RESEARCH ON THE FORMATION METHOD OF OMNIDIRECTIONAL MOBILE ROBOT BASED ON DYNAMIC SLIDING MODE CONTROL

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ABSTRACT*: The omnidirectional mobile robot formation system provides a unique way of thinking for some practical problems. In the system, each robot can accomplish the task of formation and cooperation in many applications through its own sensors and wireless communication devices. In this paper, the author analzye the formation method of omnidirectional mobile robot based on dynamic sliding mode control. In this paper, the principal and subordinate structure method is used to design the formation control system of multiple robots.The formation's navigation is completed by the leader, and the follower controller adjusts and controls the output signal to achieve the desired formation with the leader according to its formation error with the leader.The result shows that the control of the proposed method can make the sine like curve formation motion consistent with the desired trajectory, and the tracking curve is smooth, which proves the stability of formation control method proposed in this paper. However, because of the great influence of friction and communication delay, the other two methods lead to disturbance and tracking error in the process of robot motion.*

KEYWORDS*: Dynamic sliding mode control; omnidirectional movement; robot; formation; obstacle avoidance*

1 INTRODUCTION

The omnidirectional mobile robot formation system provides a unique way of thinking for some practical problems. In the system, each robot can accomplish the task of formation and cooperation in many applications through its own sensors and wireless communication devices(Shidpour, 2016). For example, in the environment of exploration, factory assembly line, logistics warehousing and other occasions, the formation and cooperation of omnidirectional mobile robot, can not only complete the task that the single robot cannot complete, but also can improve the flexibility and reliability of task implementation, reduce the cost of task (Wang, 2014; Huang, 2015).

At present, the formation methods of multiple mobile robots are mainly based on the behavior method, artificial potential field method, Leader-Follower control method, fuzzy control method, graph theory and so on (Ren,2015). The behavior method is based on the design of the basic behavior and local control rules of robot, so that the whole behavior of robot group can be generated. This method cannot guarantee the stability of formation. Artificial potential field is used to design the artificial virtual potential field and potential field function to represent the constraint relationship between each robot and the environment (Vinodh & Kamala, 2015). The method is simple and convenient for real-time control, but there is a local extreme point problem. The Leader-Follower control method is to specify a robot as Leader and the other as a Follower in multiple robots, as long as the trajectory of Leader is given, it can control the multiple robots system (Liao,2017). However, the whole control system does not feedback clear formation, if the Leader is invalid, the formation control cannot be achieved; In fuzzy control method, the linear velocity and angular velocity of each robot are real-time adjusted by the output of fuzzy controller to make path tracking control of the Leader, so that multiple robots can converge to the desired formation; In graph theory, the control charts are used to describe the shape of robot formation, which is much used for theoretical simulation research, and the computation is large, especially for mobile robots with limited computing resources (Cui,2016).

To a certain extent, the above methods can achieve the formation control of the omnidirectional mobile robot, and improve the efficiency of formation control, but it is not perfect in the aspects of stability control and theoretical analysis. To this end, a new formation method of omnidirectional mobile robot based on dynamic sliding mode control is proposed.

2 FORMATION METHOD OF OMNIDIRECTIONAL MOBILE ROBOT BASED ON DYNAMIC SLIDING MODE CONTROL

2.1 Omnidirectional mobile robot and its motion model

Omnidirectional mobile robot uses an omnidirectional vision system as a sensor to get relative position information of the surrounding robots and obstacles, and orientate in a specific environment. In terms of motion mode, the robot is installed four self-developed Nubot omnidirectional wheels at a certain angle to form an omnidirectional motion mechanism, enabling the robot to achieve any direction movement and rotation motion in the plane.

The working face of a robot is a plane. The world coordinate system $X_dO_dY_d$ and the local coordinate system $X_lO_lY_l$ which is connected to the car body and the center point can be established. (x_l, y_l, γ_l) and (x_d, y_d, γ_d) are the position and posture of the robot in two coordinate systems, and $V = [\vartheta_1\vartheta_2\vartheta_3\vartheta_4]^T$ is the linear velocity matrix of 4 driving wheels. D is the distance of wheel center between the omnidirectional rotation to the center of geometry, and $\gamma = \gamma_d = \gamma_l$ is the azimuth angle of the robot rotation. I is the velocity matrix of the center point O_l.

The translation and rotation matrices of the coordinate system are as follows:

$$G_T = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} x_l \\ y_l \\ \gamma_l \end{bmatrix} = G_T \begin{bmatrix} x_d \\ y_d \\ \gamma_d \end{bmatrix} \quad (2)$$

The kinematics model equation of the robot is as follows:

$$V = AI \quad (3)$$

$$I = \begin{bmatrix} \vartheta\cos\gamma \\ \vartheta\sin\gamma \\ \gamma \end{bmatrix} = \begin{bmatrix} \vartheta_x \\ \vartheta_y \\ \omega \end{bmatrix} \quad (4)$$

$$A = \begin{bmatrix} -\sin\gamma & \cos\gamma & d \\ -\cos\gamma & -\sin\gamma & d \\ \sin\gamma & -\cos\gamma & d \\ \cos\gamma & \sin\gamma & d \end{bmatrix} \quad (5)$$

Where, d is the following distance in the formation.

2.2 Obstacle avoidance planning

Assuming that the location of the obstacle is (x_{zi}, x_{zi}), the distance function between the robot R_i and the obstacle can be defined as:

$$D_i = \sqrt{\left(\frac{x_i - x_{zi}}{\phi_i}\right)^2 + \left(\frac{y_i - y_{zi}}{\varphi_i}\right)^2} \quad (6)$$

In the formula, $\phi_i > 0$, $\varphi_i > 0$. In order to simplify the calculation, $\phi_i = \varphi_i = 1$ is defined, and the custom obstacle avoidance function is expressed as:

$$f(x_i, y_i) = \left(\min\left\{0, \frac{D_i^2 - r_b^2}{D_i^2 - r_c^2}\right\}\right)^2 \quad (7)$$

In the formula, $r_b > 0$, $r_c > 0$, and $r_b > r_c$, r_b is the detection radius of the robot, r_c is its collision avoidance radius. The obstacle avoidance function has an infinite value in the detection area, and the outer value of the detection area is zero (Li,2017). The obstacle areas with different shapes can be defined by setting the parameter values ϕ_i and φ_i. The partial derivative of obstacle avoidance function $f(x_i, y_i)$ is solved as:

$$\frac{\partial f}{\partial y_i} = \begin{cases} 0, & D_i \geq r_b \\ \dfrac{4\left(r_b^2 - r_c^2\right)\left(D_i^2 - r_b^2\right)}{\left(D_i^2 - r_c^2\right)^3}\left(y_i - y_{zi}\right), & r_c < D_i < r_b \\ 0, & D_i < r_c \end{cases} \quad (8)$$

If the reference trajectory of the robot R_i is (x_{wi}, y_{wi}) and it satisfies that its derivative is boundedness, then the error between the actual position and the reference position is $E_{xi} = x_i - x_{wi}$, $E_{yi} = y_i - y_{wi}$.

The definitions are as follows:

$$\begin{cases} E'_{xi} = E_{xi} + \dfrac{\partial f}{\partial x_i} \\ E'_{yi} = E_{yi} + \dfrac{\partial f}{\partial y_i} \end{cases} \quad (9)$$

When $(E'_{xi}, E'_{yi}) \neq (0, 0)$, the expectation angle β_{wi} can be expressed as:

$$\beta_{wi} = \arctan\left[-E'_{yi} \big/ \left(-E'_{xi}\right)\right] \quad (10)$$

The formula (11) shows that β_{wi} is determined by the reference trajectory, the actual position of the omnidirectional mobile robot and the position of the obstacle, and the corresponding angle error is $E_{\beta i} = \beta_i - \beta_{wi}$.

In order to avoid the strange situation, the following hypotheses are made:

Hypothesis 1: The reference trajectory is smooth and satisfied:

$$\left|E_{\beta i}\right| \neq \frac{\pi}{2} \quad (11)$$

Hypothesis 2: it is kept constant in the range of detection regions, that is, $\overset{*}{x}_{wi} = \overset{*}{y}_{wi} = 0$ ($r_c \leq D_i < r_b$). This means that if the omnidirectional mobile robot meets the obstacles in the process of tracking reference trajectory, it will immediately freeze the received reference trajectory data and give priority to dealing with the obstacle avoidance problem (Raj,2017). When the obstacle avoidance is finished, the reference trajectory data is re-received.

Hypothesis 3: β^*_{wi} is an estimation which is smooth enough, and can be expressed as:

$$\beta^*_{wi} = \frac{E'_{xi}(t)E^*_{yi} - E'_{yi}(t)E^*_{xi}}{L_i^2} \quad (12)$$

$$\begin{cases} E^{*}_{xi} = \dfrac{E'_{xi}(t+T) - E'_{xi}(t)}{T} \\ E^{*}_{yi} = \dfrac{E'_{yi}(t+T) - E'_{yi}(t)}{T} \\ L_i = \sqrt{\left(E'_{xi}\right)^2 + \left(E'_{yi}\right)^2} \end{cases} \quad (13)$$

The value of T is smaller and $T > 0$. It can be obtained based on the above formula:

$$\left|\beta^{*}_{wi} - \beta'_{wi}\right| \le \xi_i \quad (14)$$

E'_{xi}, E'_{yi}, and L_i can be calculated by the reference trajectory of the robot and the position and posture of the actual state, and the ξ_i is infinitesimal, $\xi_i \ge 0$.

2.3 Kinematic error model of robot formation

In this paper, the principal and subordinate structure method is used to design the formation control system of multiple robots. The basic idea of this method is to select one or more robots in the formation as Leader and the rest robots as Follower (Zhang,2016). According to the task requirement, the formation parameters $[d_s, \psi_s]$ is determined, where, d_s and ψ_s are the expected relative distance and expected relative direction angle between Leader and Follower respectively. The formation's navigation is completed by the Leader, and the Follower controller adjusts and controls the output signal to achieve the desired formation with the Leader according to its formation error with the Leader.

The expected relative distance d_s of the formation is projected to the coordinate system x-y of the Leader robot’s team, which can be expressed as d_{xs} and d_{ys} respectively, and the expected relative direction angle of the formation is satisfied.

$$\begin{cases} d_{xs} = d_s \cos\psi_s \\ d_{xs} = d_s \sin\psi_s \end{cases} \quad (15)$$

Assuming that the current relative position of the formation is d_{qk}, it can be projected to d_x and d_y in the local coordinate system x-y of the Leader robot. The direction angle of omnidirectional mobile robot is determined according to the principle of that counterclockwise is positive (Ren,2016), then the analysis of the geometric relationship between the relative positions of the two robots can be determined.

$$\begin{cases} d_x = -\left(x_q - x_k - l_c\cos\alpha_k\right)\cos\alpha_i - \left(y_i - y_k - l_c\cos\alpha_k\right)\sin\alpha_q \\ d_y = \left(x_q - x_k - l_c\cos\alpha_k\right)\sin\alpha_q - \left(y_q - y_k - l_c\cos\alpha_q\right)\cos\alpha_q \end{cases} \quad (16)$$

In formula (16), l_c is the distance between the axis center of the driving wheel of the Follower robot and the reference point.

The formation error state variables are defined as:

$$\begin{cases} e_x = d_{xs} - d_x \\ e_y = d_{ys} - d_y \end{cases} \quad (17)$$

Dynamic model of formation error can be acquired by differential calculation:

$$\begin{cases} \overset{r}{e}_x = \omega_q e_y - v_k\cos\alpha_{qk} - l_c\omega_k\sin\alpha_{qk} + v_i - d_s\omega_q\sin\omega_s \\ \overset{r}{e}_y = -\omega_q e_x - v_k\sin\alpha_{qk} - l_c\omega_k\cos\alpha_{qk} + v_i - d_s\omega_q\cos\omega_s \end{cases} \quad (18)$$

In which $\alpha_{qk} = \alpha_k - \alpha_q$, $e = \begin{bmatrix} e_x & e_y \end{bmatrix}^{T}$, then the formula (18) can be rewritten as:

$$e' = Qe + Z\mu + \Psi \quad (19)$$

Where, $Q = \begin{bmatrix} 0 & \omega_q \\ -\omega_q & 0 \end{bmatrix}$,

$Z = \begin{bmatrix} -\cos\alpha_{qk} & l_c \sin\alpha_{qk} \\ -\sin\alpha_{qk} & -l_c \cos\alpha_{qk} \end{bmatrix}$,

$\Psi = \begin{bmatrix} v_q - d_s\omega_q \sin\psi_s \\ d_s\omega_q \cos\psi_s \end{bmatrix}$, $\mu = \begin{bmatrix} v_k \\ \omega_k \end{bmatrix}$.

In the case of uncertain factors, the dynamic model of formation error can be expressed as:

$$e^{'} = Qe + Z\mu + \Psi + \Phi \quad (20)$$

Where, $\Phi = [\Phi_1, \Phi_2]^T$ is the uncertainty of system, caused by the disturbance of the system or the measurement error of the sensor.

2.4 Design of adaptive dynamic sliding mode controller

If the dynamic process is known accurately, then the equivalent control law τ_{eq} can make the system stable on the sliding surface (Lin,2017). However, if there is uncertainty in the actual work, in order to meet the sliding condition, the discontinuous control law τ_{sw} is introduce to enhance the robustness of the system. The final control law is composed of the equivalent control law τ_{eq} and the switching control law τ_{sw} (Azizi,2014).

In order to eliminate the jitter, RBFNN (Asif,2014) is introduced to adjust the gain σ of the sliding mode control, and the sliding surface is defined as the input of the radial basis neural network. Input $x_i = u_i, i = 1,2$, the output of RBF neural network is:

$$\sigma_i = c_{i1}b_{i1} + c_{i2}b_{i2} + \cdots + c_{in}b_{in} = C_i^T B_i \quad (21)$$

In the formula, $C_i = [c_{i1} \quad c_{i2} \quad \cdots \quad c_{in}]^T$ is the weight vector of the neural network; $B_i = [B_{i1} \quad B_{i2} \quad \cdots \quad B_{in}]^T$ is the radial basis vector function; b_{ij} is the Gauss function.

$$b_{ij} = \exp\left(\frac{\|x_i - a_{ij}\|}{2\lambda_{ij}^2}\right) \quad (22)$$

In the formula, a_{ij} and λ_{ij} are the central position and the expansion constant respectively. a_{ij}, λ_{ij} is a constant greater than zero. For the gain of switching control, it is hoped that the parameters selected by the controller are optimal in design. However, because omnidirectional mobile robots have uncertain parameters and unpredictable perturbations, accurate parameters cannot be obtained.

The adaptive gain of dynamic sliding mode control can be obtained from the output of RBFNN:

$$\vec{\sigma}_i = \vec{C}_i^T B_i \quad (23)$$

In the formula, $\vec{C}_i = [\vec{c}_{i1} \quad \vec{c}_{i2} \quad \cdots \quad \vec{c}_{in}]^T$ is the estimated weight vector of the neural network. The neural network weight adaptive law is as follows:

$$\vec{C}_i = \varsigma_i B_i \cdot |u_i| \quad (24)$$

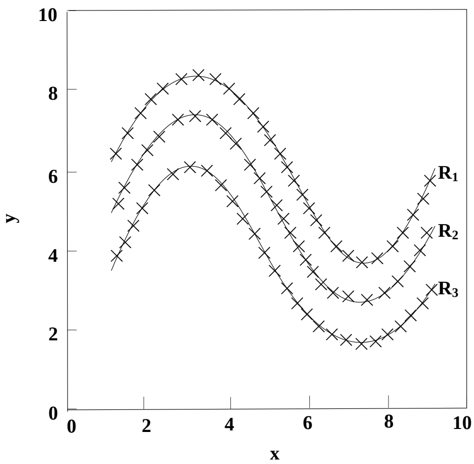
Where, $\varsigma_i > 0$ is an adaptive parameter. Therefore, the control of adaptive gain radial basis neural network (RBF) on PI dynamic sliding mode dynamic controller is designed as follows:

$$\tau = \tau_{eq} + \tau_{sw} = \overline{M}^{-1}\left[v_k + \omega_k + \kappa e^{'}(t) + \vec{\sigma}\,\mathrm{sgn}(U)\right] \quad (25)$$

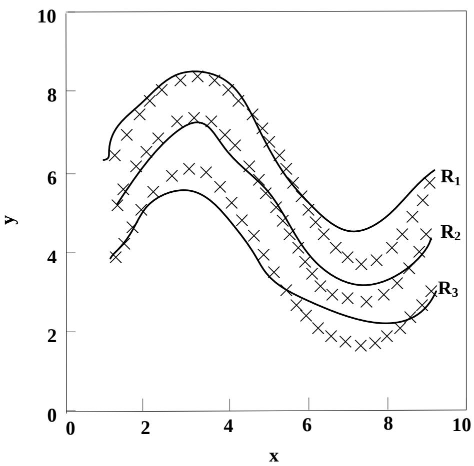
In this section, the neural network gain is used to adjust the sliding mode dynamic controller and the parameter control law. The result of the formation control of the omnidirectional mobile robot is asymptotically stable.

3 EXPERIMENT AND ANALYSIS

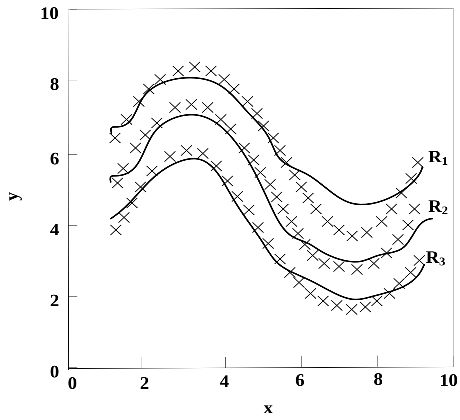
In order to verify the validity of the proposed method, the artificial potential field method and the graph theory are used as the contrast to make the formation movement of omnidirectional mobile robot along the sinusoidal curve. Figure 1 is the real-time formation trajectory of the omnidirectional mobile robot by using the three control methods obtained in the UWB positioning system. The "×" represents the desired formation trajectory of the robot, and the real line is the actual formation trajectory curve of the three omnidirectional mobile robots.



(a) The proposed method



(b) Artificial potential field method



(c) Graph theory

Fig.1. The real-time formation trajectory of an omnidirectional mobile robot under the control of three methods

From the formation trajectory in Figure 1, we can see that in this experiment, the control of the proposed method can make the sine like curve formation motion consistent with the desired trajectory, and the tracking curve is smooth, which proves the stability of formation control method proposed in this paper. However, because of the great influence of friction and communication delay, the other two methods lead to disturbance and tracking error in the process of robot motion. The sine tracking curve is not very smooth, and it is different from the desired formation trajectory.

4 CONCLUSIONS

In this paper, a new omnidirectional mobile robot formation method based on dynamic sliding mode control is proposed, to establish a motion model of omnidirectional mobile robot. Obstacle avoidance planning is implemented by defining obstacle avoidance function, and the kinematic error model of robot formation is constructed. An adaptive dynamic sliding mode controller is designed to realize the omnidirectional mobile robot formation. The experimental results show that the proposed method has high stability.

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