# Research and Application of Trajectory Tracking Control System of Mobile Manipulator Based on Fuzzy Active Disturbance Rejection Technology

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**Abstract:** Trajectory tracking control is the basis and core of mobile manipulator control, and good tracking performance plays a very important role in completing other control tasks of mobile manipulator. Some tasks need to control not only the end of the mobile manipulator to track a given trajectory, but also its joints to track a given trajectory. In this paper, the research and application of trajectory tracking control system of manipulator based on ADRC (Active disturbance rejection controller) technology are carried out. Fuzzy active disturbance rejection control technology is used to estimate and compensate the system disturbance in real time, so as to eliminate the influence of uncertain factors on the system output and improve the trajectory tracking accuracy. The research results show that the trajectory tracking performance and robustness of the system are better when the controller designed in this paper is used for control. The estimation of disturbance and modeling error is faster and smaller. Therefore, it has practical significance for engineering application.

## 1. Introduction

The manipulator is a system with time-varying parameters, strong coupling, multi-input and multi-output, and high nonlinearity, so its control law is complicated. Considering the imprecision of system modeling and the disturbance of working environment, it becomes a difficult problem to realize high-quality manipulator control. With the continuous improvement of people's living standards and industrial production requirements, the mechanical arm fixed in a certain position can no longer meet people's various needs. Therefore, it is necessary to develop the mobility of the manipulator to expand its workspace. The mobile platform was introduced into the research of manipulator, which promoted the research and development of mobile manipulator [1].

At present, sliding mode variable structure control, adaptive control and neural network control [2-4] are widely used in research methods, which will undoubtedly increase the complexity of controller design. In order to explore a method based on active disturbance rejection technology which is suitable for practical manipulator control engineering. Aiming at the difficulties in the field of manipulator control at present, introducing fuzzy active disturbance rejection control technology as the core control algorithm of mobile manipulator system has a good prospect in the engineering control of manipulator.

## 2. Research method

### 2.1. Problem description

Trajectory tracking control is the basis and core of mobile manipulator control, and good tracking performance plays a very important role in completing other control tasks of mobile manipulator. Some tasks need to control not only the end of the mobile manipulator to track a given trajectory, but also its joints to track a given trajectory.

A wheeled mobile manipulator system based on two-link is considered. The two rear wheels of the mobile robot platform are respectively driven by independent motors. A two-link manipulator is assembled at the position of the centre of mass on the mobile robot platform, and its hinge points

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are driven by a motor respectively. Connecting rod 1 can rotate around the z-axis, and connecting rod 2 can rotate up and down. In the process of movement, the mobile platform is subject to non-integrity constraints (wheels and ground pure rolling without sliding), while the mechanical arm is subject to integrity constraints[5-7].

The non-integrity constraint on the mobile platform is:

$$\dot{y}_c \cos\varphi - \dot{x}_c \sin\varphi - d\dot{\varphi} = 0 \quad (1)$$

where, $(x_c, y_c)$ is the coordinate of the platform's centroid in the world coordinate system, $d$ is the distance between the centre point of the two rear wheels and the platform's centroid, and $\varphi$ is the included Angle between the direction of the moving platform's symmetry axis and the x-axis.

Select $q = [x_c, y_c, \varphi, \theta_1, \theta_2]^T$ as the pose variable information of the robot, where, $\theta_1$ and $\theta_2$ respectively represent the angle of connecting rod 1 and 2, then equation (1) can be expressed as:

$$A(q)\dot{q} = 0 \quad (2)$$

where, $A(q) = [-\sin\varphi, \cos\varphi, -d, 0, 0]$ is a nonholonomic constraint matrix.

Dynamics describes the relationship between the force of the robot system and the motion of each rigid body of the robot [8]. As far as omni-directional mobile manipulator is concerned, dynamic modeling is much more complicated than kinematic modeling.

At present, there are mainly two methods to solve the dynamic modeling problem of omni-directional mobile manipulator. One is Newton-Euler dynamic balance method, and the other is Lagrange functional balance method. Because Lagrange method only needs to calculate the velocity variable of the mobile manipulator and does not require the internal force of the system, it is simpler and easier to use, so this paper uses Lagrange method to model its dynamics.

The Lagrange energy method can be used to obtain the dynamic equation of the system, as shown in Formula (3) :

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q,\dot{q}) + \tau_d = B(q)\tau + A^T(q)\lambda \quad (3)$$

where, $M(q)$ is the inertia matrix of the system and is a positive definite symmetric matrix; $C(q,\dot{q})$ is the matrix representing Coriolis force and centriforce; $G(q,\dot{q})$ is the gravity and friction terms; $\tau_d$ is the bounded external interference quantity; $B(q)$ is the input conversion matrix; $\tau$ is the input torque vector of the system; $\lambda$ is the Lagrange factor of the corresponding constraint. Equation (3) includes the dynamic interaction between the mobile platform and the manipulator.

Take $S(q)$ as a basis of the null space of $A(q)$, then there is $A(q)S(q) = 0$. Equation (2) can be rewritten as:

$$\dot{q} = S(q)v \quad (4)$$

where, $v = [\dot{\theta}_l, \dot{\theta}_r, \dot{\theta}_1, \dot{\theta}_2]^T$ is the input vector of the moving manipulator, and $\theta_l$ and $\theta_r$ respectively represent the rotation angles of the left and right wheels of the moving platform.

Set $X = [x_a, y_a, x_c, y_c]^T$, $(x_a, y_a)$ is the position of the end of the moving manipulator. Then there is

$$\dot{X} = J(q)v \quad (5)$$

where, $J(q)$ is called the Jacobian matrix. Formula (5) establishes the relation between the output of the moving manipulator and the rotation angular velocity of the left and right wheels of the moving platform and each connecting rod.

By substituting formula (5) into formula (4), it can be get:

$$\dot{q} = \bar{S}\dot{X} \quad (6)$$

where, $\overline{S}=S(q)J^{-1}(q)$ .By taking the derivative of formula (6) and substituting it into formula (3), the binding term can be eliminated, thus:

$$\overline{M}\ddot{X}+\overline{C}\dot{X}+\overline{G}+\overline{\tau}_d=\overline{B}\tau \quad (7)$$

where, $\overline{M}=\overline{S}^T M(q)\overline{S}$ , $\overline{C}=\overline{S}^T C(q,\dot{q})\overline{S}+\overline{S}^T M(q)\dot{\overline{S}}$ , $\overline{G}=\overline{S}^T G(q)$ , $\overline{B}=\overline{S}^T B(q)$ , $\overline{\tau}_d=\overline{S}^T\tau_d$ .

Formula (7) not only completely describes the basic dynamic properties of the mobile manipulator, but also completely eliminates the differential binding term introduced by the differential constraint.

### 2.2. System implementation

Trajectory tracking control is the core and foundation of mobile manipulator control, and good tracking performance is the key for mobile manipulator to complete a given task. In this paper, fuzzy auto-disturbance rejection control technology is used to estimate and compensate the system disturbance in real time, eliminate the influence of uncertain factors on the system output, and improve the track tracking accuracy. The structure of fuzzy active disturbance rejection controller is shown in Figure 1.

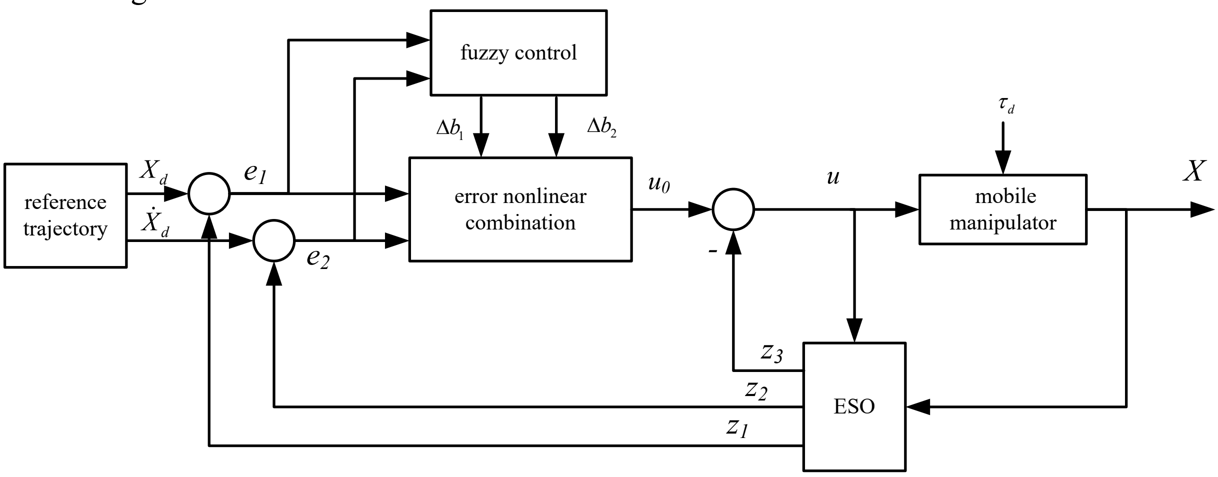



Figure 1 Fuzzy active disturbance rejection controller structure diagram

Nonlinear feedback is used to decouple the nonlinear moving manipulator system linearly. The nonlinear feedback is as follows:

$$\tau=\overline{B}^{-1}\left(\overline{M}u+\overline{C}\dot{X}+\overline{G}\right) \quad (8)$$

where, $u$ is the auxiliary control input.

By substituting formula (8) into the system equation (7) of the mobile manipulator, the system can be transformed into:

$$\ddot{X}=u \quad (9)$$

This allows the system to be transformed into four independent linear feedback systems [9]. Let $y=x_1=X, x_2=\dot{X}$ , the extension state $x_3=f$ is introduced, assuming that $f$ is differentiable, and $\dot{f}=h$ , where, $f$ is the total disturbance, which mainly includes the comprehensive effect of changes in system parameters and external disturbances. Then, the expression of the augmented state space of system (7) can be obtained:

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=x_3+u\\ \dot{x}_3=h\end{cases} \quad (10)$$

$$y=x_1$$

As the core part of ADRC, ESO can estimate the unmeasurable state and uncertain interference in real time. Its estimation ability has great influence on the overall performance of ADRC. The ESO adopted in this paper is as follows:

$$\begin{cases} \dot{z}_1 = \gamma_1 \tilde{e}_1 + z_2 \\ \dot{z}_2 = \gamma_2 \tilde{e}_2 + z_3 + u \\ \dot{z}_3 = \gamma_3 \left( \eta_1 \tilde{e}_1 + \eta_2 \tilde{e}_2 \right) \end{cases} \quad (11)$$

Where, $z_1, z_2, z_3$ is the observed values of $x_1, x_2, x_3$ respectively, $\tilde{e}_1 = y - z_1, \tilde{e}_2 = \dot{y} - z_2$, $\gamma_1, \gamma_2, \gamma_3$ is observer gains, $\eta_1, \eta_2$ is the error coefficient. Using $\tilde{e}_1$ to adjust $z_1$, using $\tilde{e}_2$ to adjust $z_2$, $z_3$ is regulated by $\tilde{e}_1$ and $\tilde{e}_2$ together, the convergence rate of the observer is accelerated.

According to the variation of the system error, fuzzy control technology is used to correct the nonlinear error feedback parameters online, so as to achieve the optimal self-tuning of parameters. The feedback control quantity $u_0$ is:

$$\begin{cases} u_0 = b_1 fal(e_1) + b_2 fal(e_2) \\ u = u_0 - z_3 \end{cases} \quad (12)$$

where, $e_1 = X_d - z_1$ , $e_2 = \dot{X}_d - z_2$ , $X_d$ and $\dot{X}_d$ are the position and velocity of the desired trajectory of the system. $b_1$ and $b_2$ are error feedback gain, *fal* is a nonlinear integrated control function [10], and its expression is as follows:

$$fal\left(\xi, \theta, \delta\right) = \begin{cases} \left|\xi\right|^{\theta} \operatorname{sgn}(\xi), \left|\xi\right| > \delta \\ \xi \big/ \delta^{(1-\theta)}, \left|\xi\right| \le \delta \end{cases} \quad (13)$$

where $\xi$ is the variable of *fal* function, $\delta$ is arbitrarily small positive number, and $0<\theta<1$.

Fuzzy control is introduced to modify the error feedback gain $b_1$ and $b_2$ online. The input language variable of the fuzzy controller is the error and error change rate of each controlled parameter, and the output language variable is the correction amount of the corresponding error feedback gain [11]. The correction parameter $\Delta b_{i1}, \Delta b_{i2}$ is found out by fuzzy inference and substituted into the calculation formula:

$$\begin{cases} b_{i1} = b_{i1}^{'} + \Delta b_{i1} \\ b_{i2} = b_{i2}^{'} + \Delta b_{i2} \end{cases} \quad (14)$$

Where, $b_{i1}^{'}, b_{i2}^{'}$ is the initial values of nonlinear proportional gain and nonlinear differential gain of each controlled parameter respectively

## 3. Analysis of experimental results

In this paper, a mobile manipulator is taken as the research object, and the fuzzy active disturbance rejection method is used to design the controller, and the effectiveness of the proposed method is verified. In MATLAB Simulink environment, S-function is used to realize active disturbance rejection control.

The system parameters of the mobile manipulator are selected as follows:

Mass of moving platform and connecting rod: $m_0 = 22kg, m_1 = 8kg, m_2 = 4kg$;

Length of each connecting rod: $l_1 = 0.5m, l_2 = 0.35m$;

The moment of inertia of the moving platform and each connecting rod:

$J_0 = 1.15kg \cdot m^2, J_1 = 0.04kg \cdot m^2, J_2 = 0.03kg \cdot m^2$;

The expected motion trajectory of the end effector of the moving manipulator and the moving platform is set as

$$\begin{cases} x_{cd} = 0.5t, y_{cd} = 0 \\ x_{ad} = 0.5t, y_{ad} = 0.3\sin(0.2t) \end{cases} \quad (15)$$

The moving platform moves horizontally and uniformly, and the end of the manipulator moves sinusoidal with time on the y-axis.

In the simulation process, random force interference with a maximum amplitude of 5N was added to the end-effector along each direction of the x and y axes. The algorithm proposed in this paper is used for control, and the trajectory tracking renderings of the mobile manipulator and the mobile platform are obtained, as shown in Figure 2. So the end-effector is very good at tracking the desired trajectory and doing sinusoidal motion.

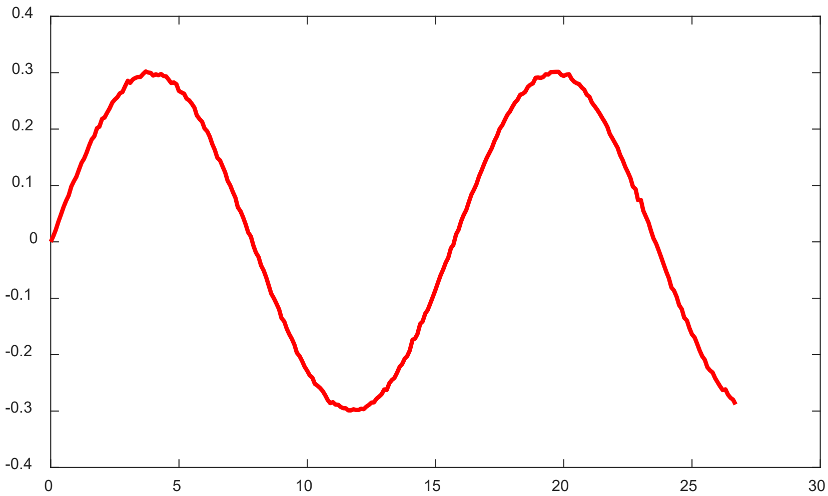
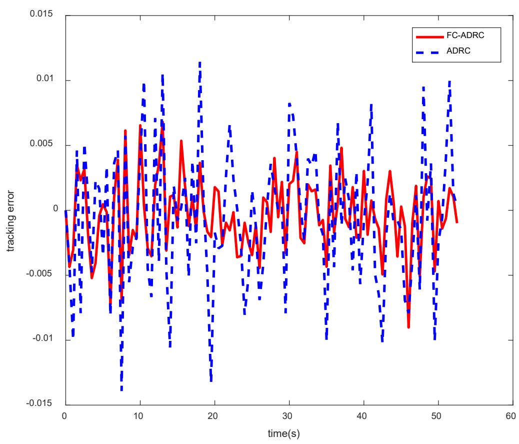



Figure 2 Tracking result of mobile manipulator

Fuzzy ADRC and ADRC are respectively used for comparative experiments. Figure 3 and Figure 4 show the tracking errors of the end-effector in the X-axis and Y-axis directions. It can be seen from the experimental results that fuzzy ADRC can achieve better control effect than the traditional ADRC.



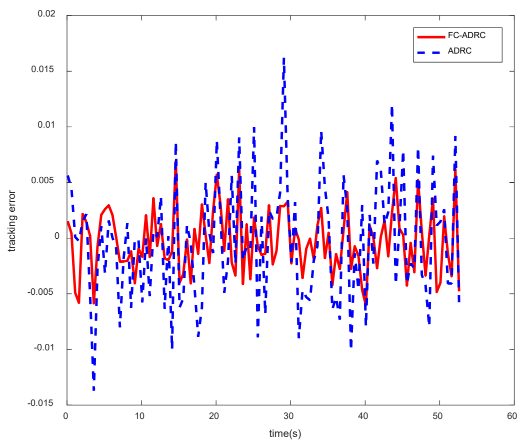




Figure 3 Comparison of error in x direction Figure 4 Comparison of error in y direction

The trajectory tracking performance of the system are better when the controller designed in this paper is used for control. The estimation of disturbance and modeling error is faster and smaller. It can be seen that the filter characteristics and anti-interference ability of ADRC are quite strong, and ADRC can well solve the noise amplification effect of traditional PID.

## 4. Conclusions

The mobile manipulator is a system with time-varying parameters, strong coupling, multi-input and multi-output, and high nonlinearity, so its control law is complicated. Considering the imprecision of system modeling and the disturbance of working environment, it becomes a difficult problem to realize high-quality mobile manipulator control. In order to explore a method based on active disturbance rejection technology, which is suitable for practical mobile manipulator control engineering. Aiming at the difficulties in the field of manipulator control at present, introducing active disturbance rejection control technology as the core control algorithm of manipulator system has a good prospect in the engineering control of manipulator. In this paper, fuzzy active disturbance rejection control technology is used to estimate and compensate the system disturbance in real time, so as to eliminate the influence of uncertain factors on the system output and improve the trajectory tracking accuracy. The research results show that the trajectory tracking performance and disturbance rejection effect of the system are better when the controller designed in this paper is used for control. The estimation of disturbance and modeling error is faster and smaller. Therefore, it has practical significance for engineering application.

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