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RESEARCH ARTICLE

A METHOD FOR TRAJECTORY TRACKING FOR DIFFERENTIAL DRIVE TYPE OF AUTOMATIC GUIDED VEHICLE

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ABSTRACT

This paper proposes trajectory tracking algorithm for differential drive type of Automatic Guided Vehicle (AGV) using backstepping control and simultaneous localization and mapping (SLAM). To guarantee the tracking errors go to zero, backstepping control method is proposed. By choosing appropriate Lyapunov function based on its kinematic modeling, system stability is guaranteed and a control law can be obtained. For its positioning, simultaneous localization and mapping (SLAM) algorithm is employed. The landmarks are detected using spike algorithm. The AGV position can be estimated using Kalman filter by combining the encoder result and landmark positions. The simulation and experimental results show that the proposed controller successfully tracks the given trajectory.

KEYWORDS

Automatic Guided Vehicle, differential drive, simultaneous localization and mapping, trajectory tracking.

1. INTRODUCTION

Trajectory tracking is the most important issue to the AGV when it operates in industrial environment. There are several control algorithms that have been proposed to accomplish this task. Particle swarm optimization (PSO) method to determining the optimal PID controller and fuzzy-PID is proposed to control the navigation of AGV (Abdalla and Abdulkarem, 2012; Doan et al., 2011). Those controllers are easy to be applied to AGV system but not robust. Parameter-based controller design method has been proposed using sliding mode control theory and linear control based on Lyapunov function (Filipescu, 2011; Bui et al., 2013). In those controllers, the stability of the system is guaranteed, but it is not an easy task to find appropriate controller law.

In the past, there were several kind navigation methods for tracking control algorithm of AGV. A researcher proposed AGV path tracking control algorithm to follow a visual line painted on the floor using camera sensor (Doan et al., 2011). This algorithm is easy and cheap, but the path should be keep clean. Inductive guidance using electrical wire buried under the floor was proposed (Chen et al., 2004). This navigation system isn't flexible since the path can't be changed easily. Semi-guided navigation method by using magnetic tapes was proposed, but not suitable for navigation on steel floors (Lee and Yang, 2012). Wall following algorithm was proposed, but it's difficult to apply the algorithm in open space (Yuan, 2009). The most advanced positioning system for indoor application was laser navigation system (Bui et al., 2013). It is flexible, but very expensive.

2. PROPOSED ALGORITHM

2.1 System Description

Figure 1: Configuration of AGV system (a), (b)

The AGV shown in Figure 1(a) has dimension 100 cm x 60 cm x 80 cm. This system uses differential drive wheeled system. Two driving wheels are mounted on the left and right sides of AGV and are driven by two BLDC motors. Two passive castor wheels are installed in front and back sides of AGV to support the AGV.

The electrical design shown in Figure 1(b) consists of sensors such as encoder and laser measurement system, controller such as Industrial PC, touch screen monitor as display, keyboard and mouse as the input, and actuators.

Kinematic equation of nonholonomic differential drive type of AGV system can be expressed as follows:

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$$\mathbf{x}_v = \int \dot{\mathbf{x}}_v dt \,; \quad \dot{\mathbf{x}}_v = \begin{bmatrix}\dot{X}_A \\ \dot{Y}_A \\ \dot{\theta}_A\end{bmatrix} = \begin{bmatrix}\cos\theta_A & 0 \\ \sin\theta_A & 0 \\ 0 & 1\end{bmatrix}\begin{bmatrix}V_A \\ \omega_A\end{bmatrix}; \quad \begin{bmatrix}V_A \\ \omega_A\end{bmatrix} = \frac{r}{2}\begin{bmatrix}1 & 1 \\ \frac{1}{b} & -\frac{1}{b}\end{bmatrix}\begin{bmatrix}\dot{\phi}_R \\ \dot{\phi}_L\end{bmatrix} \tag{1}$$

or in discrete type

$$\mathbf{x}_{vk} = \mathbf{x}_{vk-1} + \Delta\mathbf{x}_v \,; \quad \Delta\mathbf{x}_v = \begin{bmatrix}\Delta X_A \\ \Delta Y_A \\ \Delta\theta_A\end{bmatrix} = \begin{bmatrix}\cos(\theta_A + \Delta\theta) & 0 \\ \sin(\theta_A + \Delta\theta) & 0 \\ 0 & 1\end{bmatrix}\begin{bmatrix}\Delta s \\ \Delta\theta\end{bmatrix}; \quad \begin{bmatrix}\Delta s \\ \Delta\theta\end{bmatrix} = \frac{r}{2}\begin{bmatrix}1 & 1 \\ \frac{1}{b} & -\frac{1}{b}\end{bmatrix}\begin{bmatrix}\Delta\phi_r \\ \Delta\phi_l\end{bmatrix} \tag{2}$$

where is posture vector of AGV, is AGV position in global coordinates, is AGV orientation that is taken counterclockwise from the axis, is linear velocity and is angular velocity, is wheel radius, is distance between the wheels and center of AGV, and are right and left wheel angular velocities, is linear displacement of AGV, is the change of rotational angle of AGV, and are the change of right and left wheel rotation angle.

2.2 Controller Design

The purpose of this section is to design an trajectory tracking controller for AGV to track the reference position (x_r (t),y_r (t)) and reference orientation θ_r (t) with reference linear velocity V_r (t) and angular velocity ω_r (t) . The tracking error vector and its time derivative are defined as follows:

$$\mathbf{e}(t) = \begin{bmatrix}e_1 \\ e_2 \\ e_3\end{bmatrix} = \begin{bmatrix}\cos\theta_A & \sin\theta_A & 0 \\ -\sin\theta_A & \cos\theta_A & 0 \\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x_r - X_A \\ y_r - Y_A \\ \theta_r - \theta_A\end{bmatrix}; \quad \dot{\mathbf{e}}(t) = \begin{bmatrix}\dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3\end{bmatrix} = \begin{bmatrix}\cos e_3 & 0 \\ \sin e_3 & 0 \\ 0 & 1\end{bmatrix}\begin{bmatrix}V_r \\ \omega_r\end{bmatrix} + \begin{bmatrix}-1 & e_2 \\ 0 & -e_1 \\ 0 & 1\end{bmatrix}\begin{bmatrix}V_A \\ \omega_A\end{bmatrix} \tag{3}$$

To guarantee the stability of the system, Lyapunov function is chosen as:

$$V_0 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{k_2}(1 - \cos e_3) \quad \text{for} \quad k_2 > 0 \tag{4}$$

and its derivatives becomes

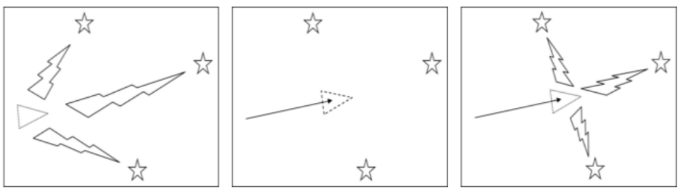
$$\dot{V}_0 = e_1\dot{e}_1 + e_2\dot{e}_2 + \frac{1}{k_2}(\sin e_3)\dot{e}_3 = e_1(-V_A + V_r\cos e_3) + \frac{1}{k_2}(\sin e_3)(\omega_r - \omega_A + k_2 e_2 V_r) \tag{5}$$

To achieve $\dot{V}_0(t) \leq 0$, the control law $\mathbf{U}$ is chosen as follows:

$$\mathbf{U} = \begin{bmatrix}V_A \\ \omega_A\end{bmatrix} = \begin{bmatrix}V_r\cos e_3 + k_1 e_1 \\ \omega_r + k_2 V_r e_2 + k_3 \sin e_3\end{bmatrix} \tag{6}$$

2.3 Simultaneous Localization and Mapping (SLAM)

The AGV position can be obtained using SLAM method using Extended Kalman filter (EKF). The EKF algorithm consists of prediction and update. Firstly, the landmarks are detected as shown in Figure 2(a). When the encoder data change because the AGV moves, AGV new position is predicted using EKF prediction step based on encoder data as shown in Figure 2(b). Secondly, Landmarks are then extracted from the environment from the AGV new position as in Figure 2(c).



(a) (b) (c)

Figure 2: SLAM algorithm

The estimation position obtained from prediction step $\hat{\mathbf{x}}_{k|k-1}$ and covariance matrix obtained from prediction step $\mathbf{P}_{k|k-1}$ at current sampling time k based on encoder data is:

Prediction:

$$\hat{\mathbf{x}}_{k|k-1} = \hat{\mathbf{x}}_{k-1|k-1} + \mathbf{F}_x^T f(\hat{\mathbf{x}}_{v,k-1}, \mathbf{u}_{k-1}) \qquad \text{for} \quad \mathbf{F}_x = [\mathbf{I}^{(3)} \quad \mathbf{O}^{(3)\times(2n)}]$$

$$\mathbf{P}_{k|k-1} = \mathbf{A}_k \mathbf{P}_{k-1|k-1}\mathbf{A}_k^T + \mathbf{W}_k \mathbf{Q}_{k-1}\mathbf{W}_k^T \qquad \text{for} \quad \mathbf{A}_k = \mathbf{I}^{(3+2n)} + \mathbf{F}_x^T \mathbf{A}_{x,k}\mathbf{F}_x \tag{7}$$

where $\mathbf{x} = [\mathbf{x}_v \quad \mathbf{y}_1 \quad \cdots \quad \mathbf{y}_n]^T$ is state vector that consists of AGV posture vector $\mathbf{x}_v = [X_A \quad Y_A \quad \theta_A]^T$ and landmark positions vector $\mathbf{y}_i = [X_i \quad Y_i]^T$. $k|k-1$ is probability of data at sampling time k given data at sampling time $k-1$. In prediction step, $\mathbf{F}_x$ is used to make sure that only AGV position is updated.

This prediction is based on the input $\mathbf{u}$ that consists of changes of right encoder $\Delta\phi_r$ and left encoder $\Delta\phi_l$ respectively. AGV mathematic modeling in discrete type in Eq. (2) is reduced as follows:

$$f(\mathbf{x}_v, \mathbf{u}) \equiv \mathbf{x}_{vk} - \mathbf{x}_{vk-1} = \Delta\mathbf{x}_v = \begin{bmatrix}\cos(\theta_A + \Delta\theta) & 0 \\ \sin(\theta_A + \Delta\theta) & 0 \\ 0 & 1\end{bmatrix}\begin{bmatrix}\Delta s \\ \Delta\theta\end{bmatrix};$$

$$\begin{bmatrix}\Delta s \\ \Delta\theta\end{bmatrix} = \frac{r}{2}\begin{bmatrix}1 & 1 \\ \frac{1}{b} & -\frac{1}{b}\end{bmatrix}\begin{bmatrix}\Delta\phi_r \\ \Delta\phi_l\end{bmatrix}; \quad \mathbf{u} = [\Delta\phi_r \quad \Delta\phi_l] \tag{8}$$

3. Simulation and Experimental Result

The simulation and experimental results are shown in Figure 4-6.

Figure 4 shows the simulation process of trajectory tracking and SLAM. The LMS measurement result is shown as 180° area in front of AGV. The positions of landmarks are estimated using EKF based on LMS measurement result. The circular area around the landmark is the probability position of the landmark. Based on the positioning obtained from SLAM, the AGV successfully tracks the given trajectory.

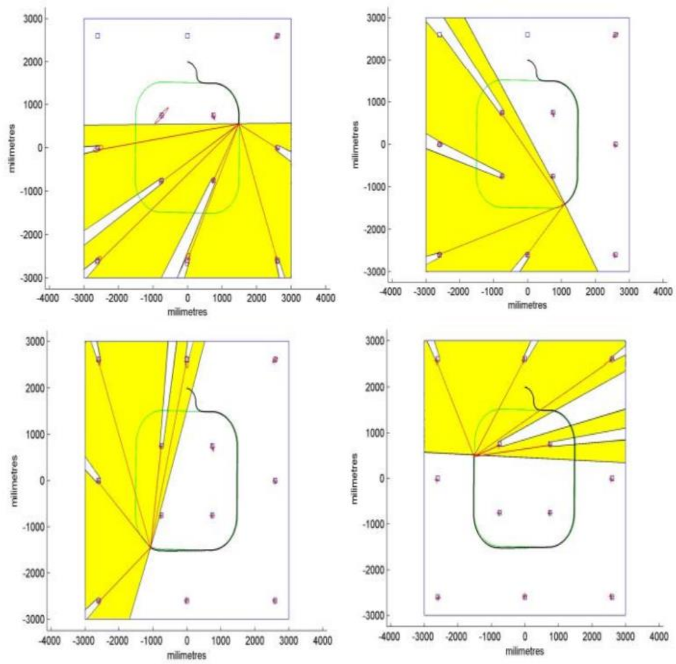


Figure 4: Simulation process

Figure 5 shows the experimental process using real AGV system. The trajectory and landmark position for experiment is similar with that is used in simulation. The landmarks are metal rods with diameter 5 cm placed within certain distance. The AGV then follows the given trajectory. This experimental result shows that the proposed algorithm is successfully applied to real system.

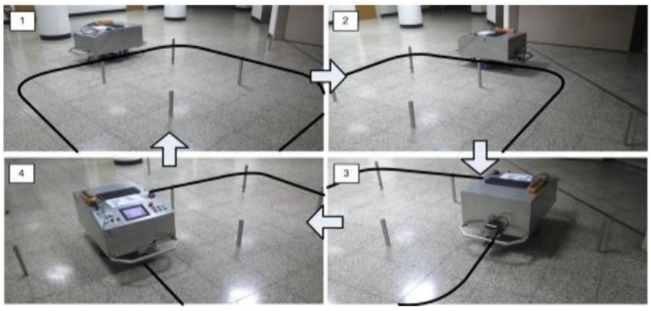


Figure 5: Experimental process

Figure 6 shows the trajectory tracking result of AGV obtained from simulation and experiment. The simulation result is similar with the experimental result. It is shown that the proposed controller successfully makes AGV track the reference trajectory in simulation and experiment.

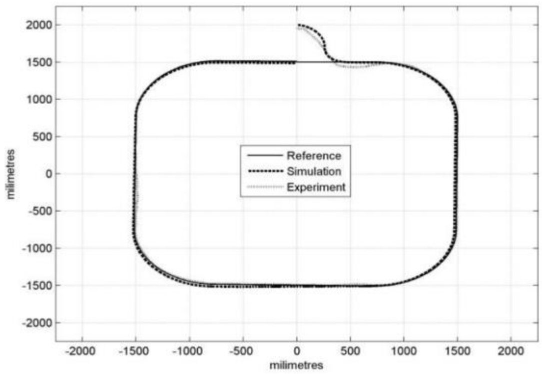


Figure 6: Trajectory tracking of AGV in simulation and experiment

4. Conclusions

This paper proposed backstepping control method for AGV to tracks the reference trajectory based on kinematic modeling of differential drive system, and simultaneous localization and mapping (SLAM) for positioning. The controlled system is stable in sense of Lyapunov stability. The simulation and experimental results show that the proposed controller successfully tracks reference trajectory with acceptable small error.

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