Research on AGV trajectory tracking control based on double closed-loop and PID control

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Abstract. Aimed at AGV motion model of two-wheeled differential drive control mode, AGV motion control is divided into double closed-loop trajectory tracking control based on Lyapunov direct method and sliding-mode control technology and speed control based on PID method through hierarchical control thought. Double closed-loop control technology researches trajectory tracking control problem of AGV under Cartesian coordinate system; PID control method researches real-time speed control problem of drive motor of AGV. Finally, circular trajectory tracking simulation test is made to AGV under Matlab/Simulink environment. Simulation result shows that system has correct positioning with fast dynamic response and good robustness, and verifies feasibility and effectiveness of scheme proposed.

1. Introduction

Automated Guided Vehicle (AGV) can be driven according to path determined in advance, and is quite popular in material transportation field because of its flexible path planning and tracking capability. In recent years, motion control and coordination cooperation problem of AGV have been increasingly concerned by people. In production practice, a control law shall be searched to make AGV reach to an expected point in motion space rapidly and steadily or trace a curve in motion space, which contains 3 kinds of basic problem, i.e. point stabilization, path following and trajectory tracking [1-3]. AGV does not meet smooth stabilization condition of Brockett due to its non-holonomic characteristic, which makes trajectory tracking control problem of AGV challenging. At present, a good deal of control methods are used to solve trajectory tracking problem of AGV, such as: Backstepping method, self-adaptation method, sliding-mode method, fuzzy control, neural network and other algorithms etc [4]. Researches mainly focus on kinematic model, and it is assumed that “perfect speed tracking” can be made, but “perfect speed tracking” cannot be realized in practical application because of AGV parameter variation caused by uncertain factors, such as friction, load change and external disturbance etc.

Based on motion model of AGV, this paper divides motion control of AGV into two layers through hierarchical control thought: the upper layer is a kind of double closed-loop control structure, realizing control to external ring pose and inner ring force through two feedbacks. External ring is pose controller constructed based on Lyapunov direct method while inner ring is driving force controller based on sliding-mode control technology. Upper layer provides speed to 2 drive motors of AGV; bottom layer is PID speed setting controller, responsible for quick response of drive motor to given speed. Circular trajectory simulation tracking test is made to AGV under Matlab/Simulink, and...
simulation result shows that AGV has accurate positioning characteristic, rapid tracking characteristic and robustness and verifies feasibility and effectiveness of method proposed.

2. Motion control system of AGV

2.1. Double closed-loop control structure
To realize coordination control of pose and force of AGV, this paper proposes a kind of double closed-loop control structure, and control strategy realizes control to external ring pose and inner ring force through two feedbacks and double closed-loop control structure is as shown in figure 1.

According to figure 1, external ring is pose controller based on Lyapunov direct method, while inner ring is driving force controller based on sliding-mode control technology. There is mutual effect between external ring and inner ring. Virtual speed vector output by external ring pose controller is expected value of inner ring. Therefore, virtual speed vector establishes relationship between system kinematics and dynamics directly. In addition, driving torque generated by inner ring driving force controller is actual input of AGV.

2.2. Motion control structure of AGV
Considering motor-driven dynamic characteristics of AGV, to make AGV finish point stabilization and trajectory tracking control objective, this paper adopts hierarchical control thought, and structure of motion control system is as shown in figure 2.

![Figure 1. Double closed-loop control structure.](image1)

![Figure 2. Structure of motion control system of AGV.](image2)
According to figure 2, target pose $q^* = [x^*, y^*, \theta^*]^T$ of AGV is input quantity, and current pose $q = [x, y, \theta]^T$ is output quantity. Upper layer trajectory tracking controller obtains system speed $V = [v, \omega]^T$ according to system pose error $\Delta q = [x^* - x, y^* - y, \theta^* - \theta]^T$. Considering the fact that relatively large inertia may be caused when AGV traces target point or target trajectory, which will cause horizontal or longitudinal sliding motion of AGV to deviate from target point, therefore, speed limit detection module is introduced in control process, which controls speed of AGV within a controlled scope to obtain control input quantity $V_c$. Through vehicle speed and driving wheel map module, $u_c$ is transformed into speed signal of 2 drive motors in left and right. Through PID speed setting controller at bottom layer, quick response of drive motor to given speed is possible. Finally, current pose of AGV can be calculated according to speed value returned by 2 drive motors to finish motion control task.

2.3. PID speed setting controller

PID controller can adjust controlled quantity through deviation between given value and actual value, so that output value can trace given value rapidly. Taking left-wheel drive motor as example, AGV drive motor model is as shown in figure 3.

![Figure 3. Figure on drive motor model.](image)

Simplify motor model to obtain $H_1(s) = \frac{K_1}{1 + T_1s}$, of which $K_1$ is motor gain, and $T_1$ is motor time constant. In practical application, photoelectric encoder is used to collect motor speed, and linear speed is adopted for control, which is beneficial to analysis comparison with actual demand. Adopt traditional PID controller: $G_1(s) = K_p(1 + \frac{1}{T_1s} + T_2s) = K_p + \frac{K_i}{s} + K_ds$, select controller parameter: $K_p = 9, K_i = 5, K_d = 2$. Effect of given speed control output tracking by PID speed setting controller is as shown in figure 4. Controller can control drive motor rapidly to make it reach to expected speed steadily.

![Figure 4. Dynamic response figure of PID control motor.](image)

3. Motion model of AGV

Research object of this paper is two-wheeled differential driving AGV having non-holonomic constraint. It consists of 1 auxiliary universal wheel and two coaxial drive wheels respectively driven by independent motor, and its simplified motion model is as shown in figure 5.
Motion of AGV is directional, so under 2-dimensional global coordinate system XOY, orientation and spatial position of AGV shall be marked, which is called as pose of AGV collectively. Taking midpoint P of 2 rear-wheel center connections as reference point, then current pose of AGV can be expressed with generalized coordinate vector \( q = [x, y, \theta]^T \) consisting of 3 spatial orientation DOF. \( \theta \) is course angle of AGV, \( v \) is speed at reference point P, i.e. vehicle, and \( 2r \) is diameter of driving wheel, and \( 2R \) is distance between 2 driving wheels. Distance between AGV centroid to point P is defined as \( d \).

For AGV as shown in figure 5, non-holonomic constraint makes motion of AGV restricted in direction vertical to drive axle, which means that pure rolling and no slipping condition must be met, expressed with formula as follows [5]:

\[
\dot{y} \cos \theta - \dot{x} \sin \theta = 0
\]

(1)

Motion state of AGV at a given moment is decided by linear speed \( v \) and angular speed \( \omega \), and denoted as \( V = [v, \omega]^T \). Assumed that AGV moves on horizontal surface, then gravity item \( G(q) = 0 \), and surface friction shall be ignored. Holonomic kinematic equation of AGV is [6-7]:

\[
\dot{q} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_c \\ \omega_c \end{bmatrix}
\]

(2)

\[
\ddot{M}_0(q)\dot{V} + \ddot{C}_0(q, \dot{q})V + \tau_d = \tau
\]

(3)

Where, \( \ddot{M}_0(q) \) is system inertia matrix, \( \ddot{C}_0(q, \dot{q}) \) is Coriolis matrix concerned with position and speed, \( \tau_d = [\tau_{dl}, \tau_{dr}]^T \) is external disturbance affecting left and right driving wheel, and \( \tau = [\tau_l, \tau_r]^T \) is moment imposed to left and right driving wheel. Each matrix is:

\[
\ddot{M}_0 = \begin{bmatrix} m & 0 & md \sin \theta \\ 0 & m & -md \cos \theta \\ md \sin \theta & -md \cos \theta & I \end{bmatrix} \quad \ddot{C}_0(q, \dot{q}) = \begin{bmatrix} 0 & 0 & md \dot{\theta} \cos \theta \\ 0 & 0 & md \dot{\theta} \sin \theta \\ 0 & 0 & 0 \end{bmatrix}
\]

In the formula, \( m \) is mass of AGV, and \( I \) is rotational inertia where AGV passes axis of point P.

Vehicle speed \( v_c \) and \( \omega_c \) are mapped as linear speed \( v^* \) and \( \omega^* \) of left and right drive motors, and mapping relation is:
4. Design to double closed-loop control structure of AGV

4.1. Lyapunov kinematics control design

Trajectory tracking problem means to design a control law actually so that AGV can trace time-varying referenced AGV expected speed $V^* = [v^* \omega^*]^T$ and pose $q^* = [x^* y^* \theta^*]^T$ defined. Pose tracking error $\Delta q$ of AGV is:

$$\Delta q = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x^* - x \\ y^* - y \\ \theta^* - \theta \end{bmatrix}$$

(5)

Differential equation of pose tracking error of AGV is:

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} \omega e_2 - v + v^* \cos e_3 \\ -\omega e_1 + v^* \sin e_3 \\ \omega^* - \omega \end{bmatrix}$$

(6)

Classical kinematics controller is speed controller designed based on Lyapunov direct method:

$$V_c = \begin{bmatrix} v_c \\ \omega_c \end{bmatrix} = \begin{bmatrix} v^* \cos e_3 + k_1 e_1 \\ \omega^* + k_2 v^* e_2 + k_3 v_c \sin e_3 \end{bmatrix}$$

(7)

In the formula, $v_c$ and $\omega_c$ respectively are linear speed and angular speed output by speed tracking controller, $k_i > 0, i = 1, 2, 3$.

4.2. Inner ring integral sliding-mode control design

Design driving force controller by adopting sliding-mode variable structure control technology, which can converge actual speed of Automated Guided Vehicle to control speed output by pose controller rapidly. Assumed that $v_c = [v_c \omega_c]^T$ is control speed output by pose controller, i.e. expected input value of inner ring driving force controller, $v = [v \omega]^T$ represents current speed value measured by sensor loaded on Automated Guided Vehicle, and then speed tracking error vector can be defined as $e_v = v - v_c$.

Because kinetic model of AGV is first-order nonlinear function, PI sliding-mode surface is introduced as follows:

$$s(t) = ce_v + \int_0^t e_v \, dt$$

(8)

Where $c = [c_1 \ c_2]^T$ is positive matrix and $c_1 > 0, c_2 > 0$. It is obvious that selecting proper positive matrix $c$ can make tracking error $e_v \to 0$.

Assumed that external disturbance $\tau_d$ is known, then input vector is defined as:

$$\tau = \overline{M}_o v_c - c\overline{M}_o e_v + \overline{C}_o (q, \dot{q}) v + \tau_d - \overline{M}_o [\delta_1 \tanh(\xi s) + \delta_2 s]$$

(9)
Where $\delta_1$ and $\delta_2$ are positive constants, $\tanh(\xi s)$ is continuous function, and it has better rejection characteristic than sign function, and $\xi > 0$ decides control step size.

5. Simulation result and analysis

In trajectory tracking simulation, trajectory generator generates given path curve, and whether AGV can trace from initial point to given path and whether speed of AGV meets control requirement shall be judged according to tracking effect diagram obtained from simulation to analyze effectiveness of control system designed. In the experiment, assumed that initial pose of circular trajectory is $[x(0), y(0), \theta(0)]^T = [0, 0, \frac{\pi}{2}]^T$, speed is $u = [v, \omega]^T = [0.5, 0.5]^T$, and initial pose of AGV is $q = [x, y, \theta]^T = [-0.5, 0, \frac{\pi}{8}]^T$. Assumed that mechanical structure parameters of AGV are as follows: $m=3$kg, $R=0.25$m, $d=0.1$m, $r=0.3$m, and to meet system control requirement, related control parameters of controller are selected as follows: $k_1 = 2$, $k_2 = 3$, $k_3 = 7$, $\delta_1 = 10$, $\delta_2 = 20$. Simulation results are as shown in figure 6 and figure 7.

According to figure 6 and figure 7, control and transient process in the whole tracking process are relatively smooth, pose error is converged to 0 within 3s, and compared with traditional control method, AGV can trace given circular trajectory rapidly, and simulation result verifies that trajectory tracking control system has rapid tracking characteristic.

6. Conclusions

In this paper, AGV motion control of two-wheeled differential drive control mode is divided into double closed-loop control based on Lyapunov direct method and sliding-mode control technology and speed control based on PID method through hierarchical control thought. Circular trajectory tracking test is made to AGV motion control under Matlab/Simulink environment. Simulation result verifies that AGV can trace given geometric path rapidly and correctly, control method is feasible and effective, and research to other non-holonomic system also has important reference value.

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