ISBN: 978-981-18-5852-9
WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications
doi: 10.18178/wcse.2022.04.136

An Arc Tracking Navigation Method for AGV with Multiple Differential Wheel Groups

Chengjie Li, Yuanqiao Li and Sanjun Duan

Beijing Specialized Machinery Institute, Beijing, China
lichengjie@bjsmi.com.cn

Abstract. With the wide application of heavy-duty AGV in different fields, AGV based on multi differential wheel groups (MDWG-AGV) has become the key equipment of heavy-duty AGV. However, MDWG-AGV can not realize continuous omni-directional motion, which increases its motion control complexity, especially arc motion. To solve the problem of arc tracking navigation of MDWG-AGV, an arc tracking navigation control algorithm to correct heading angle based on the arc radius(R-H) are proposed. Firstly, the mode of MDWG-AGV is analyzed and its motion equation is derived. Secondly, combined with the characteristics of AGV moving on the arc path, a robust R-H arc tracking algorithm suitable for AGV with multiple differential wheel groups is proposed. Finally, the effectiveness and robustness of R-H algorithm are proved by arc experiments in different cases.

Keywords: multi differential wheel group, tracking navigation, R-H tracking algorithm, arc tracking

1. Introduction

With the development of heavy industries such as aerospace, shipping and railway, MDWG-AGV, as a heavy-duty AGV, has become an indispensable equipment [1]. In order to improve the adaptability of MDWG-AGV in various occasions, the research of navigation algorithm is of great importance. Since MDWG-AGV can not realize continuous omni-directional motion, problems in arc tracking navigation are urgent to be solved. Heikkinen [2] proposed a trajectory control strategy with an inertial measurement unit for an autonomous differential drive mobile robot. A time-invariant controller for trajectory tracking applied to the differential-drive mobile robot [3]. Balkcom [4] develops the bounded velocity model for diff drive mobile robot, and derives the time-optimal trajectories. Karakaya [5] proposed a path tracking method for 4-wheeled differential drive autonomous mobile robots. A new control algorithm that incorporating the cross-coupling technology into an adaptive control architecture is developed for a differential mobile robot. [6] However, the aforementioned researches are based on two wheel differential mobile robot, and purpose of those researches are not aimed at the navigation problem of MDWG-AGV. Therefore, the research on navigation of MDWG-AGV has great significance in practical applications, especially the arc navigation.

2. Kinematic Analysis

This paper research on the classical AGV which contains four groups of differential wheel as shown in Figure 1. In detail, AGV consists of four groups of differential wheels, which are symmetrically distributed. Deviation acquisition sensors are installed at the front and rear of the AGV to acquire the deviation value between the location and the path. In order to analyze the motion characteristics of multi differential wheel groups AGV, the proposed method adopt the center of MDWG-AGV as the origin. The front and right direction are established Y axis and X axis, respectively. Hence, two-dimensional plane coordinate system xoy is determined, and the clockwise direction is specified as the positive rotation direction. It can be seen in Figure 1 that v_y denotes the y-direction speed of MDWG-AGV, v_x denotes the x-direction speed, ω denotes the rotation speed, and the rotation center offset is x_offset and y_offset, where x_offset is the x-direction deviation between the rotation center and the AGV center, y_offset is the y-direction deviation between the rotation center and the AGV center. It is assumed that the distance between the front and rear differential wheel groups is l and the distance between the left and right differential wheel sets is w. It is specified that the front right wheel groups is No. 1 wheel group, which is coded in counterclockwise direction.

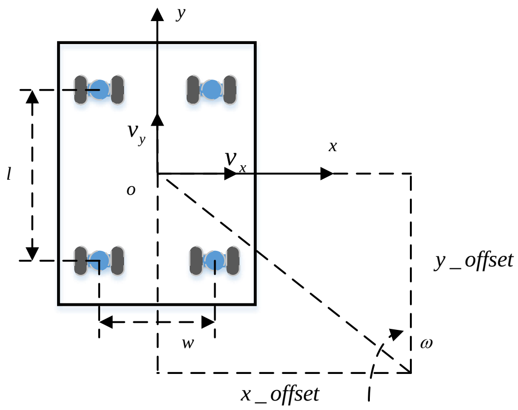

Fig. 1: Analysis of motion parameters of AGV with multiple differential wheel groups.

According to the rigid body kinematics, the central velocity of No. 1 wheel group can be calculated as shown in Equation 1:

$$\begin{bmatrix} v_{x1} \\ v_{y1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & (\frac{m}{2} - y\_offset) \\ 0 & 1 & (\frac{n}{2} - x\_offset) \end{bmatrix} \boldsymbol{\lambda} \tag{1}$$

where $\boldsymbol{\lambda} = \left[v_x, v_y, \omega \right]^{\mathrm{T}}$.

Thus, the heading angle of each differential wheel group can be obtained as following equation:

Thus, the heading angle of each differential wheel group can be obtained as following equation:

$$\theta_i = \arctan\left(\frac{v_{xi}}{v_{yi}} \right), i = 1 \cdots 4 \tag{2}$$

When the multi differential wheel group AGV rotates, i.e. $\omega \neq 0$, at this time, the left and right driving wheels in the differential wheel group adjust the heading based on the speed difference, which ensures the movement stability of the AGV.

$$\begin{bmatrix} v_L \\ v_R \end{bmatrix} = \begin{bmatrix} \frac{d}{2r} \\ -\frac{d}{2r} \end{bmatrix} \omega \tag{3}$$

where v_L is the compensation speed of the left wheel of the differential wheel group, v_R is the compensation speed of the right wheel of the differential wheel group, d is the rotation diameter of the differential wheel group, and r is the radius of the driving wheel.

The actual speed of each driving wheel can be calculated combining formulas (1) - (3).

3. Tracking Navigation Method

In Figure 2, the classical quarter arc path is studied. It is specified that the center distance of the front and rear deviation acquisition sensors is L and the radius of the arc path is R. When the relationship between L and R satisfies Equation (4), the arc motion state of MDWG-AGV can be divided into three types.

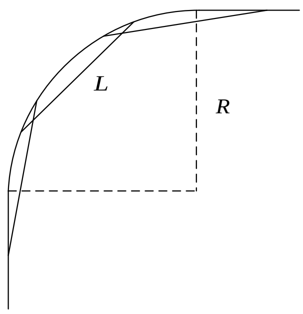

Fig. 2: Schematic of arc path.

$$L < \sqrt{2}R \tag{4}$$

3.1. Arc-Line State

As shown in Figure 3, when MDWG-AGV enters the arc from a straight line, the front deviation acquisition sensor is located on the arc path, and the rear deviation acquisition sensor is located on the straight line path. Utilize the starting point of the arc path as the origin, where two-dimensional coordinate system XOY can be determined. Thereafter, the central position coordinates of the front and rear deviation acquisition sensor are defined as (x_1, y_1) and (x_2, y_2), respectively. Assume that the heading angle of MDWG-AGV is γ. Based on the geometric relationship in Figure 3 the position coordinates of the front deviation acquisition sensor center can be established as shown in Equation 5.

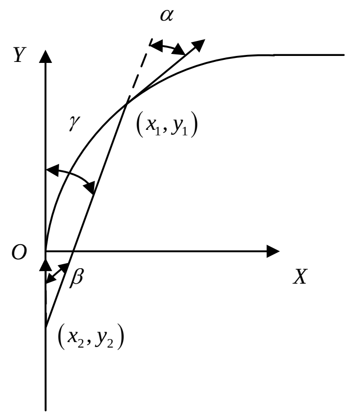

Fig. 3: Arc-Line motion state.

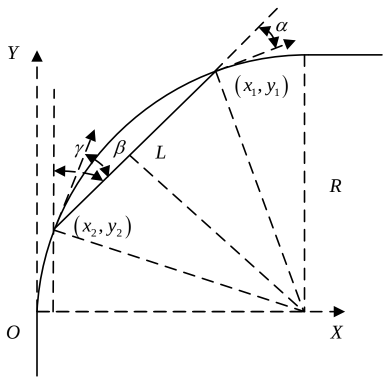

Fig. 4: Arc-Arc motion state.

$$(x_1, y_1) = \left(L\sin\gamma, \sqrt{2LR\sin\gamma - (L\sin\gamma)^2} \right) \tag{5}$$

After obtaining the real-time position of the front and rear deviation acquisition sensors, the theoretical velocity direction of the center position of the front and rear deviation acquisition sensors can be calculated as following:

$$\begin{cases} \alpha = \dfrac{\pi}{2} - \arctan\left(\dfrac{R - x_1}{\sqrt{2x_1 R - x_1{}^2}}\right) - \gamma \\ \beta = \gamma \end{cases} \tag{6}$$

According to the geometric relationship, the theoretical rotation center of MDWG-AGV can be obtained by the theoretical speed direction of the center position of the front and rear deviation sensors.

$$\begin{cases} x\_offset = \dfrac{L}{\tan\alpha + \tan\beta} \\ y\_offset = \dfrac{L}{2} - x\_offset \bullet \tan\alpha \end{cases} \tag{7}$$

Then, the real-time angular velocity ω of AGV arc motion can be calculated according to the tangent velocity of AGV.

3.2. Arc- Arc State

As shown in Figure 4, MDWG-AGV fully enters the arc. At the same time, the front and rear deviation acquisition sensors are located on the arc path. The coordinates of the center position of the front and rear deviation acquisition sensor can be calculated using the real-time AGV heading angle γ.

The theoretical coordinates of the front and rear sensor centers can be calculated via the heading angle γ, as shown in formula (8).

$$\begin{cases} x_1 = L\sin\gamma + R\left(1 - \cos\left(\gamma + a\cos\dfrac{L}{2R} - \dfrac{\pi}{2}\right)\right) \\ y_1 = \sqrt{R^2 \text{-} (x_1 - R)^2} \\ x_2 = \dfrac{2\left(\dfrac{L^2}{2} - x_1 R\right)(R - x_1) + 2y_1{}^2 R - \sqrt{\left(2\left(\dfrac{L^2}{2} - x_1 R\right)(R - x_1) + 2y_1{}^2 R\right)^2 - 4\left((R - x_1)^2 - y_1{}^2\right)\left(\dfrac{L^2}{2} - x_1 R\right)^2}}{2\left((R - x_1)^2 - y_1{}^2\right)} \\ y_2 = \sqrt{R^2 \text{-} (x_2 - R)^2} \end{cases} \tag{8}$$

Then the real-time velocity direction angle of the front and rear deviation acquisition sensor can be solved according to the geometric relationship in Figure 4.

$$\begin{cases} \alpha = a\tan\dfrac{y1 - y2}{x1 - x2} - a\tan\dfrac{R - x1}{\sqrt{2x_1 R - x_1{}^2}} \\ \beta = a\tan\dfrac{y1 - y2}{x1 - x2} - a\tan\dfrac{R - x1}{\sqrt{2x_2 R - x_2{}^2}} \end{cases} \tag{9}$$

3.3. R-H Navigation Algorithm

Systematic error and random error are inevitable when using the theoretical sensor heading angle for motion control. As shown in Figure 5, it is defined that the sensor feedback data is negative on the left and positive on the right. That is, when the path is at the lower left of the sensor, the deviation data fed back by the sensor is negative, and vice versa.

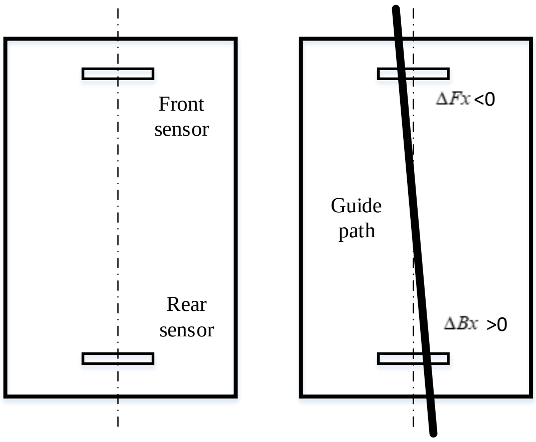

Fig. 5: Sensor deviation definition

As shown in Figure 6, in order to improve the accuracy of arc navigation and decrease the error of path, this paper introduces the error of sensor before and after AGV into arc navigation control. This paper calculates the corrected heading angles $\Delta\alpha$ and $\Delta\beta$ through the error, and compensates them to α and β respectively, so as to obtain the real speed heading angles α' and β' at the center of the sensor.

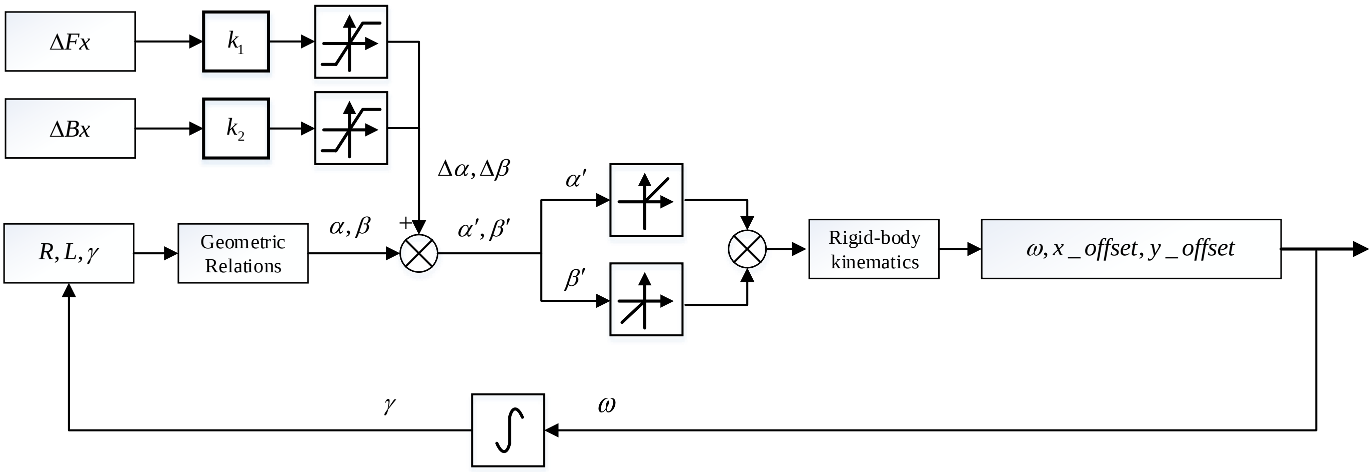

Fig. 6: Arc tracking navigation method

In order to maintain the stability of AGV in arc motion, the maximum values of corrected heading angles $\Delta\alpha$ and $\Delta\beta$ are limited. Then, the heading angles $\Delta\alpha'$ and $\Delta\beta'$ are filtered to ensure that the rotation center of AGV and the center of the arc are on the same side. Only in this way can the AGV navigate closer to the tangent direction of the arc.

According to the R-H algorithm, actual heading angle of the center position of the sensor can be calculated as shown in formula (10):

$$\begin{cases} \alpha = a\tan\dfrac{y1-y2}{x1-x2} - a\tan\dfrac{R-x1}{\sqrt{2x_1R-x_1^{\,2}}} \\ \beta = a\tan\dfrac{y1-y2}{x1-x2} - a\tan\dfrac{R-x1}{\sqrt{2x_2R-x_2^{\,2}}} \\ \alpha' = \alpha + \Delta\alpha \\ \beta' = \beta + \Delta\beta \end{cases} \tag{10}$$

4. Experimental Results And Analysis

In order to verify the effectiveness and robustness of R-H algorithm, this paper takes AGV of four groups of differential wheel groups as the experimental platform. In detail, each group of differential wheel groups is driven by two servo motors, the bottom control program of AGV is completed in CodeSys programming environment, and the experimental data are tracked and obtained in CodeSys environment. The specific parameters of the experimental platform are shown in Table I.

Table 1: Experimental Platform Parameters

l	W	***Sensor measurement range***	L
6000mm	980mm	$[-75mm, 75mm]$	6140mm

4.1. Complete Arc Tracking Navigation Experiment

Considering that the smaller the radius, the greater the impact on the AGV navigation accuracy. In order to verify the effectiveness of the arc tracking navigation algorithm, an arc guidance path with a radius of 6 meters is built, and the starting and ending points of the arc are connected as the straight path.

In this experiment, AGV travels from straight line to arc, then from arc to straight line. AGV maintains the speed of 20m/min. Deviation values collected by the front and rear sensors are shown in Figure 5.

At the same time, the speed heading angle of the center position of the front and rear sensors and the heading angle of the AGV with multiple differential wheel sets are collected as shown in Figure 7.

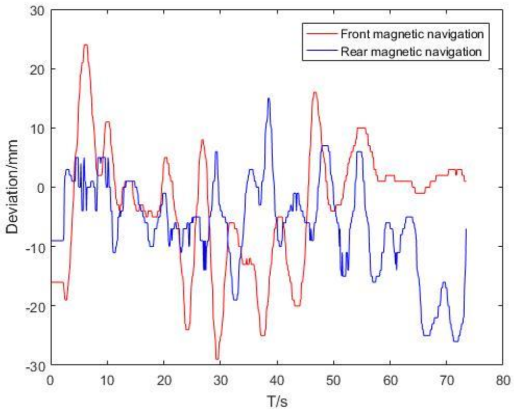

Fig. 7: The deviation value of the front and back magnetic navigation during arc navigation.

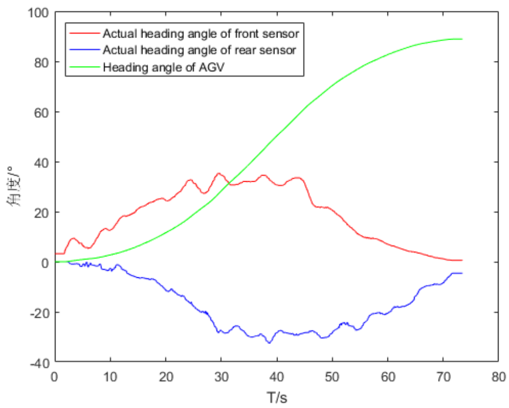

Fig. 8: The heading angle of different positions in arc navigation.

Through the analysis of Figure 7, it can be concluded that the sensor deviation is controlled within $[-30,30]$ when the multi differential wheel set AGV travels in an arc. Compared with the detection range $[-75,75]$ of the deviation acquisition sensor, the error is within a reasonable range. It can be seen from the figure that AGV can quickly converge error after traveling from arc to straight line. On the one hand, the arc navigation deviation is caused by the curvature deviation of the arc path, and on the other hand, it is caused by the real-time AGV heading angle error calculated by the integral. As can be seen in Figure 8, the speed and heading angle of the magnetic navigation center is relatively stable, which ensure the smooth movement of the AGV. The experimental results in Fig. 7 and Fig. 8 verify the effectiveness of the arc tracking navigation algorithm (R-H) proposed in this paper.

4.2. Incomplete Arc Tracking Navigation Experiment

In real navigation scenarios, there are many incomplete navigation paths. In order to verify the robustness of R-H method, a 750mm missing path is set on the arc path. The multi differential wheel set AGV travels from straight line to arc, then from arc to straight line, and maintains the speed. The actual data obtained are shown in Fig. 9 and Fig. 10.

As shown in Figure 9, the front sensor starts to lose path guidance around the 8th second, therefore, the feedback deviation value will be determined as zero. At this time, $\alpha' = \alpha$, that is, the speed and heading of the front sensor will be controlled according to the theoretically calculated heading angle. As shown in FIG. 10, the theoretical speed heading angle control starts to work at the 8th second, the guidance path appears again after 11th second, and the deviation can be quickly converged. For most industrial navigation algorithms, the loss of guidance path isn't taken in consideration. If the deviation is supposed to be zero, the AGV does not make any adjustment under the condition of path loss. Therefore, AGV will seriously leave the guidance path, resulting in the failure of navigation task.

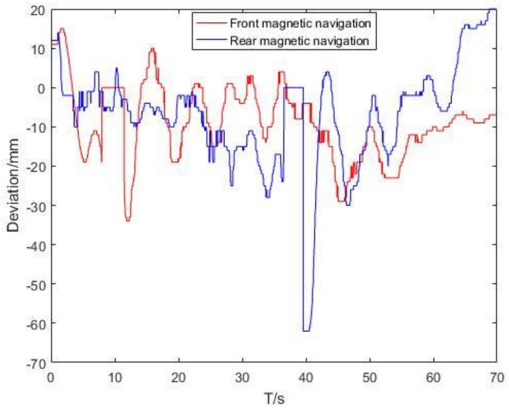

Fig. 9: The deviation value of the front and back magnetic navigation during arc navigation.

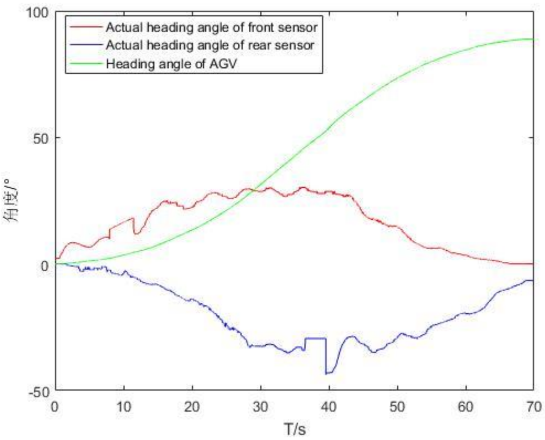

Fig. 10: The heading angle of different positions in arc navigation.

Similarly, the rear sensor passes through the missing path after the 36th second, and the speed heading of the rear sensor β' equals to β . From FIG. 9 and FIG. 10, when the rear sensor recognizes the guidance path again in about 39 seconds, deviation is been relatively large due to the cumulative error of AGV heading angle integration. However it can also quickly converge the error through the R-H algorithm. In addition, under the arc path of 6m radius set in this paper, the R-H algorithm can realize the complete navigation task of the experimental platform AGV in the case of continuous 750mm missing path. It can be concluded that if the missing path is less than 750mm, the deviation will be smaller than that shown in Figure 9 when the rear magnetic navigation recognizes the guidance path again.

5. Conclusion

This paper discusses the arc tracking navigation method of AGV with multiple differential wheel groups. Firstly, the motion model of AGV based on multi differential wheel groups is analyzed, and its velocity equation is obtained. Secondly, the motion characteristics of arc path are analyzed, and an R-H algorithm that suitable for arc navigation of AGV based on multiple differential wheel groups is proposed. In order to verify the effectiveness of the algorithm, simulation experiments are carried out. The experimental results show that the AGV based on proposed multi differential wheel groups arc navigation control algorithm can realize smooth operation of AGV on the arc path and solve the problem of excessive smooth arc path. What's more, the robustness of R-H algorithm is proved by incomplete path experiments.

6. References

[1] Vis I . Survey of research in the design and control of automated guided vehicle systems[J]. European Journal of Operational Research, 2006.

[2] Heikkinen J , Serykh E V , Minav T . [IEEE 2017 IEEE II International Conference on Control in Technical Systems (CTS) - St. Petersburg (2017.10.25-2017.10.27)] 2017 IEEE II International Conference on Control in Technical Systems (CTS) - A control strategy for an autonomous differential driv[J]. 2017:83-86.

[3] Montesdeoca J C , Santos M C P , Monllor M , et al. Trajectory tracking controller for differential-drive mobile robots[C]// 2017 XVII Workshop on Information Processing and Control (RPIC). IEEE, 2017.

[4] D .J. Balkcom, Mason M T . Time optimal trajectories for bounded velocity differential drive robots[J]. IEEE, 1999.

[5] Karakaya S , Kucukyildiz G , Ocak H . Kinematic model based path tracking algorithm for differential drive mobile robots[C]// Signal Processing & Communications Applications Conference. IEEE, 2014.

[6] Dong S , Dong H N , Tso S K . Tracking stabilization of differential mobile robots using adaptive synchronized control[C]// IEEE International Conference on Robotics & Automation. IEEE, 2002.