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Adaptive Fuzzy Control for Trajectory Tracking of Mobile Robot

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Abstract—**Trajectory tracking of the mobile robot is one research hot for the robot. For the control system of the two-wheeled differential drive mobile robot being in nonhonolomic system and the complex relations among the control parameters, it is difficult to solve the problem based on traditional mathematics model. A new control scheme combined with the fuzzy PD(Proportional and Differential) control and the separate integral control is proposed in this paper. The control scheme can not only make full use of the advantage of the fuzzy control, but also have the good steady state tracking ability of the integral control. However, this control scheme introduces so many parameters which are difficult to optimize. In order to realize the online adaptive learning of the control parameters, the modified VFSA (Very Fast Simulated Annealing) is used. The simulation results show that the method is feasible, and can quickly approach the conference trajectory in a short time, and the trajectory tracking error is very small.**

I. Introduction

Trajectory tracking of Mobile Robots [1-6] is a non-linear problem, and the trajectory tracking of mobile robot is closely related to the time, which is very difficult to research. But it is precisely these factors that attract many experts and scholars to join the research. For trajectory tracking, smooth approximation and its convergence rate are two important factors [5]. As the expected value is variable in time, the problem of trajectory tracking control is the difficulty of nonholonomic mobile robots motion control.

At present, control methods based on nonlinear control theory are emerging. The method of nonlinear state feedback [7, 8] is to design a nonlinear state feedback law to obtain a closed-loop system based on mobile robot kinematics model. The Major problem of this method is how to cause the system global asymptotic to stabilize in the zero equilibrium point. The sliding model control method [9, 10] has the outstanding merit of robustness against structured and unstructured uncertainties, however, for the discontinuous item on the control law directly transferred to the output, the control system inevitably emerges "buffeting", which cause the effect of control to be poor. Although backstepping method [11, 12] is widely applied for tracking, but the controller structure and design process are very complicated, moreover, it requests the robot to be able to provide large acceleration as possible, this is very difficult in fact. The adaptive method [13, 14] can timely adjust control law by the variable parameters on control system, and cause the system to achieve a certain performance criteria. However, its realization is too complex, and it is difficult to meet the real-time performance of nonholonomic mobile robots motion control. When parameters are uncertain, the adaptive control is difficult to guarantee system stability.

Intelligent method [15-18] causes the design of control system to be no longer relying on mathematical model and get out of the linear constraints, and provides a new approach to solve the issue of nonholonomic mobile robots motion control. So, it has great theoretical research value and application prospects. In order to solve the robustness of trajectory tracking for mobile robot, some scholars try to utilize fuzzy control [15, 17, 18] to solve the problem. However, fuzzy control rules cannot be perfectly summarized for influenced by the subjective factors of person, and the controller is difficult to eliminate the steady state error for it has not the self learning ability, and these affect the performance of fuzzy control. Intelligent optimization algorithms do not need to consider the specific form of equation, have excellent characteristics of searching the entire solution space, is not easy to falling into local optimal solution, and without restriction of the search space restrictive assumptions, so, they can solute the complicated problems. Simulated annealing (SA) algorithm [19], which is a kind of intelligent optimization algorithm, can move off of local optima solution. While the convergence speed of the improved very fast simulated annealing (VFSA) algorithm [20, 21] is faster than that of SA algorithm.

In this paper, on the basis of fuzzy tracking control for a mobile robot, the improved very fast simulated annealing algorithm and fuzzy-integral controller are introduced. The integral control is used to eliminate the steady state error for fuzzy control system, and the improved VFSA algorithm is used to optimize the fuzzy-integral controller to obtain the satisfactory result of trajectory tracking for mobile robot.

II. Kinematics Analysis of Mobile Robot

A two-wheel differential drive mobile robot was chosen as the object in this paper. Its wheel rotation is limited to one axis. Therefore, the navigation is controlled by the speed a change on either side of the robot. This kind of robot has

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nonholonomic constraints. The kinematics scheme of a two-wheel differential drive mobile robot is as shown in Fig. 1, where $\{O, X, Y\}$ is the global coordinate, v is the velocity of the robot centroid, ω is the angular velocity of the robot centroid, v_L is the velocity of the left driving wheel, v_R is the velocity of the left driving wheel, D is the distance between two driving wheels, R is the radius of each driving wheel, x and y are the position of the robot, and θ is the orientation of the robot. According to the motion principle of rigid body kinematics, the motion of a two-wheel differential drive mobile robot can be described using equations (1) and (2), where ω_L and ω_R are angular velocities of the left and right driving wheels respectively.

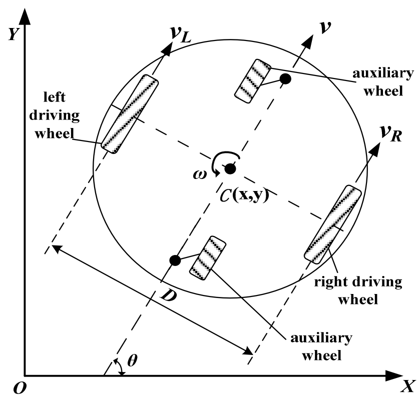

Fig. 1. The kinematics scheme of differential drive mobile robot.

$$\begin{cases} v_L = \omega_L R \\ v_R = \omega_R R \end{cases} \tag{1}$$

$$\begin{cases} v = (v_L + v_R)/2 \\ \omega = (v_R - v_L)/D \end{cases} \tag{2}$$

The nonholonomic constraint equation of the robot is as following:

$$\dot{x}\sin\theta - \dot{y}\cos\theta = 0 \tag{3}$$

Deriving (4) from (1) and (2):

$$\begin{cases} v = \dfrac{\omega_R + \omega_L}{2} R \\ \omega = \dfrac{\omega_R - \omega_L}{D} R \end{cases} \tag{4}$$

Moreover, we can define the dynamic function of the robot as formula (5).

$$\dot{x} = v\cos\theta, \quad \dot{y} = v\sin\theta, \quad \dot{\theta} = \omega \tag{5}$$

Combining (4) and (5), we can obtain

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{R}{2}\cos\theta & \frac{R}{2}\cos\theta \\ \frac{R}{2}\sin\theta & \frac{R}{2}\sin\theta \\ -\frac{R}{D} & \frac{R}{D} \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} \tag{6}$$

All variables are interrelated in equation (6), which causes the controller design to be more complex. Therefore, equation (6) should be decoupled. For θ is only related to ω, x and y are only related to v. So, the kinematics model of the robot is as following:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} = Jq \tag{7}$$

Therefore, in order to obtain the real-time position of the robot, we can control the control law as $U = [v, \omega]^T$.

The issue of mobile robot trajectory tracking can generally be transformed into following one reference car. To assume the robot current position to be $p = (x, y, \theta)^T$, and the speed to be $q = (v, \omega)^T$, the reference car position is $p_r = (x_r, y_r, \theta_r)^T$, and the speed to be $q_r = (v_r, \omega_r)^T$, as shown in Fig. 2 [22].

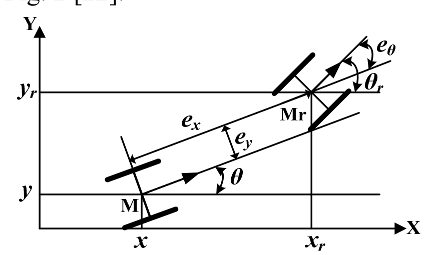

Fig. 2. The position error of mobile robot under Cartesian coordinate.

To order $e = (e_x, e_y, e_\theta)^T = (x_r - x, y_r - y, \theta_r - \theta)^T$, and the mobile robot position error equation (8) is obtained from the geometric relationship shown in Fig. 2.

$$e = \begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} (p_r - p)$$

$$= \begin{bmatrix} (x_r - x)\cos\theta + (x_r - x)\sin\theta \\ -(y_r - y)\sin\theta + (y_r - y)\cos\theta \\ \theta_r - \theta \end{bmatrix} \tag{8}$$

Then the position error differential equation is as following:

$$ec = \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \\ \dot{e}_\theta \end{bmatrix} = \begin{bmatrix} e_y\omega - v + v_r\cos e_\theta \\ -e_x\omega + v_r\sin e_\theta \\ \omega_r - \omega \end{bmatrix} \tag{9}$$

Trajectory tracking of mobile robot based on kinematics model is to search the bounded input as $q = (v, \omega)^T$, that causes $e = (e_x, e_y, e_\theta)^T$ to be bounded, and $\lim_{t\to\infty}\left\|(e_x, e_y, e_\theta)^T\right\| = 0$, with arbitrary initial error and the equation (9) controlled by the control law.

III. Basic Fuzzy Controller for Mobile Robot Trajectory Tracking

Commonly, fuzzy control theory is used in control system or process control, which is difficult to model, nonlinear and complex. The basic fuzzy control consists of conventional fuzzy controller and the controlled object, which are composed of single-loop feedback control system.

A. Basic Fuzzy Controller

To take the position deviation vectors *e* and its rate of change *ec* as the input parameters of the fuzzy controller, to take the controlled variable $u = (v, \omega)^T$ as the output parameter of the fuzzy controller, to design three two-dimensional fuzzy controllers with the same structure, respectively. The design of conventional fuzzy controller is shown in Fig. 3.

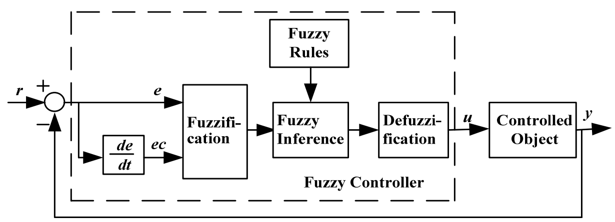

Fig. 3. The structure of basic fuzzy controller.

To take the fuzzy sets of e, ec and u as {*NB*, *NM*, *NS*, *Z*, *PS*, *PM*, *PB*} , where *B* is Big; *N* is Negative; *M* is Middle; *S* is Small; *Z* is Zero; *P* is Positive, and according to the fuzzy numbers are E, EC and U, and their domains are [-6, 6]. To take the typical triangle function as the membership functions, and the fuzzy control rules are adopted as following:

$$L_m: \text{IF } e \text{ is } E_i \text{ AND } ec \text{ is } EC_j \text{ THEN } u \text{ is } U_k$$

where, m is the number of fuzzy control rules, and $i = j = k = 1, 2, \cdots, 7$.

Then to realize the fuzzy control rules to eliminate or reduce the output error of the controlled object is shown in Table I.

TABLE I
FUZZY CONTROL RULES

U \ E / EC	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	NS
NS	PB	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NM	NM	NB
PM	PS	Z	NS	NM	NB	NB	NB
PB	Z	NS	NM	NB	NB	NB	NB

The output that obtained by the fuzzy inference combination rules is fuzzy variable, while the controlled object can only receive accurate variable, so the fuzzy output must be defuzzified. There are many defuzzification, such as Center of Gravity defuzzification, Center-Average defuzzification, maximum defuzzification. In this paper, the Center of Gravity defuzzification is used.

B. Fuzzy-Integral Hybrid Controller

From Fig. 3, it can be seen that the basic two-dimensional fuzzy controller takes the error and its rate of change as its input variables, and only has the fuzzy proportion-differentional control, and lacks the fuzzy integral control. So the system steady is poor. To introduce the integral control to the fuzzy controller to form a fuzzy-integral mixed controller [23, 24], as shown in Fig. 4. The integral control in the mixed controller can improve the steady-state performance of fuzzy controller.

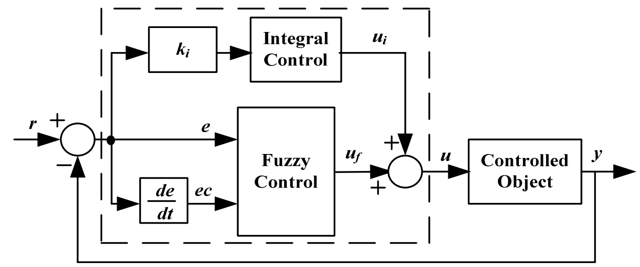

Fig. 4. The structure of fuzzy-integral mixed control system.

After the structure of fuzzy controller has been defined, namely, fuzzification, fuzzy inference and defuzzification have been defined; there are two factors to affect the response characteristics of control systems: the dynamic characteristic of the open-loop control object and the value of the fuzzy controller factors as k_e、k_{ec} and k_u.

IV. Adaptive Fuzzy Controller Design

Generally, the structure and parameters of fuzzy-integral mixed controller are mainly selected the through the experience of operators or experts. For the controller has many parameters, and the experience of experts can only play a guiding role, and it is difficult to accurately determine the parameters, so it can only repeatedly try to determine the parameters with a certain degree of blindness. The process of selection parameters is essentially a process of parameters optimization. It is more effective to define the structure and parameters of the controller by using optimization algorithm to optimize parameters. In this paper, we use the improve VFSA algorithm to optimize the fuzzy-integral mixed controller.

A. The Improvement VFSA Algorithm

SA algorithm, a valid method in local search, accepts generated candidates probabilistically based on Boltzmann selection mechanism and accepts inferior candidates sometime. Although SA algorithm can move off the local minimum, it spends more time for searching global optimal solution.

SA algorithm comes from annealing in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one. By analogy with this physical process, each step of the SA algorithm replaces the current solution by a random "nearby" solution, chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature), that is gradually decreased during the process. The dependency is such that the current solution changes almost randomly when T is large, but increasingly "downhill" as T goes to zero. The allowance for "uphill" moves saves the method from becoming stuck at local minimum—which are the bane of greedier methods.

SA is an asymptotic convergence algorithm, but the speed of convergence is slowly, and it difficultly meets the real-time performance. Therefore, in order to improve its computing efficiency and convergence rate, a lot of improved SA algorithms [20, 21, 25, 26] have appeared. The improvement algorithms are mainly to improve some certain functions of the SA algorithm, such as using the disturbance model based on Cauchy distribution or approximating Cauchy distribution in stead of gauss distribution that depends on the temperature, Basu used experimental method to determine the critical temperature and the initial temperature was slightly above the critical one, Press proposed a synthesis algorithm with the simplex algorithm and SA algorithm, etc..

For SA algorithm, to solve the cost function $f(x)$ is token as the internal energy in the status x of the system, and control parameter T as temperature; to cause T to slowly drop from enough high temperature. For each T, the current status x generates a new status x' with random disturbance. To calculate the increment $\Delta f = f(x') - f(x)$, if $\Delta f < 0$, to take the x' as the new current status; if $\Delta f > 0$, to accept the x' as the new current status with probability $\exp(-\Delta f / kT)$. So repeatedly carrying on until the solution meets the stop conditions.

The distinction between VFSA [21, 27] based on Cauchy mechanism and SA is as following:

(1) To take the equation (10) as cooling schedule

$$T(t) = T_0 / (1 + t) \tag{10}$$

where, T_0 is initial temperature, and t is time.

(2) To take approximating Cauchy distribution as the disturbance model, the equations are as following

$$m_i' = m_i + y_i (B_i - A_i) \tag{11}$$

$$y_i = T(t)\,\mathrm{sgn}(\mu - 0.5)\{[1 + \frac{1}{T(t)}]^{|2\mu - 1|} - 1\} \tag{12}$$

where, m_i is i^{th} parameter of current model; μ is a random number of uniform distribution, and $\mu \in [0,1]$; $[A_i, B_i]$ is the range of m_i; m_i' is i^{th} parameter after the current model disturbed, and $m_i' \in [A_i, B_i]$.

The flow of VFSA algorithm is just as that of SA algorithm. In order to guarantee the convergence within a limited time, the disturbance model, acceptance probability, and cooling schedule of VFSA algorithm are improved based on SA algorithm. However, many studies [21, 27, 28] indicate that the efficiency is somewhat low in the actual application.

In view of the cooling schedule and the model disturbance mechanism, VFSA algorithm is divided into two procedures [21]: the first procedure is to take the high initial temperature as the cooling schedule of VFSA algorithm, and randomly disturb the disturbance model in global solution scope, and the purpose is to search and lock the optimal solution interval; the second one is to take lower temperature as a new cooling schedule, and to randomly disturb the disturbance model in local solution scope, and the purpose is to narrow the optimal solution interval and enhance the model acceptance probability. The temperature of the new cooling schedule is appropriate tempering warming, so that it can cause the current model to move off the local minimum interval, and the final solution is more reliable. The improvements of annealing temperature and disturbance model are closely.

B. Optimizing Fuzzy Controller Parameters

To take the typical triangle functions as membership function, as shown in Fig. 5. In order to reduce the scale of parameters, order $k = l_1/l_2 = l_2/l_3 = l_3/l_4 = l_4/l_5 = l_5/l_6$, where k is adjustment coefficient. To adjust the value of k, can obtain different forms of membership function, and that finally affects the sensitivity and stability of fuzzy controller.

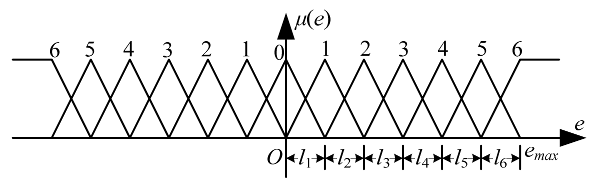

Fig. 5. The curve of triangle membership function.

To take the position deviation vector $e = (e_x, e_y, e_\theta)^T$ and its rate of change $ec = (\dot{e}_x, \dot{e}_y, \dot{e}_\theta)^T$ as the input parameters of the fuzzy controller, to take the controlled variable $u_f = (u_x, u_y, u_\theta)^T$ as the output parameter of the fuzzy controller, and k_i is the parameter of integral controller, to design three two-dimensional fuzzy controllers with the same structure, respectively. Then the parameters of the adjustments coefficients according to e, ec, u_f are optimized, and so to the parameter of integral controller k_i. Order k_{ex}, k_{ecx}, k_{ux} are the adjustment coefficients of membership functions according to e_x, $\dot{e}_x$, u_x, respectively;

Order k_{ey}, k_{ecy}, k_{uy} are the adjustment coefficients of membership functions according to e_y, $\dot{e}_y$, u_y, respectively; Order $k_{e\theta}$, $k_{ec\theta}$, $k_{u\theta}$ are the adjustment coefficients of membership functions according to e_u, $\dot{e}_u$, u_u, respectively. And the parameter set is as following:

$$X = (x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12})^T$$
$$= (k_{ex}, k_{ecx}, k_{ux}, k_{ix}, k_{ey}, k_{ecy}, k_{uy}, k_{iy}, k_{e\theta}, k_{ec\theta}, k_{u\theta}, k_{i\theta})^T \quad (13)$$

In order to optimize the parameter set *X*, we take the integral performance *ITAE* as the energy function of the improved VFSA algorithm [23], namely

$$J(ITAE) = \int_0^\infty t|e(t)|dt = \min \quad (14)$$

where, *J*(·) is the size of area integral of the error function with time weighed, *I* is integral, *T* is time, *A* is absolute value, *E* is error.

Equation (15) can comprehensively evaluate the dynamic and static performance of the control system, such as fast response, short adjustment time, very small overshoot, and very small steady state error. In order to convenience computer implementation, equation (15) must be converted into discrete forms, namely

$$\Delta J = J(t+\Delta T) - J(t)$$
$$= \int_0^{t+\Delta T} \tau|E|d\tau - \int_0^t \tau|E|d\tau \quad (15)$$
$$= \int_t^{t+\Delta T} \tau|E|d\tau$$

where, ΔT is sampling interval. Usually, for ΔT is very small, the integrand $\tau|E|$ can be regarded as constant, and set the value as $t|E|$, then equation can be converted into equation (17).

$$\Delta J(ITAE) = t|E|\Delta T \quad (16)$$

According to the performance of equation (17), to take it as the energy function of the improvement VFSA, and parameter optimization process is a principle which the value of energy function reduces gradually. To continually optimize the parameters can obtain a set of optimal parameters.

V. Computer Simulation Results

In order to test the method of this paper, the controller is simulated with the circular track and the line track as conference trajectories, respectively.

The first simulation: the conference track is as $x_r^2 + y_r^2 = 1$, the conference velocity is as $v_r = 0.2$, and the conference angular velocity is as $\omega_r = 0.2$. While the initial velocity of the mobile robot is as $v_c = 0.4$, and the initial angular velocity of the mobile robot is as $\omega_c = 0.3$, the initial position error is as $P_e = (1.2, -0.3, 2\pi/3)^T$. The simulation results are shown in Fig. 6.

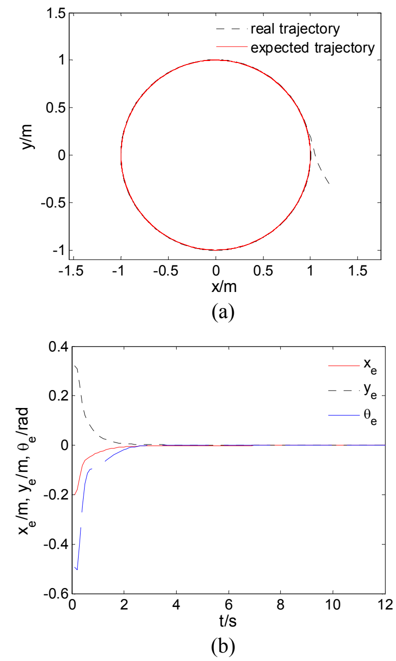

Fig. 6. (a) The result of tracking circular route;(b) Tracking error cure.

The second simulation: the conference track is as $y_r = \sqrt{3}x_r - \sqrt{3}$; the conference velocity is as $v_r = 0.2$, and the conference angular velocity is as $\omega_r = 0$. While the initial velocity of the mobile robot is as $v_c = 0.4$, and the initial angular velocity of the mobile robot is as $\omega_c = 0.3$, the initial position error is as $P_e = (1.2, -2, \pi/2)^T$. The simulation results are shown in Fig. 7.

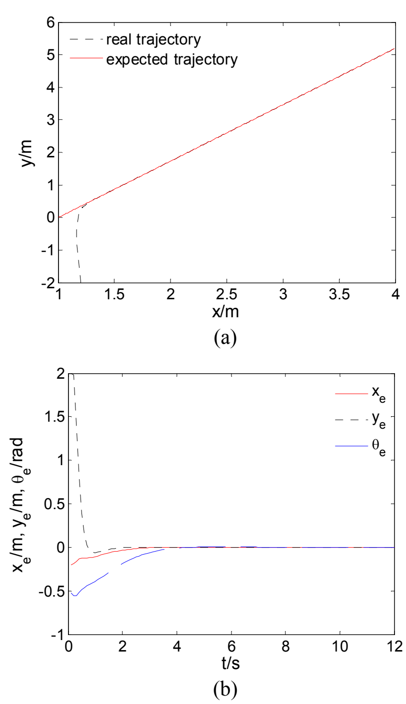

Fig. 7. (a) The result of tracking line route;(b) Tracking error cure.

VI. Conclusion

The kinematics model of two-wheeled differential drive mobile robot is presented in this paper, and the trajectory tracking is also introduced; to research the fuzzy control for trajectory tracking, and to use the improvement VFSA algorithm to optimize the parameters of fuzzy-integral hybrid controller. The simulation results show that the method is feasible, and can quickly approach to the conference trajectory in a short time, and the trajectory deviation is very small.

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