Modeling and Simulation Research of Heavy-duty AGV Tracking Control System Based on Magnetic Navigation

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Abstract. This paper studies tracking control problem which is applied on the 16-wheel heavy-duty AGV (Automated Guided Vehicle). Firstly, the trajectory detection scheme is designed based on magnetic navigation sensors. Secondly, the 16-wheel heavy-duty AGV control model is simplified as a two-wheel AGV model according to Ackermann steering principle, and fuzzy trajectory control regulation is established based on car driving experience. Finally, a trajectory control simulation system for circular/straight trajectories is built in MATLAB Simulink to verify the effectiveness on trajectory control.

Keywords: AGV, magnetic navigation, fuzzy control.

1. Introduction
As an important transportation tool in the modern logistics industry, AGV is widely used in various processing industries due to its stable operational performance and considerable labor cost savings. It quickly replaces traditional manual transportation tools recently. Optimizing Relevant technologies of AGV is more and more important in the production industry[1-3].

PID (Proportion-Integral-Derivative) control is generally applied in the traditional AGV tracking control. BoYang Xu and Dongqing Wang proposed a AGV navigation with magnetic nail positioning method based on Kalman Filtering (KF) and PID control[4]. Jian Kang and Jeisung Lee et al. designed a parameter extraction method based on computer vision to realize the navigation of AGV[5]. Gomez et al. Developed an algorithm that uses PID control and RGB cameras to ensure that a single-wheeled AGV follows a predetermined straight trajectory and avoids oscillations in its motion[6].

2. Magnetic Navigation Sensor Settings
The setting of the magnetic sensor should first consider the accuracy and validity of the trajectory detection. The validity of the detection means the magnetic strip should be detected when the AGV trajectory is offset. At the same time, the detection system should be able to detect the distance and angle deviation of the AGV from the trajectory, so as to control the AGV turning radius to determine the steering and speed of each wheel.

The overall dimensions of the vehicle are: 12m in length, 2.3m in width, 1m in height, and tracking accuracy ≤10mm. In this system, magnetic sensors are set along C which crosses the AGV geometric center, as shown in Fig.1. Other magnetic sensors along A and B, respectively, are set on the front and rear of AGV. A and B are 800mm away from the geometric center point C, refer to figure 1.

Along A or B or C, 64 magnetic sensors are set, respectively. Sensing width range is 640mm, and 320mm on each side. The distance and angle deviation between the AGV and the expected trajectory attached with the magnetic stripe can be detected, according to the trajectory set for AGV. For example, the radii of the two circles are 5m and 10m. For a circle with a radius of 5m, the detection offset at A...
and B can reach 60 mm, or 6 units. For a circle with a radius of 10m, the detection offset at A and B can reach 30mm, or 3 units, to ensure detection accuracy.

Figure 1. Magnetic sensor settings.

3. Control Model of AGV

The AGV has eight independent drive system, each independent drive system consists of a pair of differential driving wheels. Its control model can be derived from the typical Ackerman steering model of four-wheel differential independently driving AGV\[7\].

When the turning radius and running speed are given, the angular velocity of each wheel can be obtained. All the wheels of the AGV can be rolled with a steering center to ensure that the tire and the ground are in a pure state of Rolling without sliding friction\[8\].

The global coordinate system is established based on the desired circle center, which is the origin of the coordinate system. In this coordinate system, \((x_r, y_r)\) is the coordinate of AGV centroid, and AGV pose is known at this point. \((x_a, y_a)\) is the coordinate of the desired point, and the speed is given as \(v_r\). The mathematical model of the expected trajectory that changes with time can be obtained:

\[
\begin{align*}
    x_a &= R \cdot \cos(\arctan \frac{y_r}{x_r} - v_r \cdot t/5) \\
    y_a &= R \cdot \sin(\arctan \frac{y_r}{x_r} - v_r \cdot t/5) \\
    a_a &= 90 - (\arctan \frac{y_r}{x_r} - v_r \cdot t/5) \cdot 180/3.14
\end{align*}
\]  

(1)

Since the coordinate systems of the expected trajectory and the actual running trajectory are different, for unified calculation, a local coordinate system is established with the steering circle center M as the coordinate origin\[9-11\]. The spatial relationship between the global coordinate system XOY and the local coordinate system \(X_a-M-Y_a\), taking the reference point in Fig.2 as an example, the coordinates of the starting point \(G\) are \((x_r, y_r)\), the angle is \(\theta\), the steering radius is r, the reference point G is expressed as \((x_c, y_c)\) in the global coordinate system, and the angle is \(\theta\), the given travel speed is \(v_r\).

Figure 2. AGV circular trajectory motion model.
The mathematical model of operation under the circular trajectory at each time is:

\[
\begin{align*}
    x_c &= x_r + 2r \sin \frac{v_r t}{2r} \cos (\theta_r + \frac{v_r t}{2r}) \\
    y_c &= y_r - 2r \sin \frac{v_r t}{2r} \sin (\theta_r + \frac{v_r t}{2r}) \\
    \theta_c &= \theta_r + \frac{v_r t}{2r}
\end{align*}
\]

(2)

The mathematical model of operation under the circular trajectory at each time is: Because the AGV runs at a very low speed, it is unnecessary to consider its kinetic model. The error generated in the adjustment process is negligible. In the same way, the mathematical model of the operation under a straight line can be obtained.

4. Fuzzy Controller Design

The AGV is simplified as a mass point in the coordinate system, and the desired trajectory laid by magnetic strip is simplified as a planned trajectory in the coordinate system. The angle deviation of the vehicle’s centroid between the current angle and the desired angle is \( \alpha \), and the distance deviation is \( d \).

According to the distance deviation and the angle deviation, the pose state is divided into five areas, as shown in Figure 3. In the process of pose adjustment, the displacement offset and angle offset are in the enclosed area to ensure that the detection is not lost during the operation. During the adjustment process, when the pose is in the area No.5, the tracking operation is in good condition, and no adjustment will be made within this range.

![Figure 3. AGV pose range chart.](image)

4.1. Controller’s Input and Output and its Membership Function

The angle deviation \( \alpha \) and the distance deviation \( d \) are the inputs of the controller, and the turning radius \( r \) is the output of the controller.

The fuzzy subsets of \( \alpha \) and \( d \) are divided as follows: \{large negative, small negative, negative zero, positive zero, positive small, positive large\}={NB, NS, NO, PO, PS, PB}. The range of distance deviation \( d \) is \([-160,-32] \cup [32,160]\), the unit is millimeter, and the corresponding output \( r \) range is \([-5,-3] \cup [3,5]\), the unit is meter. The range of degree deviation \( \alpha \) is \([-13,-2.5] \cup [2.5,13]\), the unit is degree, and turning radius \( r \) output range is \([-5,-2.5] \cup [2.5,5]\), the unit is meter.

Considering the real-time control and complexity of the system, the form of a trigonometric function and a trapezoidal membership function are applied to the input membership function of the fuzzy subset\(^{[12-13]}\). The triangular membership function and the z-shaped membership function are selected as the output membership function. Figure 4 depicts the input membership function of the distance deviation, Figure 5 is the output membership function of the distance deviation.

![Figure 4. Distance deviation input membership function.](image)
4.2. Design of Control Rules

If the actual coordinate is below the desired trajectory, the distance deviation is negative, and the output radius is positive in the same direction as the trajectory, and vice versa. The larger the deviation, the smaller the steering, and the larger the turning arc. \( d \) is within the specified tolerance range, and \( r \) is the standard trajectory radius, then the fuzzy rules of distance deviation are shown in Table 1. The rules are formulated step by step according to the adjustment process. In the beginning of the adjustment, \( d \) is bigger than a certain value, called threshold, adjusting \( \alpha \) to change the value of \( d \) until \( d \) is less than the threshold, \( \alpha \) is within the limit value through the process. Then, \( \alpha \) is adjusted gradually under the condition that \( d \) is smaller than the threshold until the AGV pose enters area NO.5, no more adjustment.

| \( d \) | NB | NS | NO | PO | PS | PB |
|--------|----|----|----|----|----|----|
| \( r \) | NS | NB | NO | PO | PB | PS |

5. Simulation Construction and Analysis

5.1. Trajectory Tracking Model Construction

In order to build a simulation model of the entire AGV trajectory tracking control system in the Simulink environment, it is necessary to use the Fuzzy logic toolbox in MATLAB/Simulink to establish two fuzzy controllers, and write the desired trajectory generation function as well as the AGV control function. Figure 6 and Figure 7 are the circular trajectory simulation model and the linear trajectory simulation model respectively.
5.2. Simulation Result Analysis

In the actual AGV operating environment, the guiding path of the AGV on the ground is generally composed of straight and circular trajectories. This paper simulates the trajectory tracking of the mixed path to verify the trajectory tracking effect of the designed trajectory tracking controller. The first mixed trajectory is a path connecting a straight line to an arc, while the second mixed trajectory is a path connecting an arc to a straight line.

1) Analysis of trajectory tracking results of hybrid path one: The driving speed of the given AGV is $v_r = 0.4m/s$, and the trajectory radius is $R = 5m$. First, AGV runs in the linear range of $x = [-5,0], y = [5,5]$, the initial pose error is $x(0) = -5.0, y(0) = 4.9, \theta(0) = -10$; next, it runs on a circle with the origin as the center, the steering angle is within the range of $0-90^\circ$, and the radius is 5 meters. Fig. 8 depicts the trajectory and distance deviation and angle deviation of hybrid path 1. Initially, $d<0, \alpha<0$, at this time, the AGV pose is in the third quadrant shown in Figure 3. $d$ is adjusted first according to the control rules to reduce the distance deviation, resulting in a decrease in $\alpha$, because the accumulation of angle deviation will lead to distance deviation, so it will continue to rise after $d$ reaches zero. When $d$ rises to exceed the threshold, the controller adjusts it according to the rules, causing $\alpha$ to increase suddenly and remain unchanged. Adjusting $d$ to decrease its absolute value while $d$ is reduced to less than -0.02, $\alpha$ changes from positive to negative; continue to adjust $d$, so that $d$ and $\alpha$ are reduced,
d is kept within the allowable range. Then, α is adjusted to decrease d, α tends to zero, indicating that the adjustment process ends. At last, d remains at -0.02 and α tends to zero. The simulation results show that the AGV has a good tracking effect in the straight part of the mixed path from a straight line to an arc. The distance deviation of the circular path is controlled within the threshold, and the angle deviation is also maintained in a reasonable range.

![Figure 8. Running result of mixed track 1.](image)

2) Analysis of trajectory tracking results of hybrid path two: The AGV first runs on a circular trajectory with a radius of 5 meters and an angle of 0-90°, and then runs on a linear trajectory of $x = [-5, -5], y = [0, -5]$, other conditions remain. Figure 9 shows the trajectory and distance deviation and angle deviation of the second hybrid path. Figures (b) and (c) are the distance deviation and angle deviation diagrams after the arc trajectory enters the straight trajectory. The abscissa is the y-axis coordinate while the ordinate is the deviation value. Since the route is from 0 to -5, the distance deviation should start from 0 and end at -5. The distance deviation should gradually decrease to about 2mm at the endpoint. The angular deviation remains unchanged from the initial deviation, about -0.2°.
6. Conclusion
By setting the position of the magnetic sensor, simplifying the sixteen-wheeled heavy-duty AGV to a two-wheel mechanism, and combining with fuzzy control, the design of the tracking control system for the sixteen-wheeled heavy-duty AGV in a fixed path is realized. Experimental simulations show that the tracking system designed has a good tracking effect on straight trajectories, circular trajectories, and their mixed trajectories, and can correct distance and angle deviations during operation to keep them within a reasonable threshold range.

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