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Development of an omnidirectional Automated Guided Vehicle with MY3 wheels☆

Suyang Yu*, Changlong Ye, Hongjun Liu, Jun Chen

School of Mechatronics Engineering, Shenyang Aerospace University, Shenyang, China

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Summary This paper presents an omnidirectional Automated Guided Vehicle (AGV) with a novel omnidirectional wheel named MY3 wheel. Due to the special structure and material of the MY3 wheel, the AGV has full three DOFs in the motion plane and good capabilities of load carrying and slip resisting. In addition, the kinematic model of the AGV is derived, and the guiding method that can make the AGV to follow a specified path is established. Finally, experiments are performed to verify the kinematic model and guiding method.
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Introduction

An Automated Guided Vehicle (AGV) is a driverless transport system used for horizontal movement of materials (Vis, 2004). Nowadays, AGVs have been widely used in industrial applications such as transporting materials around manufacturing facilities or warehouses automatically to increase efficiency and reduce costs (Ronzoni et al., 2011; Bui et al., 2013; Kirsch et al., 2012). In addition, AGVs have also showed great potential value in office, domestic, and outdoor services (Tsumura, 1994; Vamossy et al., 2014).

For most of the existing AGVs, the differential driving method is adopted due to its simplicity and zero-radius turning. However, the differential driving method cannot work effectively in the narrow space, because it cannot perform the lateral translation (Ronzoni et al., 2011; Bui et al., 2013). In order to enable AGVs to have full three DOFs in the motion plane (two translations and one rotation), some researchers have tried to equip AGVs with omnidirectional wheels to construct omnidirectional AGVs (Kim et al., 2012; Kirsch et al., 2012; Kumra et al., 2012).

A variety of omnidirectional wheels have been proposed over the past few decades, and most of them are designed based on the concept that achieving the active motion in one direction and allowing the passive motion in another direction. A general type of the omnidirectional wheel is an assembly of a traditional wheel and some passive rollers mounted at the periphery such as the Mecanum wheel (Muir

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* Corresponding author.
E-mail address: yu_suyang@163.com (S. Yu).

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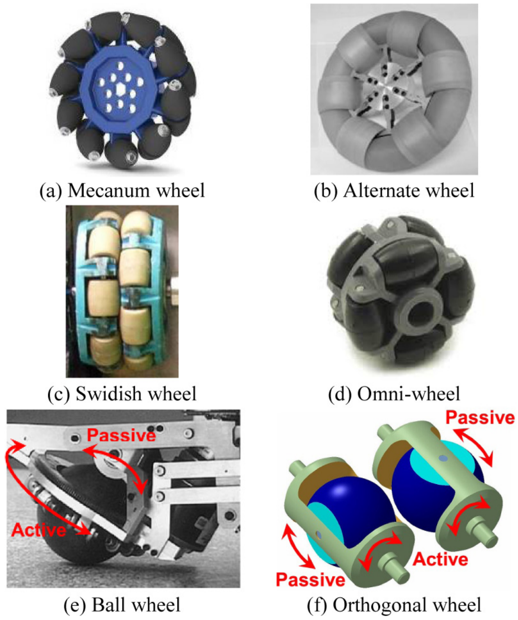


Figure 1 Omnidirectional wheels.

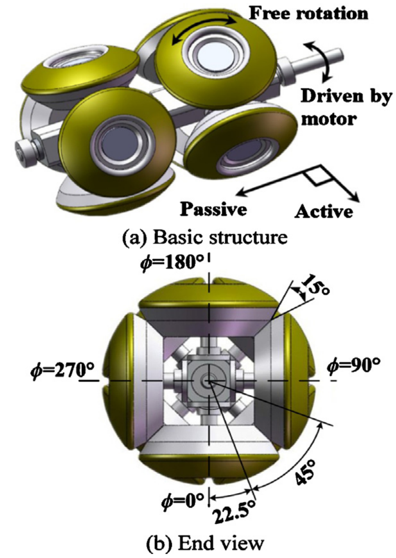


Figure 2 MY3 wheel.

and Neuman, 1987), Alternate wheel (Byun and Song, 2003), Swedish wheel (Indiveri, 2009), and Omni-wheel (Asama et al., 1995) (shown in Fig. 1a—d). This type of wheel can accomplish omnidirectional motions, but the mechanism has a low load carrying capability and is sensitive to dirt and fragments on the ground. Wada and Asada proposed an omnidirectional ball wheel and applied it to wheelchairs (Wada and Asada, 1999) (shown in Fig. 1e). The ball wheel is very flexible on the ground, but the mechanism is complex. Pin and Killough proposed the ''orthogonal-wheel'' concept and two major wheel assemblies (Pin and Killough, 1994) (shown in Fig. 1f). The mechanism of the orthogonal-wheel is compact, but the load carrying capability also needs to be improved.

In our previous work, a novel omnidirectional wheel named MY wheel has been proposed (Ye and Ma, 2009; Ye et al., 2012, 2014). Compared to conventional omnidirectional wheels, the MY wheel is insensitive to dirt and fragments on the ground and has larger load carrying capability. In this paper, an omnidirectional AGV with the third generation of the MY wheel named MY3 wheel is proposed, and the remainder of this paper is organized as follows. In Section ''MY3 wheel'', the design of the MY3 wheel is introduced. In Section ''AGV with MY3 wheels'', the omnidirectional AGV with MY3 wheels is presented. In section ''Kinematic model'', the kinematic model of the AGV is derived. In Section ''Guiding method'', the guiding method of the AGV is established. In Section ''Experiments'', experiments are performed to verify the kinematic model and guiding method. Finally, some conclusions and future work are given in Section ''Conclusions and future work''.

MY3 wheel

Fig. 2 shows the basic structure of the MY3 wheel. The wheel consists of two balls with equal diameter on a common shaft. The two balls are both sliced into four spherical crowns, and each spherical crown can rotate freely around its own shaft. The two sets of spherical crowns are mounted at 45° from each other to produce a combined circular profile. When the common shaft is driven, the two sets of spherical crowns can make an alternate contact with the ground to realize a continuous active motion for the MY3 wheel, and the free rotation of the crown contacting with the ground can realize a passive motion for the MY3 wheel. A 15° gap is designed between two adjacent spherical crowns to make the MY3 wheel much more insensitive to dirt and fragments on the ground, and the precision of the circle profile which can be influenced by the gap has been checked by Ye et al. (2014). Moreover, because the four spherical crowns in one set can realize a mutual support with each other, the MY3 wheel has a good capability of load carrying compared to conventional omnidirectional wheels. In addition, the cover of the spherical crown of the MY3 wheel is made up by polyurethane (PU) but not aluminium alloy which is adopted by earlier MY wheels, and this modification is very useful for resisting the slippage between the wheel and the ground.

AGV with MY3 wheels

The prototype of the omnidirectional AGV with the MY3 wheel is shown in Fig. 3. The mechanical system of the AGV consists of a mobile platform and a three-layer carrier. On the mobile platform, four MY3 wheels are arranged evenly with a 90° interval angle to realize the omnidirectional motion, and some optical color sensors that can guide the AGV is also installed on the platform. As to the three-layer carrier, the bottom layer is used for carrying four DC motor modules (including the motor, motor driver, gearbox, and encoder) that actuate the four MY3 wheels respectively. The middle layer is used for carrying the controller and battery of the AGV. The top layer is used for carrying the material transported by the AGV, and a camera and a WIFI module are installed on the top of this layer. The specifications of the AGV are listed in Table 1, and some geometric parameters in the table are shown in Fig. 5.

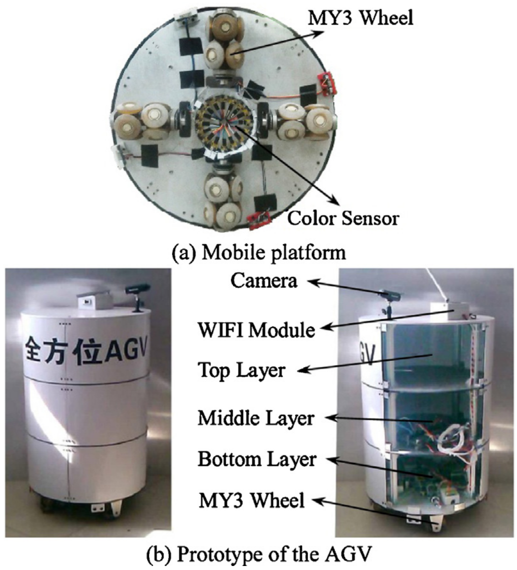


Figure 3 Omnidirectional AGV with MY3 wheels.

Table 1 Specifications of the omnidirctional AGV.

Symbol	Quantity	Value
R	Body radius	500 mm
r	Wheel radius	40 mm
h	Body height	780 mm
R_1, R_2	Contact radius	135 mm, 190 mm
W	Weight	33 kg
W_P	Payload	50 kg

The framework diagram of the AGV control system is shown in Fig. 4. The control system consists of three levels. In the top level, a laptop is used to realize the human-computer interaction, through which the operator can send commands to the AGV and observe working conditions of the AGV. The middle level is a single-board controller carried by the AGV. The controller can process demands from the top level and acquire the sensor information for the top level, and the communication between the top and middle levels is realized by the WIFI module. In the bottom level, four DC motor modules are used to actuate the AGV, and the optical color sensor and camera are used for acquiring the environment information of the AGV.

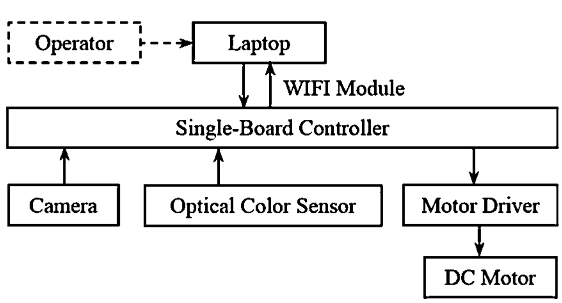


Figure 4 Framework diagram of the AGV control system.

Kinematic model

In order to derive the kinematic model of the omnidirectional AGV, firstly, two coordinate frames are defined in the motion plane of the AGV as shown in Fig. 5. In Fig. 5, $\{O_w\}$ is the world coordinate frame, and $\{O_m\}$ is the moving coordinate frame fixed on the geometric center of the AGV. The coordinate transformation matrix from frame $\{O_w\}$ to frame $\{O_w\}$ is as follows:

$$
{}^{w}R_m = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

where θ is the rotation angle of frame $\{O_m\}$ with respect to frame $\{O_w\}$.

Assuming that no slippage will occur between the wheel and the ground, the kinematic relationship between the AGV and its MY3 wheels in frame $\{O_m\}$ can be described as follows:

$$
\begin{cases} r\dot{\phi}_1 = {}^{M}V_Y + L_1\dot{\theta} \\ r\dot{\phi}_2 = -{}^{M}V_X + L_2\dot{\theta} \\ r\dot{\phi}_3 = -{}^{M}V_Y + L_3\dot{\theta} \\ r\dot{\phi}_4 = {}^{M}V_X + L_4\dot{\theta} \end{cases} \Leftrightarrow r\begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \\ \dot{\phi}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & L_1 \\ -1 & 0 & L_2 \\ 0 & -1 & L_3 \\ 1 & 0 & L_4 \end{bmatrix} \begin{bmatrix} {}^{m}V_x \\ {}^{m}V_y \\ \dot{\theta} \end{bmatrix} \tag{2}
$$

where ϕ_i denotes the rotation angle of the wheel, and ${}^{m}V_x$ and ${}^{m}V_y$ denote the translational velocity of the geometric center of the AGV described in frame $\{O_m\}$, and L_i denotes the distance between the geometric center of the AGV and the contact point with the ground of each wheel. Since the two sets of spherical crowns in one MW3 wheel will make an alternate contact with the ground during the movement of the AGV, L_i will switch between the inner and outer contact radius R_1 and R_2 as follows:

$$
L_i = \begin{cases} R_1 \quad \text{if} \quad \frac{\pi}{8} + \frac{n\pi}{4} < \phi_i < \frac{3\pi}{8} + \frac{n\pi}{4} \\ R_2 \quad \text{if} \quad -\frac{\pi}{8} + \frac{n\pi}{4} < \phi_i < \frac{3\pi}{8} + \frac{n\pi}{4} \end{cases} \qquad n = 0, \pm 1, \pm 2 \ldots \tag{3}
$$

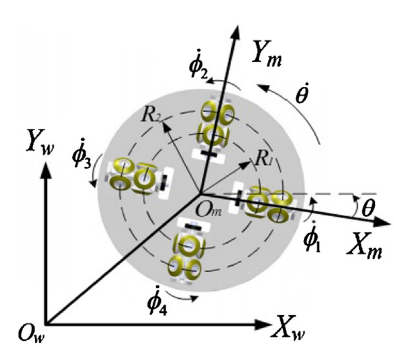
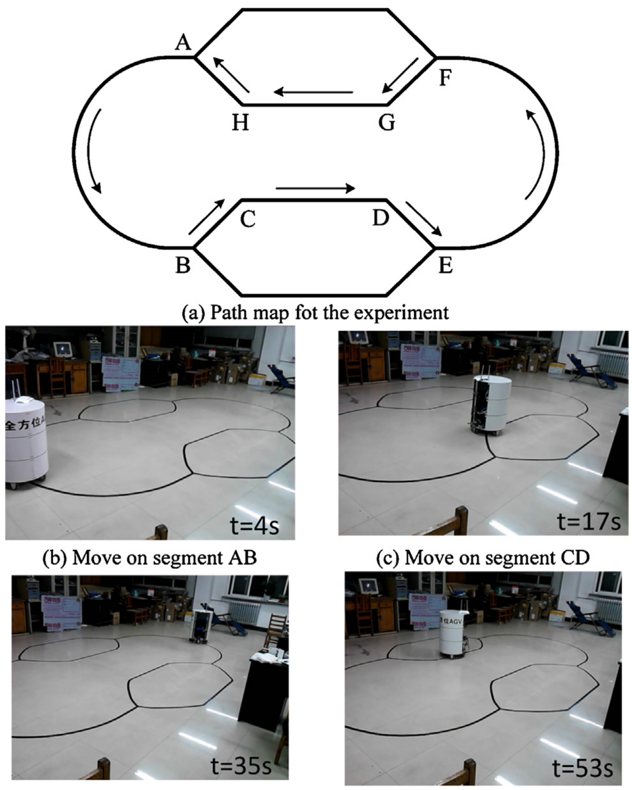


Figure 5 Coordinate system of the AGV.



(a) Path map fot the experiment

(b) Move on segment AB

(c) Move on segment CD

(d) Move on segment EF

(e) Move on segment GH

Figure 6 Experiment for following a specific path.

Combining (1) and (2), the inverse kinematic equation of the AGV in frame $\{O_w\}$ can be expressed as:

$$\dot{\vec{\phi}} = \frac{1}{r} J^{-1} \dot{\vec{q}}$$

$$\vec{\phi} = \begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \\ \dot{\phi}_4 \end{bmatrix}, \quad J^{-1} = \begin{bmatrix} 0 & 1 & L_1 \\ -1 & 0 & L_2 \\ 0 & -1 & L_3 \\ 1 & 0 & L_4 \end{bmatrix} ({}^{w}R_m)^{-1} = \begin{bmatrix} -\sin\theta & \cos\theta & L_1 \\ -\cos\theta & -\sin\theta & L_2 \\ \sin\theta & -\cos\theta & L_3 \\ \cos\theta & \sin\theta & L_4 \end{bmatrix}, \quad \vec{q} = \begin{bmatrix} {}^{w}x \\ {}^{w}y \\ \theta \end{bmatrix} \tag{4}$$

where J^{-1} is the inverse Jacobian matrix, and $\vec{q}$ is the position and attitude vector of the AGV in frame $\{O_w\}$.

From (4) it can be seen that if the angular velocity of the AGV $\dot{\theta}$ is not zero, the switch of L_i will influence the wheel angular velocity $\dot{\phi}_i$. That means when the rotational motion is adopted by the AGV, the wheel angular velocity will fluctuate. Because the fluctuation cannot be realized easily by controllers, some analysis has been performed for obtaining an optimal approximate value to replace the switched L_i by Ye et al. (2011) and Ma et al. (2012). In this paper, the average value $L_i = R_1 + (R_2 - R_1)/2$ is used for solving the wheel angular velocity in (4).

Guiding method

On the omnidirectional AGV, the optical color sensor and camera are installed for acquiring the environment information. In our present work, the camera is only used for the operator to observe the working environment, and the optical color sensor is used for guiding of the AGV to follow a specified path.

In order to detect the position of the path relative to the AGV, sixteen optical color sensors are used, and they are arranged in a circle array as shown in Fig. 3a. The radius of the circle array is set as 60 mm, so the distance between adjacent detecting points is 23.55 mm. That means in order make sure that the path can be detected by two sensors at the same time, the width of the path must be larger than 23.55 mm.

In this paper, the AGV will adopt both translational and rotational motions during following a specified path. Before the following motion, the moving direction in frame $\{O_m\}$ should be determined, and this direction can be described by two adjacent color sensors. During the following motion, the translational motion will be performed in the determined moving direction, and the rotational motion will be performed according to the deviation angle of the moving direction relative to the objective path.

Experiments

In the experiment for the onmidirectional AGV to follow a specified path, a black tape with a 30 mm width is used to form a path map on the white ground as shown in Fig. 6a, and the AGV will start from the circular segment AB to make an anti-clock movement. When the AGV arrives at a junction point of three ways such as point B, the left way will be selected as the new objective path.

The moving direction of the AGV in frame $\{O_m\}$ is set as 45° with respect to O_mX_m, and the velocity in this direction is set as 0.1 m/s. The rotational velocity of the AGV $\dot{\theta}$ will be determined according to the deviation angle of the moving direction relative to the objective path γ divided by the adjusting time t_a as $\dot{\theta} = \gamma/t_a$, and t_a is set as one second. When the translational and rotational velocities of the AGV have been determined, the wheel angular velocity $\dot{\phi}_i$ can be solved by (4).

The snapshots of the experiment are shown in Fig. 6b–e. In the experiment, the AGV follows the path and goes through points B, C, D, E, F, G, H, and A in sequence successfully. This result can give a preliminary verification for the effectiveness of the proposed kinematic model and guiding method.

Conclusions and future work

In this paper, an omnidirectional AGV with MY3 wheels is proposed. This omnidirectional AGV is superior to most existing omnidirectional mobile platforms because it is more insensitive to dirt and fragments on the ground and has good capabilities of load carrying and slip resisting. The kinematic model of the AGV is derived, and the guiding method for following a specified path is established with optical color sensors. The experiment is performed with the prototype, and the result indicates that the proposed kinematic model and guiding method are effective.

In the future work, the factors that influence the error of the kinematic model and guiding method will be studied in detail, and the kinematic model and guiding method with better accuracy will be proposed.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgements

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