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# Moving Trajectory Tracking Method of Multi Degree of Freedom Manipulator Based on Particle Filter Algorithm

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**Abstract**

In this study, a moving track tracking method of multi degree of freedom manipulator based on particle filter algorithm is proposed. By constructing the transformation matrix and the Jacobian matrix, the kinematics of the multi degree of freedom manipulator is analyzed. According to the three coordinates of the end of the multi degree of freedom manipulator, the forward kinematics model is solved and the inverse kinematics model is obtained. Particle filter algorithm is adopted to track the moving trajectory of multi degree of freedom manipulator, and the trajectory tracking error is corrected. Experiments show that this method has the advantages of small difference between the trajectory of the multi degree of freedom manipulator and the actual target trajectory, such as high trajectory tracking accuracy and short tracking time, and can meet the requirements of people for the trajectory control accuracy of the joint manipulator. It is expected that this paper can provide valuable references and help for the application field of robots as well as the actual life and production activities.



**Keywords:** Particle filter algorithm; Multiple degrees of freedom; Mechanical arm; Moving track; Kinematic model.

## 1. Introduction

The 20th century is the golden age of the rapid development of human science and technology, and major breakthroughs have been made in many fields. Among them, the breakthrough of robot technology is one of the best representatives. Since the 1950s, remarkable achievements have been made in just over a decade. Nowadays, the field of robot service is more and more extensive. For example, its shadow can be seen from the machining of mechanical parts in industry to the sweeping robot in life [1-3]. With the enrichment of application scenarios, the definition of robot has become more and more clear. Especially after entering the new century, the application field of robot has become more and more colorful. Robot control technology as the core technology of robot technology, more and more experts and professionals engaged in this field have invested in the research and work of related contents, and achieved a lot of results. As a kind of robot with obvious structural characteristics, the most basic function of articulated manipulator is to accept instructions and complete basic operations, such as positioning and trajectory tracking. Therefore, the realization of accurate positioning and tracking task is the premise for the articulated manipulator to complete various complex and specific tasks. In practical application, considering the complex structure of the manipulator, the motion system is highly combined, the interference of the working environment and the existence of uncertain factors, such as joint friction. Conventional control strategies are more and more difficult to meet people's requirements for the trajectory control accuracy of articulated manipulator [4,5].

Articulated manipulator is the basic unit of many robots with complex structure. At the same time, it is also the most widely used robot in the field of application. At present, the proportion of articulated robots in the field of robots in the world is more than 50%. The world's first articulated manipulator was born in a laboratory engaged in radioactive material research in the United States. The purpose is to help workers avoid damage to their health caused by direct contact with radioactive materials. The articulated manipulator is mainly composed of base, vertical arm, horizontal arm, terminal unit (hook, claw, suction cup, welding gun, etc.) and joints connecting each arm. Each joint of the manipulator can move independently or cooperatively. The superposition of all these joint movements determines the action of the manipulator [6]. The primary problem to be solved is to realize the positioning control of the manipulator to ensure that the manipulator maintains a desired attitude at the correct time and the operation terminal of the manipulator is in a correct position. In addition, sometimes we need to plan the whole movement process of the manipulator task, that is, the path planning of the manipulator [7]. Accurate trajectory tracking and positioning control is the focus of this paper. Robot control technology, as the brain of robot, plays a very important role. Therefore, the research on robot control technology is of positive significance to industrial production and daily life. In terms of manipulator positioning and trajectory tracking control, people have high requirements for control accuracy and speed. However, many advanced control algorithms need a large number of complex online operations, which greatly

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limits the working efficiency of the control system [8]. Moreover, it can be seen from the previous introduction that a large number of advanced control algorithms will use the specific model knowledge of the manipulator or rely on the experience accumulation of experts. However, the structure of the articulated manipulator itself is complex and establishment of an accurate mathematical model is difficult. Moreover, with the operation of the equipment, the state of the manipulator is constantly changing, and there are insufficient experienced relevant talents, which makes it difficult for many excellent control algorithms in theory to be applied in industrial practice. In addition, China has a weak foundation in the field of robot control. Domestic robot control is basically monopolized by foreign companies, and faces foreign technical barriers, which has seriously affected the development of robot control technology in China [9].

In view of the current difficulties in the field of manipulator control, reference [10] proposes a variable gain iterative learning trajectory tracking control method for a three degree of freedom manipulator. The Lagrange method is used to establish the dynamic equation, design a variable gain iterative learning controller for the three degree of freedom manipulator structure, and analyze the convergence to realize the trajectory tracking control of the manipulator. Reference [11] proposes a manipulator trajectory tracking control method based on hybrid interpolation, constructs a three degree of freedom manipulator dynamic model, determines the position and attitude of the manipulator in combination with the reference coordinate system, uses the Lagrange function method to analyze and display the structure of the manipulator, selects the first-order differential Prewitt operator with direction for edge detection, and uses cubic convolution and bicubic interpolation algorithm, Process the edge pixels of the manipulator trajectory, extract the edge information in the movement process of the manipulator, and provide the basis for the tracking of the manipulator trajectory. The fuzzy variable structure compensation method is used to achieve the tracking control of the manipulator trajectory. Reference [12] proposes automatic trajectory tracking control of multi axis series manipulator based on joint angle compensation. Firstly, the spatial pose description and coordinate transformation of multi axis series manipulator are described by rotation matrix, and then the joint angle at the end of multi axis series manipulator is compensated and calculated by joint angle compensation. The expected trajectory of multi axis series manipulator is planned according to the calculation results, and finally the motion variable of multi axis series manipulator is controlled by synovial controller, In this way, the automatic trajectory tracking control of multi axis series manipulator based on joint angle compensation is completed. Reference [13] proposes a manipulator trajectory tracking method based on adaptive robust control. The manipulator structure is designed independently by SolidWorks, the controller is designed according to the designed manipulator parameters, the manipulator control system model is established by Simulink, and the trajectory tracking control is verified under two moving target trajectories of straight line and curve. The adaptive robust control method can control the end trajectory of the manipulator more accurately. Reference [14] proposes a robot trajectory tracking control method based on variable gain active disturbance rejection technology. However, the motion trajectory of the multi degree of freedom manipulator tracked by the above five methods is quite different from the actual target trajectory, the tracking accuracy is low, and it takes a long time to track the motion trajectory, resulting in poor tracking effect and low efficiency.

To this end, this paper presents a moving trajectory tracking method of multi degree of freedom manipulator based on particle filter algorithm, and the feasibility of this method is verified by simulations. This study has a very positive significance for the application field of robot and the actual life and production activities.

## 2. Moving trajectory tracking method of multi degree of freedom manipulator

### *2.1. Kinematic analysis and model establishment*

Motion trajectory refers to the spatial characteristics of the action composed of the route that a part of an object passes from the starting position to the end, which is expressed by the direction, form and amplitude of the motion trajectory. From the perspective of mechanics, the object has only 6 degrees of freedom in space. The general special manipulator has only 2 ~ 4 degrees of freedom, while the general manipulator has mostly 3 ~ 6 degrees of freedom. The realization of trajectory tracking control of multi degree of freedom manipulator is based on kinematic analysis, which is to transform the expected trajectory in Cartesian space and the joint angle in joint space [15].

*(1) Transformation matrix*

Usually, a fixed coordinate system is defined on each link of a multi degree of freedom manipulator, and the two adjacent coordinate systems can represent each other. Generally, their relative positions are described by the transformation matrix between the two adjacent links. The connecting rod is numbered from the fixed base of the multi degree of freedom manipulator. Generally, the coordinate system at the fixed base is $O_0$, and so on. Therefore, the coordinate system on the connecting rod $i$ is $O_i$, and Fig. 1 shows the schematic diagram of the position and attitude of the connecting rod [16].

The coordinate system of all links can be established in sequence according to the following steps:

1. Find out the joint axis corresponding to each connecting rod and extend it in the direction of its axis.
2. Find out the common vertical line between joint axis $i-1$ and joint axis $i$ or the intersection of joint axis $i-1$ and joint axis $i$, and establish the coordinate system with the intersection of the common vertical line and joint axis or the intersection of joint axis $i-1$ and joint axis $i$ as the origin of connecting rod coordinate system $O_i$.
3. Specify that the direction of the $Z_i$ axis is the direction of the $i$ axis [17].
4. Specify that axis $X_i$ points from joint axis $i-1$ to joint axis $i$ along the direction of the common vertical line between joint axis $i-1$ and joint axis $i$. if joint axis $i-1$ and joint axis $i$ intersect, specify that axis

$X_i$ is perpendicular to the plane of joint axis $i-1$ and joint axis $i$.

5. The $Y_i$-axis direction is determined by the right-hand rule based on the $X_i$-axis and $Z_i$-Axis directions.
6. In special cases, when the first joint variable is 0, coordinate system $O_0$ and coordinate system $O_1$ coincide. For coordinate system $O_n$, the origin and the direction of axis $X_n$ can be arbitrarily selected. When selecting, the connecting rod parameter is usually 0.

According to the provisions established by the coordinate system, when the $Z_i$ axis coincides with the axial direction of joint $i$, the direction of $Z_i$ can be selected from axial direction and reverse extension line direction, and either one can be selected without affecting the final result. When the two joint axes intersect, it is impossible to determine which joint axis is in the front and which is in the back. The direction of the $X_i$ axis cannot be defined according to the rules. It can be selected arbitrarily among the two possibilities. Then, on the basis of the previous determination, the direction of the $Y$ axis is determined based on the right-hand rule. When the joint axis $i-1$ is parallel to the joint axis $i$, the origin position of the coordinate system $O_i$ can be selected arbitrarily [18]. Therefore, the choice of coordinate system is arbitrary.

In Figure 1, $a_i$ represents the positive direction along the $X_i$ axis, and the distance from the $Z_{i-1}$ axis to the $Z_i$ axis; $\alpha_i$ represents the positive rotation around the $X_i$ axis, and the angle value from $Z_{i-1}$ to $Z_i$; $d_i$ represents the direction along the $Z_{i-1}$ direction as Positive, the distance from $X_{i-1}$ to $X_i$; $\theta_i$ represents the angle value of the positive rotation around the $Z_{i-1}$ axis, from $X_{i-1}$ to $X_i$. $a_{i+1}$ is usually set to $a_i > 0$ because $a_i$ corresponds to distance, but the value of $\alpha_i, d_i, \theta_i$ can be positive or negative. The coordinate system $O_i$ can be regarded as the coordinate system $O_{i-1}$ rotates $\alpha_i$ degrees around $X_{i-1}$, denoted as $A_{Rx}$; then translates $a_i$ along $X_{i-1}$, denoted as $A_{Tx}$; then translates $d_i$ along $Z_i$, denoted as $A_{Tz}$; and finally rotates around $Z_i$ by $O_i$ degrees, Denoted as $A_{Rz}$. According to these four steps, the method of relative position movement of two adjacent links is recorded as the standard D-H method [19].

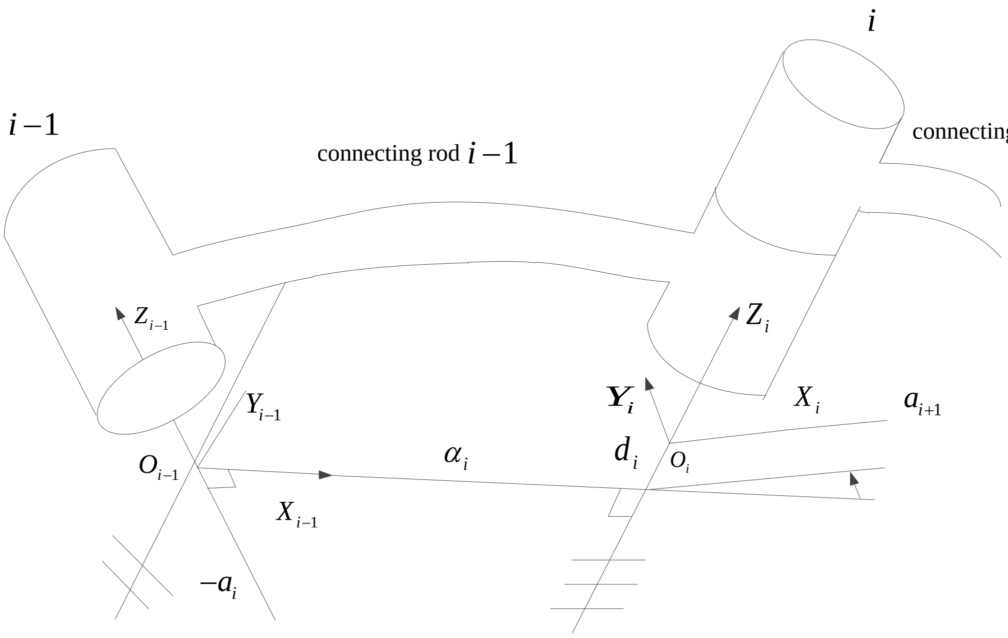



**Figure 1.** Schematic diagram of four parameters and coordinate system of connecting rod

The specific forms of $A_{Rz}, A_{Tz}, A_{Tx}$ and $A_{Rx}$ are as follows:

$$A_{Rz} = \begin{pmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

$$A_{Tz} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

$$A_{Tx} = \begin{pmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

$$A_{Rx} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i & 0 \\ 0 & \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (4)$$

The coordinate system $O_{i-1}$ corresponding to the connecting rod $i-1$ is transformed into the transformation matrix $A_i$ of the coordinate system $O_i$ corresponding to the connecting rod $i$ to express as follows:

$$A_i = A_{Rz} \times A_{Tz} \times A_{Tx} \times A_{Rx} = DH(\theta_i, d_i, a_i, \alpha_i) \quad (5)$$

It is easy to find by substituting $A_{Rz}, A_{Tz}, A_{Tx}$ and $A_{Rx}$ into the above equation:

$$A_i = \begin{pmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & \alpha_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\sin\alpha_i \cos\theta_i & \alpha_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (6)$$

*(2) Jacobian matrix*

The relationship between the linear velocity of the end of the multi-degree-of-freedom manipulator in Cartesian space and its joint angular velocity in joint space is represented by the Jacobian matrix.

The equation assumption of the desired trajectory of the end of the manipulator is shown in equation (7):

$$x = x(q) \quad (7)$$

In the formula, $x$ represents the trajectory of the end of the manipulator in Cartesian space, and $q$ denotes the rotation angle of each joint of the manipulator in the joint space [20]. The relationship between $q$ and $x$ is obtained by derivation of time on both sides of the above formula, as shown in formula (8):

$$x' = J(q)q' \quad (8)$$

In the formula, $x'$ is the velocity of the end of the manipulator in Cartesian space; $q'$ is the angular velocity of the rotation of each joint of the manipulator in the joint space; $J(q)$ is the Jacobian matrix of the manipulator. The elements in row $i$ and column $j$ of this matrix are:

$$J_{ij}(q) = \frac{\partial x_i(q)}{\partial q_j} \quad (9)$$

According to the above analysis, the inverse kinematics model of the multi degree of freedom manipulator is established, which lays the foundation for the next multi degree of freedom manipulator trajectory tracking.

Set $\theta_i$ to represent the joint angle (joint displacement), $b$ and $c$ to represent the distance between the center of gravity of the second link and the third link relative to the joint axis, and $m_i, I_i, L_i$ to represent the mass, moment of inertia and length of each link, respectively [21]. Obtain the three coordinate values of the end of the manipulator:

$$\begin{cases} x = (L_2\cos\theta_2 + L_3\cos(\theta_2+\theta_3))\cos\theta_1 \\ y = (L_2\cos\theta_2 + L_3\cos(\theta_2+\theta_3))\sin\theta_1 \\ z = L_1 + L_2\sin\theta_2 + L_3\sin(\theta_2+\theta_3) \end{cases} \quad (10)$$

Where $x, y, z$ is the coordinate value of the end of the manipulator in the $X$-axis, $Y$-axis and $Z$-axis directions, respectively.

The inverse kinematics model can be obtained by solving the forward kinematics model, which is easily obtained by dividing the second formula by the first formula in formula (10):

$$\theta_1 = \arctan(\frac{y}{x}) \quad (11)$$

It is also easy to obtain from formula (10):

$$\begin{cases} \dfrac{x}{\cos\theta_1} = L_2\cos\theta_2 + L_3\cos(\theta_2+\theta_3) \\ z - L_1 = L_2\sin\theta_2 + L_3\sin(\theta_2+\theta_3) \end{cases} \quad (12)$$

By squaring both sides of the above equation (12) and adding them together, we can obtain:

$$\theta_3 = \arctan\left[((x/\cos\theta_1)^2 + (z-L_1)^2 - L_2^2 - L_3^2)/2L_2L_3\right] \quad (13)$$

Expand the right side of the equal sign in formula (12) to get:

$$\begin{cases} \dfrac{x}{\cos\theta_1} = (L_2 + L_3\cos\theta_3)\cos\theta_2 - L_3\sin\theta_3\sin\theta_2 \\ z - L_1 = (L_2 + L_3\cos\theta_3)\sin\theta_2 + L_3\sin\theta_3\sin\theta_2 \end{cases} \quad (14)$$

Solving the above equation system can get:

$$\theta_2 = \arctan\left(\frac{(z-L_1)(L_2+L_3\cos\theta_3) - (x/\cos\theta_1)L_3\sin\theta_3}{(x/\cos\theta_1)(L_2+L_3\cos\theta_3) + (z-L_1)L_3\sin\theta_3}\right) \quad (15)$$

Finally, the solution of the positive kinematics formula (10) can be obtained by sorting out:

$$\begin{cases} \theta_1 = \arctan(\frac{y}{x}) \\ \theta_2 = \arctan\left(\frac{(z-L_1)(L_2+L_3\cos\theta_3)-(x/\cos\theta_1)L_3\sin\theta_3}{(x/\cos\theta_1)(L_2+L_3\cos\theta_3)+(z-L_1)L_3\sin\theta_3}\right) \\ \theta_3 = \arctan\left[((x/\cos\theta_1)^2+(z-L_1)^2-L_2^2-L_3^2)/2L_2L_3\right] \end{cases} \quad (16)$$

*2.2. Trajectory tracking of multi-degree-of-freedom manipulator based on particle filter algorithm*

The particle filter algorithm is a very common algorithm in the tracking field of multi-degree-of-freedom manipulators in recent years. Particle filter is a method for Bayesian estimation based on sampling Monte Carlo. Monte Carlo method is a statistical method, which is based on the probability model and estimates the unknown characteristic quantity through many simulation experiments [22]. Bayesian estimation is the use of Bayesian theorem combined with new evidence and previous prior probability to get a new probability [23].The core is to use Monte Carlo method to modify the prior probability density obtained by the target motion model based on statistical principles based on the theorem of large numbers [24]. The basic process is: first, based on the prior conditional distribution of state variables, and sampling according to certain rules in the prior probability distribution, the samples are particles. Then use the new measurement value for correction, and this posterior density distribution will be used as the prior probability density of the next recursive process to complete the parameter estimation process.

The probability density function $P(x_t|z_{1:t})$ is represented by a finite set of weighted particles $(s_t^{(i)}, w_t^{(i)})$. Among them, $s_t^{(i)}$ is the sampled particle, and $w_t^{(i)}$ is the corresponding weight of the particle. The algorithm is divided into the following three basic steps:

(1) Sampling

Select N particles from the previous set of particles $s_{t-1}^{(n)}$ to form a new set of sample particles $s_t^{(n)}$. State variables with high weights will be sampled multiple times, while state variables with low weights may not be sampled. This ensures the validity of the sample. The number of particles usually depends on the dimensionality of the state space [25]. The larger the number of particles, the better the true posterior density is reflected, and the more accurate the tracking results are. However, too many particles will increase the amount of calculation, make the processing time of the system longer, and affect the rapidity of tracking; while too few particles will make the predicted state variables too small, so that the particles that match the actual state of the observed object cannot be generated.

(2) Prediction

In order to generate more effective prediction particles, the standard random variable $\eta$ is added to the particles obtained in step (1), so that the particles repeatedly sampled at the same place are separated, which is:

$$s_t^{(n)} = s_t^{(n)} + \eta \quad (17)$$

This new set of particles can be viewed as an approximate set of samples randomly selected from the prior probability density function $P(x_t|z_{1:t-1})$.

*(3) Update*

According to a set observation model, the similarity of each sample is calculated, and the weight of the sample is configured accordingly. The observation model must be able to truly reflect the similarity between the particle state and the actual observed state, and be simple and universal. At the same time, the type and parameters of the introduced noise must be moderate, so that the prediction process of the particle is neither so large that it exceeds the range of motion, nor so small that it cannot keep up with the motion of the object [26]. Finally, normalize the weights such that:

$$\sum_{i=0}^{N} \omega_t^{(n)} = 1 \quad (18)$$

Therefore, this paper uses the particle filter algorithm to track the movement trajectory of the multi-degree-of-freedom manipulator.

Using particle filter algorithm to track the trajectory of multi degree of freedom manipulator requires the particle filter tracking framework to be built. The particle filter tracking framework provides attachment conditions for the construction of the multi-DOF manipulator trajectory tracking environment. To guarantee that the hidden layer organization can maintain a benign distribution state, the framework structure mainly includes target change description, state Variables work together to handle two main functions. Among them, the target change description is the basic execution function of the particle filter tracking framework. The hidden layer organization will make every part that affects the movement trajectory of the manipulator set as a co-node. In a period of time, the displacement difference between the head node and the tail node is the motion displacement of the movement trajectory of the robot arm, and the motion curve between the head node and the tail node is the movement trajectory of the robot arm. The specific tracking process is shown in Figure 2.

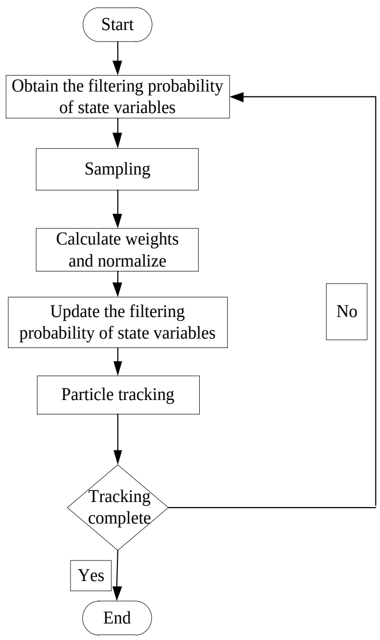



**Figure 2.** Particle filter tracking flow chart

Assuming that at time $k-1$, the filtering probability distribution of the state variable $x_{k-1}$ of the manipulator is:

$$P(x_{k-1}|z_{0:k})=\sum_{i=1}^{G}\omega_{k-1}N(x_{k-1},u_{k-1},\sum k-1) \quad (19)$$

When the measured observations at time k are obtained, the probability distribution can be expressed as:

$$P(x_k|z_{0:k})=C_k\sum_{i=1}^{G}\omega_{ki}N(x_{k-1},u_{k-1},\sum k-1) \quad (20)$$

Sample $x_{ki}^j$ is drawn using the importance function, weights $\omega_{ki}^j$ are calculated, and Monte Carlo estimates of the mean $u_{ki}$ and covariance $\sum k-1$ of $x_{ki}$ are obtained. Then the filtering probability distribution of the state variables of the manipulator at time k after the update is approximately expressed as:

$$P(x_k|z_{0:k})\approx\sum_{i=1}^{G}\omega_{ki}N(x_k,u_{ki},\sum ki) \quad (21)$$

Then the predicted probability distribution of the state variable at time $k+1$ is:

$$P(x_k|z_{0:k})=\sum_{i=1}^{G}\omega_{(k+1)i}N(x_{k+1},u_{(k+1)i},\sum(k+1)i) \quad (22)$$

Assuming that there are G sums of Gaussian terms, the importance function required for the sample collection of the manipulator is $q=P(x_k|z_{0:k-1})$, and the importance function is sampled to obtain the sample point set $x_{ki}^j$ and calculate the sample weight $\omega_{ki}^j$, the main process is as follows:

1. Measurement update process:

- The approximate filtering probability distribution of the state variables of the $k-1$ manipulator is known. When the measured observation value of the moving manipulator at time k is obtained, the probability distribution function can be expressed by equation (18).
- Calculate the Monte Carlo estimation of the filter mean $u_{ki}$ and covariance $\sum ki$ of the multi-degree-of-freedom manipulator sample point set $x_{ki}^j$ at time k:

$$u_{ki}=\frac{\sum_{j=1}^{M}\omega_{ki}^j x_{ki}^j}{\sum_{j=1}^{M}\omega_{ki}^j}a \quad (23)$$

$$\sum ki=\frac{\sum_{j=1}^{M}\omega_{ki}^j(x_{ki}^j-u_{ki})(x_{ki}^j-u_{ki})^T}{\sum_{j=1}^{M}\omega_{ki}^j} \quad (24)$$

Update the weights and normalize the weights:

$$\bar{\omega}_{ki}=\frac{\bar{\omega}_{ki}}{\sum_{i=1}^{G}\bar{\omega}_{ki}} \quad (25)$$

2. Forecast update process:

- (1) Based on the measurement and observation of the multi-degree-of-freedom manipulator at time $k$, the state particle $x_{(k+1)i}$ at time $k+1$ is obtained by sampling from the state transition distribution $p(x_{(k+1)i}/x_{ki})$ of $i=1,2,...,G$ in turn.

  (2) Update the weights

$$\bar{\omega}_{(k+i)i}=\omega_{ki} \quad (26)$$

3. Calculate the Monte Carlo estimation of the filter mean $\bar{u}_{(k+i)i}$ and the covariance $\sum(k+1)i$ of the multi-degree-of-freedom manipulator sample point set $x_{ki}^j$ at time $k+1$:

$$\bar{u}_{(k+i)i}=\frac{1}{M}\sum_{i=1}^{M}x(k+1)i \quad (27)$$

$$\sum(k+1)i=\frac{1}{M}\sum_{i=1}^{M}(\bar{u}_{(k+i)i}-x_{(k+i)i}) \quad (28)$$

4. From equation (21), we can get the approximate filtering probability distribution of the state variables of the manipulator at time k+1, and the measurement update process at time k+1 is returned.

According to the above update process, set the tracking conditions for the movement trajectory of the manipulator:

$$w=\frac{x_1x_1}{2}\sum_{i=1}^{M}\zeta(e_1-e_2)^2 \quad (29)$$

In the formula, $i$ represents the lower limit execution parameter of the transport trajectory node, $e_1,e_2$ represents the filter coefficient related to the change description and state variable co-processing, and $\zeta$ represents the standard power term coefficient of data processing.

The tracking error of the movement trajectory of the multi-degree-of-freedom manipulator is a physical parameter condition related to the particle filter, which can fully express the highest quality value focal element of the positioning removal advantage, and can also define the low quality assumption coefficient of the autonomous robot movement and displacement tending to the degenerate value. Let d represent the ideal calibration physical vector of the particle filter, and $\zeta$ represent the operating conditions of the moving trajectory of the manipulator. Combined with the above equations, the tracking error coefficient of the moving trajectory of the manipulator can be expressed as:

$$\varphi=1-\prod(1-dg^{\varepsilon}\gamma j) \quad (30)$$

In the formula, $g$ represents the maximum displacement difference allowed by the movement trajectory of the manipulator, $\varepsilon$ represents the power term parameter related to the displacement difference, and $\gamma$ represents the relevant correction coefficient. On the basis of formula (30), set $\theta$ to represent the upper threshold of paranoid co-processing, and $\varphi$ to represent the lower threshold of paranoid co-processing, then formula (31) reflects the complete multi-DOF manipulator trajectory tracking error correction result.

$$m = \int_{\varphi}^{\theta} \frac{\lambda - u}{\sqrt{kz - x_v}} \tag{31}$$

Where $\lambda$ denotes the maximum value of the tracking error coefficient of the movement trajectory of the manipulator in the ideal state, $K$ represents the permission coefficient of cooperative processing, $z$ represents the order of magnitude condition of the movement trajectory of the manipulator, and $x_v$ represents the correction offset of Co-processing variance at $v$ .

## 3. Simulation experiment analysis

The 6-DOF AUBO i5 lightweight robotic arm has the characteristics of light weight and high precision. The positioning accuracy can reach 0.05mm. It adopts open software architecture and can integrate existing software and algorithms; the mobile target is the built-in gc-cc-306 high-precision micro magnetic basic sensor electric drive device box, as shown in Figure 3.

In order to verify the effectiveness of the proposed tracking method, a six-degree-of-freedom AUBO i5 light manipulator was selected as the experimental object to conduct a simulation experiment. Figure 4 shows the scene diagram of the experimental platform, and the location distribution of each part is shown in the mark. The moving target moves in the plane space relative to the base frame, and its motion trajectory is tracked. The experimental operation procedure is controlled by the upper computer program developed based on the VS++ platform.

The binocular camera in the experimental platform consists of two CMOS cameras, the model is Micron AR0330, as shown in Figure 5; the parameters are: focal length 8 mm; pixel size 5.07 μm*3.38 μm; the highest resolution is 2048*1536; It is connected to the host computer through a USB type data line, and the sampling frequency is 30 frames per second.

(a) Robotic arm

(b) Moving objects

**Figure 3.** Robotic arm and moving target

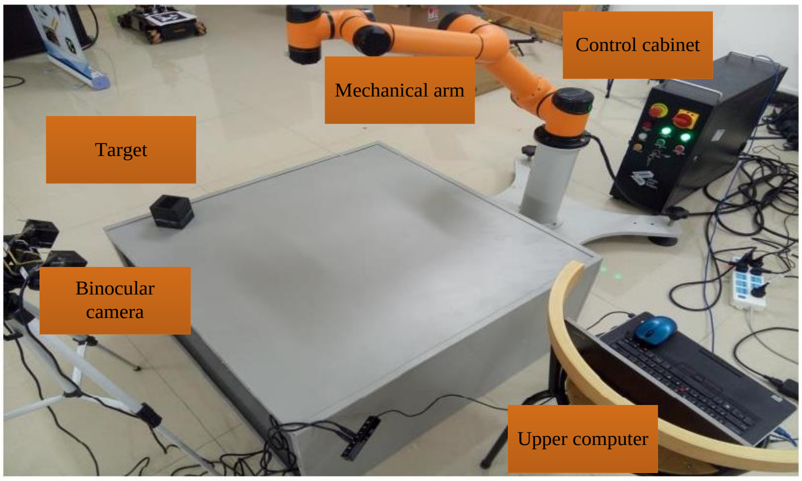



**Figure 4.** Experimental platform

**Figure 5.** Camera equipment

The actual motion trajectory of the 6-DOF manipulator target is a cosine curve, as shown in Figure 6. After obtaining the image information, the vision system performs image preprocessing to obtain image features, then stereo matches depth information, and then combines the information with the motion model to obtain the estimated value and filters to obtain the required amount of feedback. The feedback amount is transmitted to the upper computer control program, the joint variable information is obtained through the kinematics solution of the robot arm, and then the API function interface provided by the robot controller is called to realize the realization, and finally the motion of the robot arm is realized through the servo driver. The whole process is closed-loop continuous reciprocating.

Through this method and literature [8], a variable gain iterative learning trajectory tracking control method for 3-DOF manipulator is proposed, and the automatic trajectory tracking control and reference of multi axis series manipulator based on joint angle compensation proposed in literature [9] The robot arm trajectory tracking method based on adaptive robust control proposed in document [10] tracks the motion trajectory of the six degree of freedom robot arm, and the robot trajectory tracking control method based on variable gain active disturbance rejection technology proposed in document [11] tracks the robot arm trajectory, and compares the tracking trajectory results with the actual target trajectory. The comparison results are shown in Figure 7.

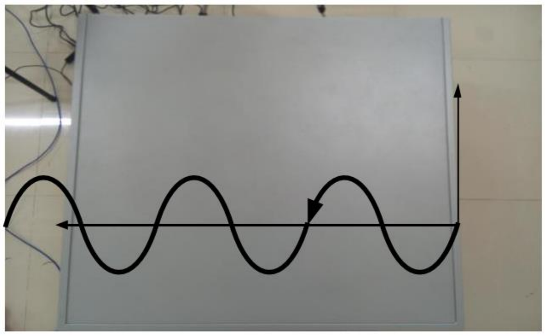
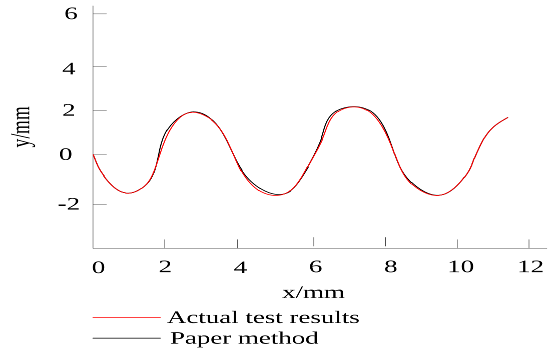
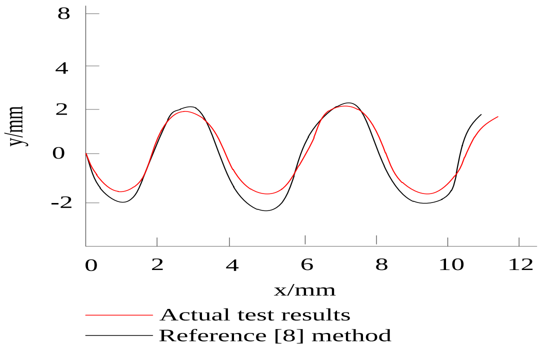


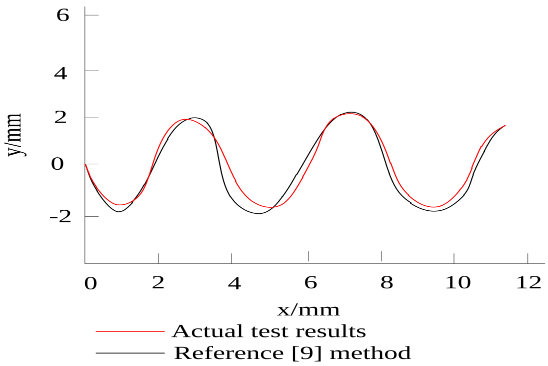
**Figure 6.** Target trajectory



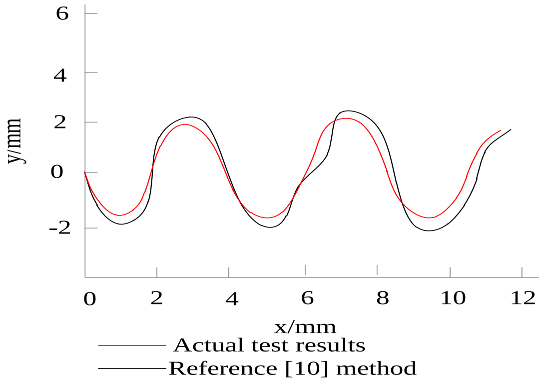

**(a)** Tracking results of our method



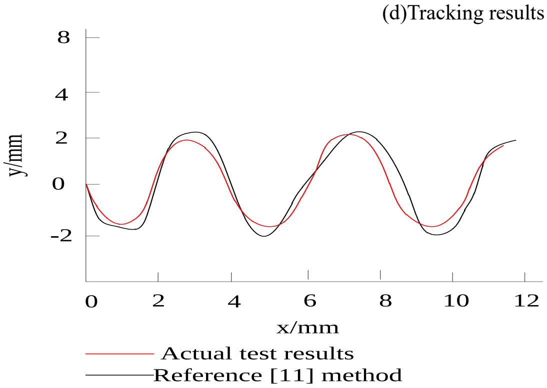

(b) Tracking results of the method in Reference [8]




(c) Tracking results of the method in Reference [9]




(d)Tracking results of the method in Reference [10]




(e) Tracking results of the method in Reference [11]

**Figure 7.** The tracking results of the three methods and the actual target trajectory error

According to Figure 7, Compared with the methods proposed in references [8], [9], [10] and [11], the error between this method and the actual target trajectory tracking results is small, close to 100%, indicating that this method has high accuracy for the trajectory tracking of six degree of freedom manipulator.

The tracking time of the proposed method is compared with the methods in references [8], [9], [10] and [11], as shown in Figure 8.

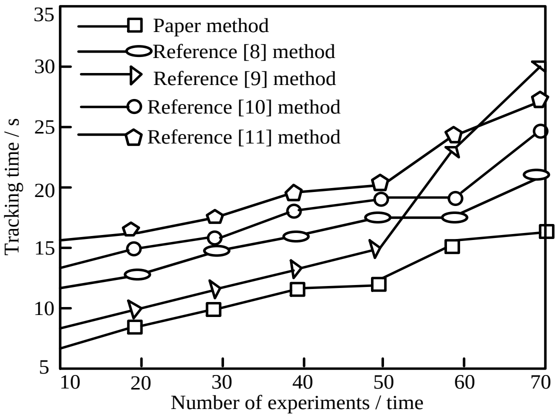



**Figure 8.** Tracking time of the movement trajectory of the 6-DOF manipulator by the three methods

According to Figure 8, the proposed method takes less than 15s to track the movement trajectory of the 6-DOF robot arm, while the tracking time of the reference [8],[9],[10] and [11] method and the reference [9] method is within 30s ,28s, 25s and 20s, respectively.

## 4. Conclusion

The control of multi-degree-of-freedom manipulators can usually be divided into two types: fixed-point position control and movement trajectory tracking control. Fixed-point position control is mainly used to complete point-to-point operations, such as handling, loading and unloading, spot welding, etc. The tracking control of the movement trajectory of the multi-degree-of-freedom manipulator needs to design a control strategy to make each joint of the manipulator run according to the expected movement trajectory. During the operation, it is necessary to ensure that the tracking error is as close to zero as possible and the system is stable, mainly to meet some accuracy requirements. Nowadays, high and repetitive jobs such as part machining, assembly, grinding, etc. with the increasing demand for socialized mass production, multi-degree-of-freedom manipulators are playing an increasingly important role in various fields, many of which require high-speed, high-precision tracking control of moving tracks. However, the multi-degree-of-freedom manipulator system is a complex nonlinear system. Its parameter uncertainty, strong coupling, internal friction and external disturbance make it difficult to establish an accurate dynamic model. Therefore, this paper proposes a multi-DOF manipulator trajectory tracking method based on the particle filter algorithm. However, when analyzing the tracking problem of multi-degree-of-freedom manipulators, the control algorithm only learns a specific trajectory and realizes the trajectory tracking. When the expected trajectory changes, the algorithm must perform new learning, and the control algorithm lacks due generalization ability, which needs further research and discussion.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