesian space is set as Q , the distance between the telescopic arm and the target position is set as T , and the middle position is distributed as $Y1$ and $Y2$. Through kinematic analysis, the parameters of each joint are applied to the 5-5-5 polynomial trajectory planning of the robot arm. The expression is as follows:

$$\begin{cases} M_{i1}(t) = e_{i5}t_{i1}^5 + e_{i4}t_{i1}^4 + e_{i3}t_{i1}^3 + e_{i2}t_{i1}^2 + e_{i1}t_{i1} + e_{i0} \\ M_{i2}(t) = f_{i5}t_{i2}^5 + f_{i4}t_{i2}^4 + f_{i3}t_{i2}^3 + f_{i2}t_{i2}^2 + f_{i1}t_{i2} + f_{i0} \\ M_{i3}(t) = g_{i5}t_{i3}^5 + g_{i4}t_{i3}^4 + g_{i3}t_{i3}^3 + g_{i2}t_{i3}^2 + g_{i1}t_{i3} + g_{i0} \end{cases} \quad (7)$$

In the above formula, t_{i1} , t_{i2} , and t_{i3} are the three stages of operation of the underwater telescopic arm; t_{i1} , t_{i2} , and t_{i3} are the trajectory curves of the underwater telescopic arm when it contacts the target. e_{ij} , f_{ij} , and g_{ij} are the coefficients to be determined.

To ensure that the underwater telescopic arm always adheres to the principle of smooth high order during contact with the target, the individual velocity, acceleration, and acceleration of the underwater telescopic arm's starting and target end points are zeroed.

The e_{ij} , f_{ij} , and g_{ij} were copied into MATLAB according to the continuity principle of the robot arm, and the parameters before 5-5-5 polynomial trajectory planning of the telescopic arm were shown in Figure 4.

The simulation results show that the position, velocity, acceleration, and acceleration (impact) of the six joints are relatively stable under the 5-5-5 polynomial trajectory planning, and there are no obvious abrupt changes. However, before the planning, the velocity, acceleration, and impact of each joint appeared to be unstable fluctuations, and the position curves of each joint were not easy to concentrate on, so it took too long to complete the target search. It shows that the trajectory of the telescopic arm has fluctuation and interference collisions under 5-5-5 polynomial trajectory planning.

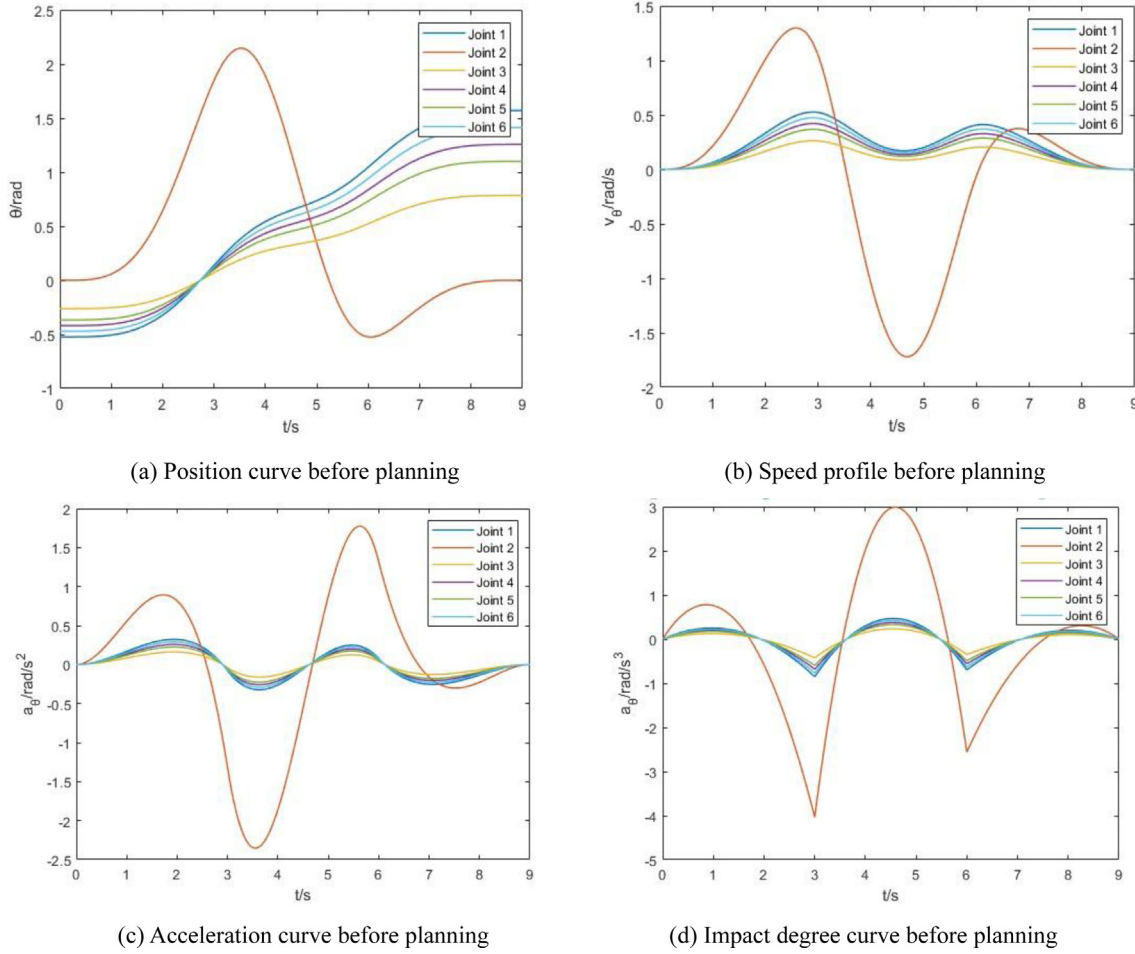


Fig. 4. Parameters of each joint before trajectory planning.

3.2 Differential evolutionary algorithm

3.2.1 Optimal solution of the differential evolutionary algorithm

The differential evolution algorithm is a kind of intelligent optimization algorithm that intersperses heredity, variation, and selection. It generates a new generation of individuals through multi-layer iteration and mutation crossover and uses its strong difference strategy to make the new generation of individuals undergo one-to-one mutation layer by layer. The convergence ability is significantly improved compared with other algorithms. This solves the disadvantage of searching for elements. The basic difference algorithm flow established in this trajectory planning is as follows:

- Initializing the population: The first step of the evolutionary algorithm is to generate an initialized population, which is formed in the following way:

$$\{X_i(0) | x_{i,j}^L \leq x_{i,j}(0) \leq x_{i,j}^U; i = 1, 2, \dots, N; j = 1, 2, \dots, D\} \quad (8)$$

$$x_{i,j}(0) = x_{i,j}^L + rand(0, 1)(x_{i,j}^U - x_{i,j}^L). \quad (9)$$

- In the above formula, $x_i(0)$ is the i chromosome produced by the first generation of the population; $x_{j,i}(0)$ is the proto-chromosome gene that should be located in column i of row j of the sequence chromosome; $[x_{j,x}^L, x_{j,x}^U]$ are the maximum and minimum values of the original sequence $x_{j,i}(0)$ chromosomes; N_p is the population size D applied to the three-dimensional space dimension; and $rand(0, 1)$ is the random variable in the interval.
- Changes: To find the optimal value, it must be combined with the telescopic arm for layer-by-layer iterative optimization. Therefore, the difference strategy chosen is DE/rand-to-best/1/bin. Compared with the traditional differential strategy, this differential strategy focuses on selecting high-quality individuals in the original random population and inserting the vector difference of high-quality individuals into the scaling factor to enter the variation layer. The constant quantity is recombined and then iterated again to form the optimal evolutionary variant. The expression is:

$$v_i(u+1) = x_{ri}(u) + F(x_{r2}(u) - x_{r3}(u)) \quad (10)$$

$$v_i(u+1) = x_i(u) + \lambda(x_H(u) - x_i(u)) + F(x_{r2}(u) - x_{r3}(u)). \quad (11)$$

- In the above formula, λ is the evolutionary factor, F is the scale factor, $x_{r1}(g)$ is the individual that should be born in column i of row g of the sequence chromosome, $x_H(u)$ is the optimal value of the evolutionary individual, and the rule $i \neq r1 \neq r2 \neq r3$ is set.
- Crossover: The number of individuals targeted by the crossover is based on the total number of search targets in the total input group. The mutated evolutionary individual $v_i(u+1)$ is crossed in parallel to form a new optimized individual $m_{j,i}(u+1)$.

$$m_{j,i}(u+1) = \begin{cases} v_{j,i}(u+1), & \text{rand}(0,1) \leq CR \text{ or } j = j_{rand} \\ x_{j,i}(u), & \text{rand}(0,1) > CR \text{ or } j \neq j_{rand} \end{cases} \quad (12)$$

- Selection: According to the greed criterion, the experimental group is mediated to select the individuals of the next generation of eugenics in the group. The method is as follows:

$$x_i(u+1) = \begin{cases} m_i(u+1), & f(m_i(u+1)) \leq f(x_i(u)) \\ x_i(u), & \text{other} \end{cases} \quad (13)$$

In general, the offspring are transformed into the previous generation through generation iteration. After recross and mutation selection, the individual with less variation is the new generation of the next generation.

3.2.2 Differential evolution algorithm steps

The differential evolution algorithm is applied to the trajectory planning process of the telescopic arm of the underwater vehicle. The flow chart of the differential algorithm adopted in this paper is shown in Figure 5.

Based on the complex and changeable underwater environment, the planning process is as follows:

Step 1: Define the original population size P and evolutionary dimension Q , and select the high-quality population size through eugenics.

Step 2: Initialize the entire population and iteratively generate the population component $x_{j,x}(0)$.

Step 3: Mutation is realized, the next order population of the iteration level is $v_i(u+1)$, and the optimal iterative evolutionary individual is $x_H(u)$.

Step 4: Achieve crossover and further increase the search population of the whole army to the optimal range of population $m_{j,i}(u+1)$.

Step 5: Select the overall scope, define the upper and lower limits, and ensure the accuracy of the overall search scope.

Step 6: Apply the greed principle to further screen the resulting population.

Step 7: Search and filter until you find the optimal value Y and the optimal fitness, otherwise, the step will be repeated.

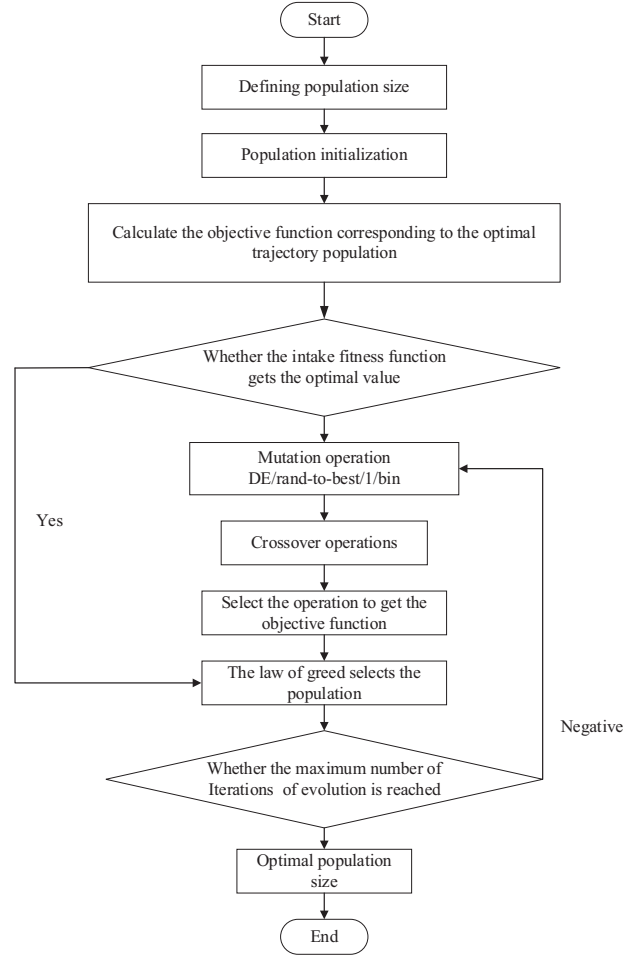


Fig. 5. Flow chart of differential evolution algorithm.

4 Time trajectory optimal planning solution

Aiming at the problem that the path of the target object is unknown in an unknown underwater environment, this paper combines the differential evolution method applied to the whole motion path with dynamic analysis to plan the optimal solution for the robot arm.

4.1 Time planning path simulation solution

4.1.1 Trajectory optimization results

On the basis of the motion model of the underwater telescopic arm constructed before, the parameters of the solution are input into the subroutine by MATLAB. On the basis of the established 5-5-5 polynomial trajectory planning, three hierarchical interpolation segments are inserted. N_p sets the population size to 100, the number of variables $\bar{D}$ to 3, the scale factor F to 0.6, the crossover probability CR to 0.8, the finite precision to 0.001, and the restricted algebraic maximum to 100. The lower limit of time and the upper limit of range are set to ensure the accuracy of the solution process. Figure 6 reflects the adaptive values of the six joints over 100 iterations.

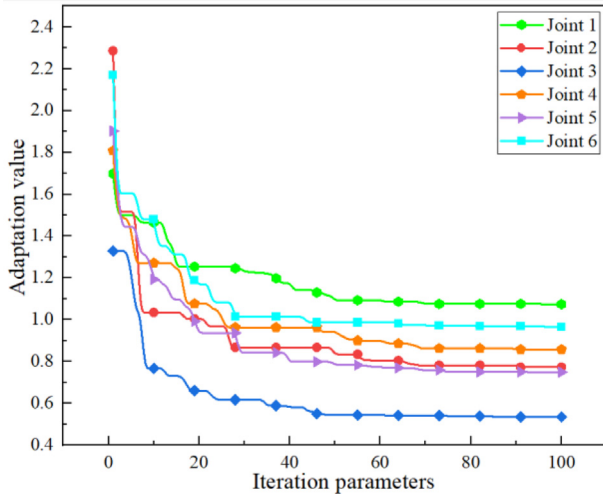


Fig. 6. Adaptation curve of trajectory positioning.

As can be seen from the running track diagram of the target captured by the telescopic arm above, the curve of the six joints is smooth, without mutation, and the descent speed is fast. This shows that the differential evolution method applied to the telescopic arm is applicable and stable, which reflects the accuracy of the algorithm.

4.1.2 Comparison of planning results

In order to test the practicability and global applicability of the differential evolution algorithm applied to the underwater telescopic arm, a system is designed to analyze the optimal trajectory effect of the underwater telescopic arm in different moving paths when capturing the same object. The 5-5-5 polynomial trajectory planning path optimized in this paper is given for global tracking. The non-interference measurement was carried out under the same three-point path of starting point, middle point, and end point, and the speed, position, acceleration, and acceleration indexes were set for comparison. The test results are shown in Figure 7.

The aforementioned simulation results demonstrate that the underwater telescopic robot's trajectory planning can effectively address the phenomenon of differential mutation in an unknown underwater environment, guarantee the continuity of the displacement, velocity, and acceleration curves planned by the optimization results when capturing the target object throughout the underwater environment, and prevent potential staggered impact and trajectory fluctuation. By comparing Figures 4 and 7, it can be clearly seen that the planned trajectory curve significantly reduces the planning time, thus facilitating the discovery of the water route and the faster discovery of the target object under the telescopic arm, ensuring the accuracy of application in practice.

4.2 Impact optimal planning solution verification

Given the buoyancy of the underwater environment, the drag will cause motion interference to the underwater telescopic arm. Therefore, the analysis in this paper relies

on ADAMS software to contact the target under the path of the differential evolution algorithm, and the simulation environment is shown in the figure below Figure 8.

4.2.1 Impact collision model

The complex underwater environment causes the telescopic arm to produce a collision force when it comes into contact with the target object. The Hertz contact model is used to verify the presence of interference. The *Lankarani-Nikraresh (L-N)* model is used to establish the impact force model of the underwater telescopic arm without considering the energy dissipation in the whole collision process. Due to the low probability of elastic collision in underwater environment, this model is not considered, and its expression is as follows:

$$F_N = K\delta^n \left[1 + \frac{3(1 - c_e^2)\dot{\delta}}{4\delta(-)} \right]. \quad (14)$$

In the above formula, $\dot{\delta}$ and $\delta(-)$ are the collision velocity under the relative state and initial state, c_e is the material recovery coefficient of the underwater telescopic arm, n is the material coefficient, K is the contact stiffness coefficient, and the expression is:

$$K = \frac{4}{3(\delta_a - \delta_b)} \sqrt{\frac{R_a R_b}{R_a + R_b}}. \quad (15)$$

To verify the advanced application of the differential evolution algorithm in underwater telescopic arms, ADAMS software is used to plan the single motion trajectory of the telescopic arm model in a given underwater environment. Exercise planning takes 30s. The motion impact force effect curve is shown in Figure 9.

The previously mentioned simulation results demonstrate that when approaching the target, the underwater telescopic arm's gap length, which is determined by the differential evolution algorithm, does not alter abruptly. When the end comes into contact with the target, the entire differential change is combined. Due to their contact with the target, the Y and Z axes cause very little vibration, and their torque, which ranges from -20 to 10 N/S, allows the motion process to be completed continuously.

5 Virtual prototype verification

In order to verify the performance of the underwater telescopic robot, a test platform was built. The grasping effect of different line diameters on the same target is tested. The obstacles and targets that can be passed are added, which makes it convenient to observe the operation of the whole telescopic arm grasping the target in different diameters. This will improve the practicability of the whole experimental device applied to the search trajectory. The prototype design of the underwater telescopic robot is shown in Figure 10.

We conducted two comparative experiments to confirm the superiority of the differential evolution algorithm used on the underwater telescopic arm. This will ensure the

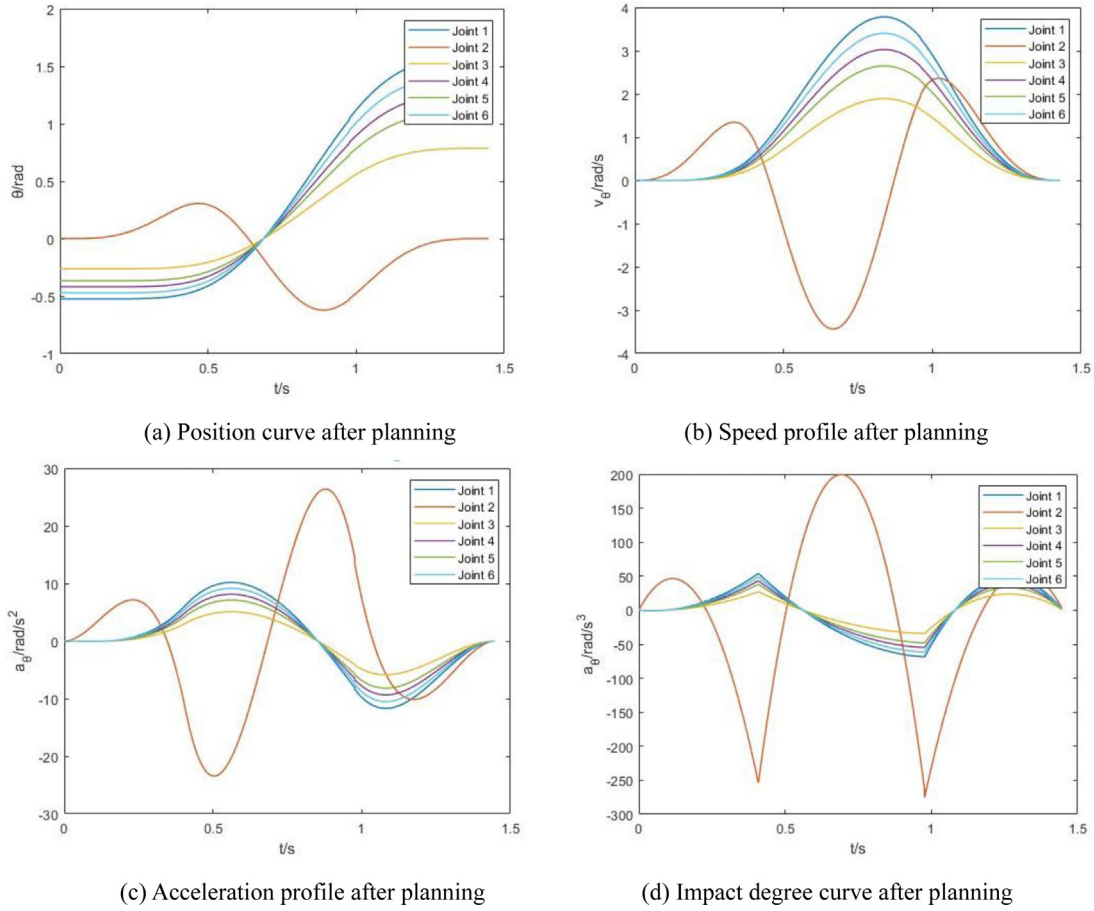


Fig. 7. Parameters of each joint after trajectory planning.

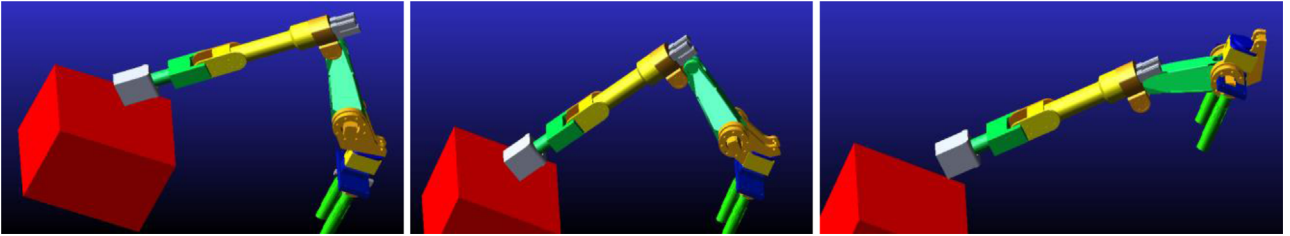


Fig. 8. Underwater simulation environment.

effect of the telescopic arm touching the target through the obstacle through straight insertion in path direction 1 without applying the algorithm when the robot arm captures the target in the same way. On the other hand, the algorithm is applied to the trajectory planning of the telescopic arm. When planning the optimal route, path direction 2 is used to approach the target. The experimental comparison is shown in Figure 11. The response angular acceleration and velocity parameters of the sensor used at the end of the telescopic arm in the experiment are shown in Figure 12.

The experimental results show that the trajectory path planned by the telescopic arm in the differential evolution algorithm can avoid obstacles, and the planned path time of 1.6 s is obviously better than the time of the original

telescopic arm directly over the obstacles to capture the target object 2 s. This further verifies the globality and accuracy of the differential evolution algorithm. Compared with the smooth linear velocity of path direction 2, the linear velocity of path direction 1 has a sudden change in the front segment. This shows that the application of the differential algorithm to trajectory planning is global, which minimizes the fluctuation of the running trajectory and increases the smoothness of the running stage.

In order to verify the adaptability of the underwater telescopic robot to target acquisition, a telescopic arm target experiment is designed. The attitude angle of the robot is adjusted to 0, and the telescopic arm is driven to capture and grasp the target within a certain range. The process of grabbing the target is shown in Figure 13. The

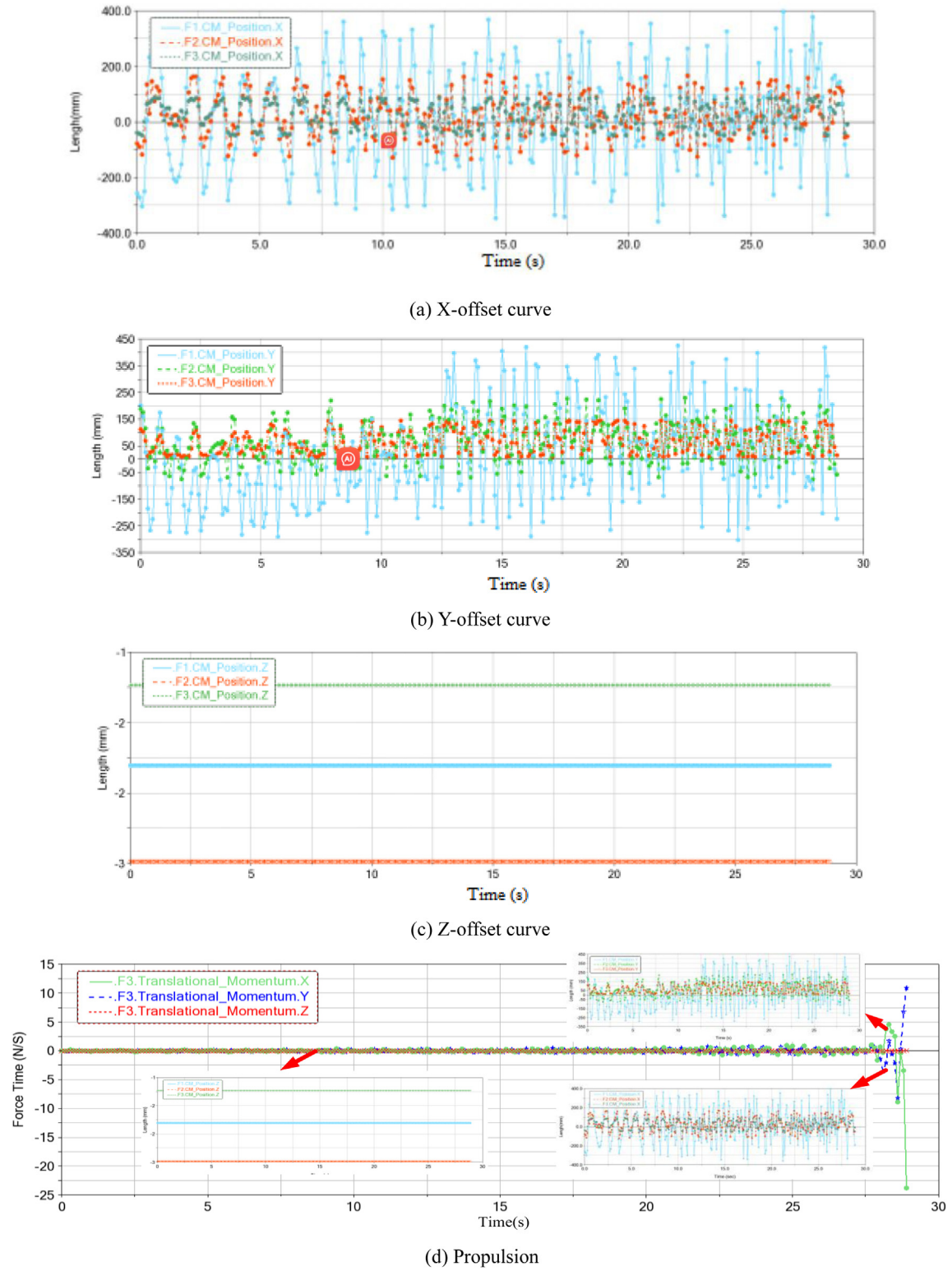


Fig. 9. Effectiveness curve of motion collision force.

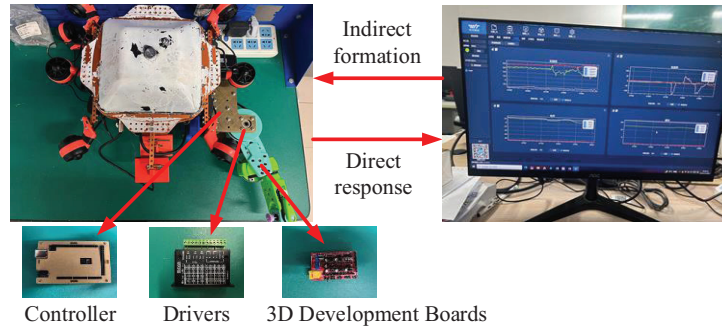


Fig. 10. Underwater telescopic arm robot prototype.

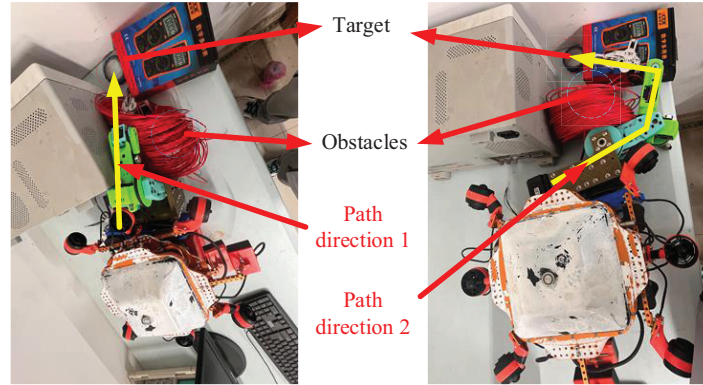


Fig. 11. Comparison experiment between planned and for-planned paths.

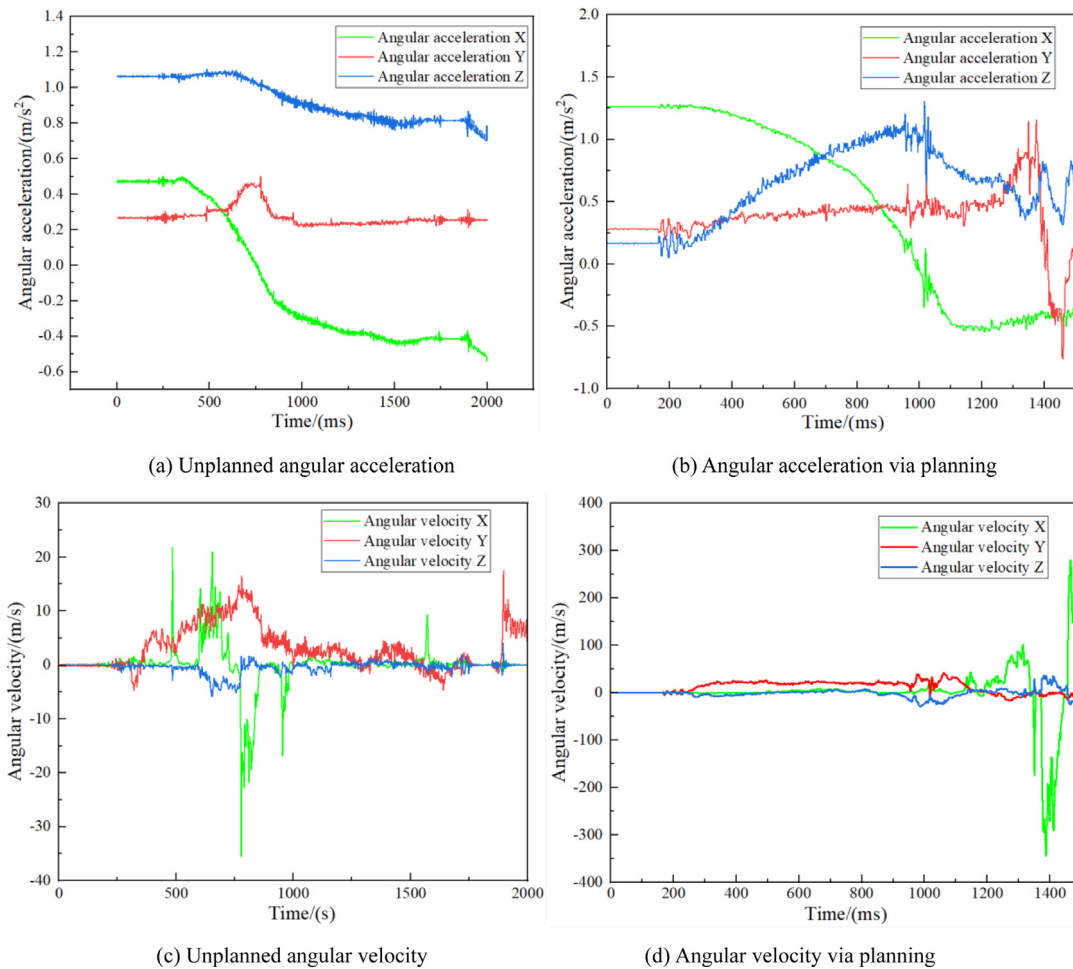


Fig. 12. Planning parameters with path 1 and path 2.

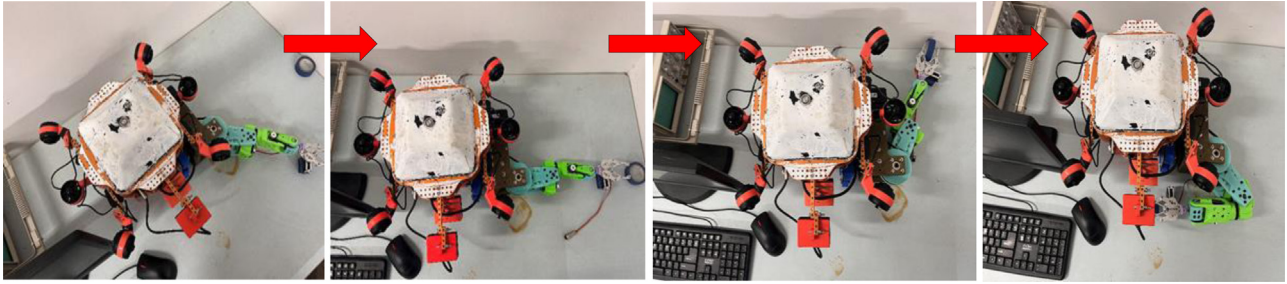


Fig. 13. Capture operation of robot telescopic arm.

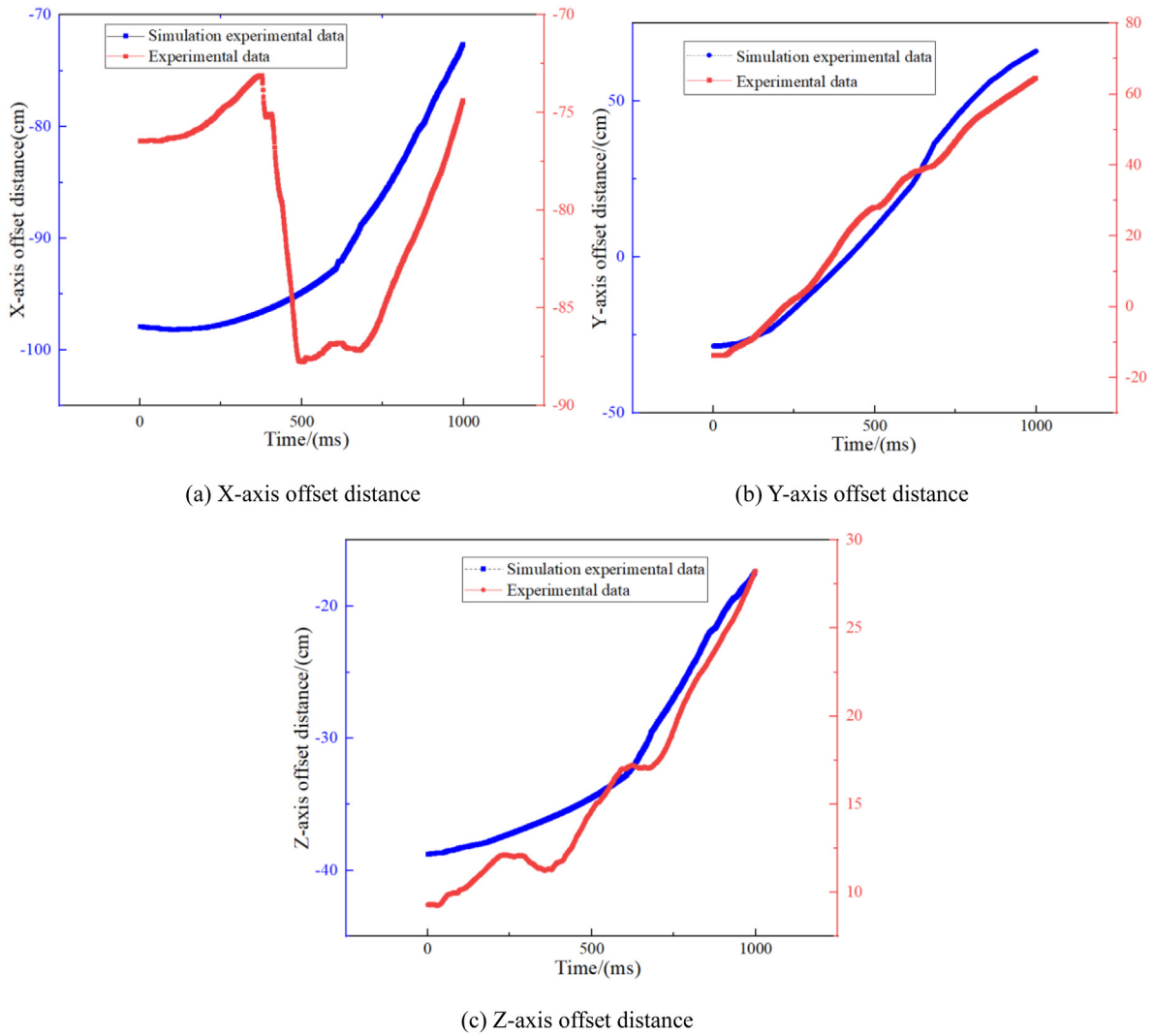


Fig. 14. Offset error of end-effector geometric.

experimental results of the manipulator's path planning based on the end-effector displacement sensor are compared with the simulation results based on the differential optimization trajectory, as shown in Figure 14.

The experimental results show that both experimental and simulation curves are smooth when the telescopic arm is completed. This shows that the positioning accuracy of the telescopic arm can meet the expected target of the task. The mutation of the front 0.5 s X axis indicates that in actual gripping operation, the telescopic arm may produce slight fluctuations when it encounters the target. But the deviation distance of the Y-axis and Z-axis is basically consistent with the simulation results. It shows that the whole algorithm can be applied to the trajectory planning of the telescopic arm and further verifies the accuracy of the geometric deviation of the telescopic arm.

6 Conclusion

In this study, an underwater telescopic arm robot is designed for the complex and changeable underwater environment. Based on 5-5-5 polynomial trajectory planning, the optimal time planning of the telescopic arm in underwater environment is carried out to ensure that the end effector can capture the target in a controllable range. The differential evolution algorithm is introduced, the optimal time planning of the telescopic arm is carried out, and the optimal obstacle avoidance path of the underwater trajectory is selected by variational, crossover, and ADAMS simulation. By fitting the route, the superiority of differential evolution is further verified. The experimental results show that the differential evolution telescopic arm can capture the target in the shortest time and reduce the location error without interference to a certain extent. It is proved that the three servo motors have the advantages of high transmission precision and low contrast, and the overall design and accuracy of the structure are further verified.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

All relevant data are within the paper.

Author contribution statement

Conceptualization, HW.J. S.L. and HT.J.; data curation, HW.J. and HT.J.; formal analysis, HW.J. and HT.J.; funding acquisition, HW.J. and WJ.L.; investigation, HT.J., FZ.Y. and WL.L.; methodology, HW.J. and HT.J.; project administration, CY.X.; resources, FZ.Y. and WL.L.; software, CX.X.; supervision, HW.J. and HT.J.; validation, HT.J. and HW.J.; writing original draft preparation, HT.J.; writing review and editing, HT.J., HW.J., S.L. and WJ.L.

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