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Trajectory Tracking Control of AGV Based on Sliding Mode Control With the Improved Reaching Law

YUXING HAN [1], YI CHENG [2], AND GUOWEI XU [2]
[1]School of Software, Beijing Institute of Technology, Beijing 100081, China
[2]School of Electrical Engineering and Automation, Tianjin Polytechnic University, Tianjin 300387, China

Corresponding author: Yuxing Han (hyx_0502@sina.com)

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ABSTRACT In order to quicken the response of the sliding mode control system, a novel reaching law with the dynamic coefficients, which could strengthen the role of the major term and weaken the role of the minor term, respectively, in the different stages, is proposed. The finite-time convergence of the improved reaching law is proved. The kinematical and the dynamic models of the automated guided vehicle are established, and a double closed-loop control is designed to perform the trajectory tracking. The sliding mode control method based on the improved reaching law is used to control the attitude of the automated guided vehicle, and the outer loop controller outputs the desired attitude. The simulation results show that the improved reaching law could make the system arrive at the sliding surface more rapidly than the conventional reaching laws, the automated guided vehicle could have faster attitude response speed, and the different given trajectories could be tracked effectively by the double closed-loop control method.

INDEX TERMS Automated guided vehicle, sliding mode control, reaching law, trajectory tracking, double closed-loop control.

I. INTRODUCTION

An automated guided vehicle (AGV) belongs to a kind of mobile robot. It could be used universally in many fields, such as the military or the civil itinerant inspection, the logistics distribution [1]–[3]. AGV has become a key device in the flexible manufacturing system and the automatic transportation system of the logistics [4]–[6]. Generally, a fully functional AGV is composed of the motion mechanism, the sensing system and the control system [7], [8]. The motion mechanism determines the moving mode, and the sensing system determines the navigation model. There are many common sensors, such as the laser sensor, the ultrasonic sensor, the electro-optic sensor, the electromagnetic sensor, CCD vidicon, the infrared sensor, and GPS. The control system determines the overall performance of AGV [9], [10].

Generally, in order to perform the cargo handling between the two positions, AGV must have the function of the trajectory tracking [11]. That is, AGV can move along a given trajectory. However, the AGV based on the differential steering has three degrees of freedom and two control inputs, so it is a complex under-actuated system [12]. Even so, many control methods have been applied to track the trajectory [13]–[17], and it is important to establish the kinematics model and the dynamics model to control the trajectory tracking of the AGV. Furthermore, because of the complexity of under-actuated AGV system, robust control methods could be considered to be used to improve the control performance. For instance, sliding mode control method has the good robustness to the uncertainty of the system internal parameter and external disturbances [18], [19]. In many complex under-actuated systems, sliding mode control method shows good control effectiveness [20]. However, the chattering phenomenon is one of the major issues of the sliding mode control. Of course, there are some strategies could be use to reduce the chattering. For instance, the high-order sliding mode control method which could act the discontinuous control effects on the higher order differential of the sliding

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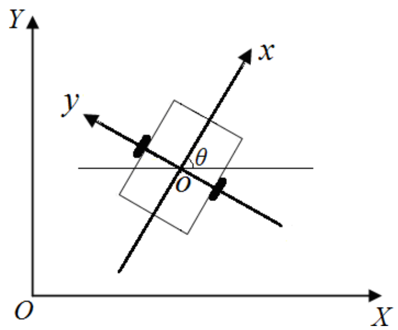

FIGURE 1. The coordinate systems of AGV.

mode could alleviate the chattering [21], [22]. Furthermore, the sliding mode control method based on the reaching law is another valid method to reduce the chattering [23]–[25]. There are many forms of the reaching laws which have been designed, such as, the constant reaching law, the exponential reaching law, the power reaching law, the quick power reaching law, the double power reaching law, and so on. Among them, the double power reaching law has better control performance because it could make two power terms play separately major role in the different stages. However, the coefficients of the two power terms are invariant in the whole control process, so it lacks the adaptivity to strengthen the role of the major term in the different stages.

In order to further improve control performance, a new double power reaching law with the dynamic coefficients is proposed in this paper. It could strengthen the role of the major term and weaken the role of the minor term in the different stages to quicken the system response. Thus, the new reaching law could be applied to control the attitude of AGV to improve the control performance, and a double closed loop control strategy based on the sliding mode control is designed to perform the trajectory tracking. Both the theoretical analysis and the simulation results are given to prove the validity of the method.

II. THE COORDINATE SYSTEMS OF AGV

AGV could be designed as many different structures. For instance, the number of the wheels could be designed as two, three, four or six, and the steering mechanism could be designed by the two-wheel differential or the engine. AGV in this paper has two driving wheels and two universal wheels. The driving wheels supply both the movement power and the differential steering, and the universal wheels mounted separately on the front and the rear of the vehicle are used to support the vehicle body. The mass center of the vehicle body could be set at the middle of the two driving wheels by adjusting the counter weight as shown in Fig. 1.

Two coordinate systems, the world coordinate system XOY and the vehicle coordinate system xoy, are established in Fig.1. The rotation angle between the world coordinate system and the vehicle coordinate system is θ, and the coordinate of the origin o in the XOY is (x_c, y_c). Based on the homogeneous coordinate form, the coordinate transformation between the two coordinate systems could be described as:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -x_c \\ 0 & 1 & -y_c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{1}$$

or,

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & x_c \\ 0 & 1 & y_c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2}$$

III. THE TRAJECTORY TRACKING CONTROL

In order to improve the control performance, a double closed-loop control is designed to perform the trajectory tracking. The structure of the trajectory tracking control is shown in Fig.2.

The double closed-loop model which consists of an inner attitude loop and an outer position loop is used to control AGV to track the desired trajectory. The controller of the outer loop gives the desired velocity and the desired attitude angle for the inner loop control sub-system according to the trajectory errors. And a sliding mode control method based on a new reaching law is designed in the inner loop to control the attitude of AGV.

A. THE OUTER LOOP CONTROLLER

Set (X, Y) to be the position coordinates of AGV. In order to perform the trajectory tracking, the kinematical equation of the AGV could be modeled as:

$$\dot{X} = v\cos\theta \tag{3}$$

$$\dot{Y} = v\sin\theta \tag{4}$$

Set the desired the trajectory to be $[X_d(t), Y_d(t)]$, the tracking error could be defined as $[e_X, e_Y]$, and the error equations could be described as:

$$\dot{e}_X = v\cos\theta - \dot{X}_d \tag{5}$$

$$\dot{e}_Y = v\sin\theta - \dot{Y}_d \tag{6}$$

Suppose $u_1 = v\cos\theta$, $u_2 = v\sin\theta$, $s_1 = e_X$ and $s_2 = e_Y$. The control laws u_1 and u_2 are designed as:

$$u_1 = \dot{X}_d - k_1 s_1 \tag{7}$$

$$u_2 = \dot{Y}_d - k_2 s \tag{8}$$

Thus,

$$\dot{s}_1 = -k_1 s_1 \tag{9}$$

$$\dot{s}_2 = -k_2 s_2 \tag{10}$$

where, $k_1 > 0$ and $k_2 > 0$. Define two lyapunov functions as:

$$V_X = \frac{1}{2} s_1^2 \tag{11}$$

$$V_Y = \frac{1}{2} s_2^2 \tag{12}$$

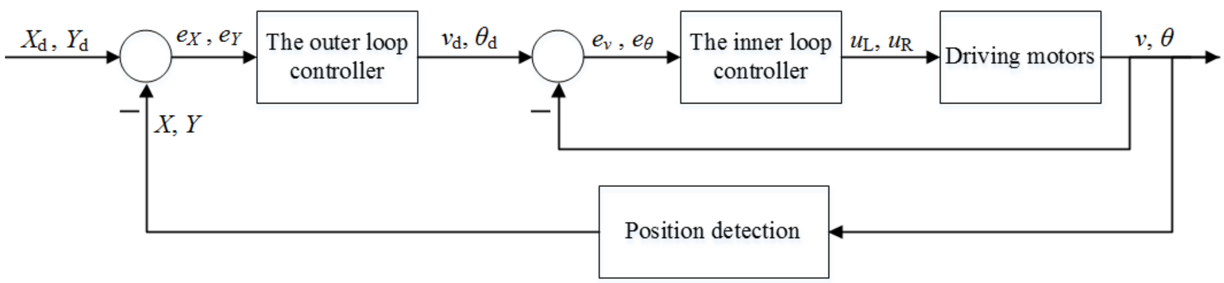

FIGURE 2. The trajectory tracking control structure of AGV.

So,

$$\dot{V}_X = s_1\dot{s}_1 = -k_1 s_1^2 = -2k_1 V_X \tag{13}$$

$$\dot{V}_Y = s_2\dot{s}_2 = -k_2 s_2^2 = -2k_2 V_Y \tag{14}$$

According to Eq.(13) and Eq.(14), the stability of the system could be proved. Combining Eq,(9) and Eq.(10), it can be seen that the errors e_X and e_Y could converge exponentially to zero. That is, the control laws designed in Eq.(7) and Eq.(8) could control AGV to track the desired trajectory. Thus, the desired angle θ_d and the desired velocity v_d could be resolved as:

$$\theta_d = \arctan\frac{u_2}{u_1} \tag{15}$$

$$v_d = \begin{cases} \sqrt{u_1^2 + u_2^2}, & \text{if } -\dfrac{\pi}{2} < e_\theta < \dfrac{\pi}{2} \\ 0, & \text{if } e_\theta = \pm\dfrac{\pi}{2} \\ -\sqrt{u_1^2 + u_2^2}, & \text{else.} \end{cases} \tag{16}$$

where, e_θ is the error between the desired attitude angel and the actual attitude angle. When e_θ falls inside the range $(-\pi/2, \pi/2)$, AGV moves forwards; when e_θ falls outside the range $[-\pi/2, \pi/2]$, AGV moves backwards; and when e_θ is $\pm\pi/2$, AGV would stop to wait for the attitude angle adjustment.

The attitude desired angle θ_d and the velocity v_d are given in Eq.(15) and Eq.(16). In order to improve the robustness, the sliding mode control would be used to perform the inner loop control.

In summary, in the double closed-loop model above, the control laws, u_1 and u_2, of the outer loop could be obtained according to trajectory errors, and the desired attitude angle θ_d and the desired velocity v_d could be calculated according to Eq. (eq15) and Eq.(16).

B. THE INNER LOOP CONTROLLER

The attitude control system is designed as the inner loop control. Generally, the angular velocities of the driving wheels could be used as the control variables. However, in the actual system, the angular velocity is not a direct controllable quantity. For DC motor, the angular velocity of the motor could be controlled by changing the armature voltage. That is, the armature voltage could be regarded as the direct controllable quantity.

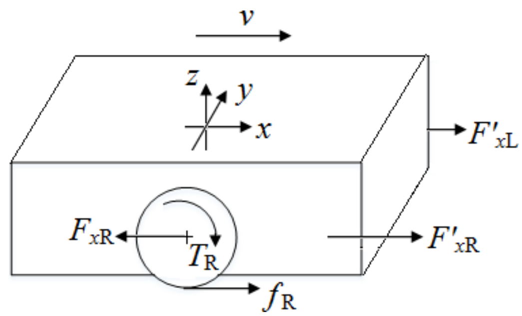

FIGURE 3. The force analysis of the vehicle.

For this, the dynamics model of AGV is rebuilt, and the attitude control equations with the armature voltage as the controlling quantity are given. In order to improve the control performance, the sliding mode control method would be used to control the attitude of AGV in the inner loop.

1) THE DYNAMICS MODEL OF AGV

Suppose that the parameters of the left and the right driving wheels are same. That is, the mass of the driving wheel is m, the radius of the driving wheel is r, the moment of inertia of the driving wheel is J, and the moment of inertia of the vehicle body around the axis z is J_z. The force analysis of the vehicle is shown in Fig.3.

According to Newton's laws, the torque balance equations of left and right wheels could be described as:

$$T_L - T_{zL} = J\frac{d\omega_L}{dt} \tag{17}$$

$$T_R - T_{zR} = J\frac{d\omega_R}{dt} \tag{18}$$

where, T_L and T_R are separately the electromagnetic torques of the left and the right motors. T_{zL} and T_{zR} are separately the load torques of the left and the right motors.

$$T_L = T_{zL} + J\frac{d\omega_L}{dt} = f_L r + J\frac{d\omega_L}{dt} \tag{19}$$

$$T_R = T_{zR} + J\frac{d\omega_R}{dt} = f_R r + J\frac{d\omega_R}{dt} \tag{20}$$

where, f_L and f_R are separately the frictional forces on the left and the right wheels.

$$f_L - F_{xL} = m\frac{dv_L}{dt} = mr\dot{\omega}_L \tag{21}$$

$$f_R - F_{xR} = m\frac{dv_R}{dt} = mr\dot{\omega}_R \tag{22}$$

where, F_{xL} and F_{xR} are separately the forces of the vehicle to the left and the right wheels in x direction, and their reaction forces are separately F'_{xL} and F'_{xR}. According to Newton's Third Law of Motion action and reaction are equal and opposite. That is, $F_{xL} = -F'_{xL}$ and $F_{xR} = -F'_{xR}$.

$$F'_{xL} + F'_{xR} = M\dot{v} = M(\dot{\omega}_L + \dot{\omega}_R)r/2 \tag{23}$$

where, M is the mass of the vehicle body, and v is the velocity of the vehicle body.

$$(F'_{xR} - F'_{xL}) \cdot l/2 = J_z\ddot{\theta} = J_z(\dot{\omega}_R - \dot{\omega}_L)r/l \tag{24}$$

The voltage equations of the left and the right motors could be described as:

$$u_L = k_T\dot{T}_L + k_R T_L + k_e\omega_L \tag{25}$$

$$u_R = k_T\dot{T}_R + k_R T_R + k_e\omega_R \tag{26}$$

where, $k_\mathrm{T}, k_\mathrm{R}, k_\mathrm{e}$ are the parameters of motors. Substitute Eq.(19) and Eq.(20) into Eq.(25) and Eq.(26):

$$\begin{aligned} u_L = &\, k_T(J\ddot{\omega}_L + r^2 m\ddot{\omega}_L + \dot{F}_{xL}r) \\ &+ k_R(J\dot{\omega}_L + mr^2\dot{\omega}_L + F_{xL}r) + k_e\omega_L \end{aligned} \tag{27}$$

$$\begin{aligned} u_R = &\, k_T(J\ddot{\omega}_R + r^2 m\ddot{\omega}_R + \dot{F}_{xR}r) \\ &+ k_R(J\dot{\omega}_R + mr^2\dot{\omega}_R + F_{xR}r) + k_e\omega_R \end{aligned} \tag{28}$$

Suppose $u'_1 = u_\mathrm{L} + u_\mathrm{R}$ and $u'_2 = u_\mathrm{R} - u_\mathrm{L}$:

$$\begin{aligned} u'_1 = &\, k_T(J\frac{2}{r} + 2mr - rM)\ddot{v} \\ &+ k_R(J\frac{2}{r} + 2mr - rM)\dot{v} + k_e\frac{2}{r}v \end{aligned} \tag{29}$$

$$\begin{aligned} u'_2 = &\, k_T(J\frac{l}{r} + rml - \frac{2r}{l}J_Z)\dddot{\theta} \\ &+ k_R(J\frac{l}{r} + rml - \frac{2r}{l}J_Z)\ddot{\theta} + k_e\frac{l}{r}\dot{\theta} \end{aligned} \tag{30}$$

Thus,

$$\begin{aligned} \dddot{v} = &-\frac{k_R}{k_T}\dot{v} - \frac{2k_e/r}{k_T(J\frac{2}{r} + 2mr - rM)}v \\ &+ \frac{1}{k_T(J\frac{2}{r} + 2mr - rM)}u'_1 \end{aligned} \tag{31}$$

$$\begin{aligned} \theta = &-\frac{k_R}{k_T}\ddot{\theta} - \frac{k_e l/r}{k_T(J\frac{l}{r} + rml - \frac{2r}{l}J_Z)}\dot{\theta} \\ &+ \frac{1}{k_T(J\frac{l}{r} + rml - \frac{2r}{l}J_Z)}u'_2 \end{aligned} \tag{32}$$

Suppose $S_v = J\frac{2}{r} + 2mr - rM$ and $S_\theta = J\frac{l}{r} + rml - \frac{2r}{l}J_Z$, and the attitude control equations of AGV could be modeled as:

$$\begin{bmatrix} \dot{v} \\ \ddot{v} \\ \dot{\theta} \\ \ddot{\theta} \\ \dddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ \frac{-2k_e}{rk_T S_v} & -\frac{k_R}{k_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \frac{-k_e l}{rk_T S_\theta} & -\frac{k_R}{k_T} \end{bmatrix} \begin{bmatrix} v \\ \dot{v} \\ \theta \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{k_T S_v} & \frac{1}{k_T S_v} \\ 0 & 0 \\ 0 & 0 \\ \frac{-1}{k_T S_\theta} & \frac{1}{k_T S_\theta} \end{bmatrix} \begin{bmatrix} u_L \\ u_R \end{bmatrix} \tag{33}$$

2) SLIDING MODE CONTROL

In order to enhance the robustness of the system, based on the attitude control equations above, sliding mode control method is used to control the attitude of AGV. However, the chattering phenomenon is an inherent problem to restrict the application of sliding mode control. For this, many valid control strategies have been proposed to reduce chattering in sliding mode control. For instance, the sliding mode control method based on the reaching law could not only reduce the chattering but also reach the sliding mode surface quickly. There are many reaching laws which have been designed to make the system reach the sliding mode surface with the different speed, such as the constant reaching law, the exponential reaching law and the power reaching law. Combining the exponential reaching law and the power reaching law, the quick power reaching law could be described as:

$$\dot{s} = -k_1\,|s|^\beta\,\mathrm{sgn}\,(s) - k_2 s \tag{34}$$

Furthermore, the double power reaching law has the better reaching performance. The double power reaching law could be designed as:

$$\dot{s} = -k_1|s|^\alpha \mathrm{sgn}(s) - k_2|s|^\beta \mathrm{sgn}(s) \tag{35}$$

where, s is the switching function, $\alpha > 1, 0 < \beta < 1, k_1 > 0$, and $k_2 > 0$. The reaching law is composed of two power terms. When $|s| > 1$, the first term plays the major role, and when $|s| < 1$, the second term plays the major role. In this way, the double power reaching law could ensure the system always has a fast reaching speed whether far from or close to the sliding mode surface. In fact, the advantages of the double power reaching law could be further explored to improve the reaching performance by strengthening the roles of the two terms separately. For this, an improved reaching law is proposed as:

$$\dot{s} = \frac{-2k_1}{1 + e^{-c'_1(|s|-1)}}|s|^\alpha \mathrm{sgn}(s) + \frac{-2k_2 e^{-c'_2(|s|-1)}}{1 + e^{-c'_2(|s|-1)}}|s|^\beta \mathrm{sgn}(s) \tag{36}$$

where, $c'_1 > 0$, and $c'_2 > 0$. Compared with the double power reaching law, the coefficients of the new improved reaching law in Eq.(36) could be dynamically changed according to $|s|$. That is, when $|s| > 1$, the first term of the improved reaching law play a stronger role and the second term of the improved reaching law play a less role. Instead, when $|s| < 1$, the first term of the improved reaching law play a less role and the second term of the improved reaching law play a stronger role. To conclude, the role of the major term could be further strengthened and the secondary term could be further weakened. Thus, the system could quickly reach the surface with the desired speed, which could help to improve the control performance of the system.

Theorem 1: The state variables, s and $\dot{s}$, of the system defined in Eq.(36) could converge to the equilibrium point $(0, 0)$ in a finite-time, i.e., $\dot{s} = s = 0$ after a finite convergence time.

Proof: According to the conditions: $\alpha > 1$, $0 < \beta < 1$, $k_1 > 0$, $k_2 > 0$, $c'_1 > 0$, and $c'_2 > 0$,

$$s\dot{s} = \frac{-2k_1}{1+e^{-c'_1(|s|-1)}}|s|^{\alpha+1} + \frac{-2k_2 e^{-c'_2(|s|-1)}}{1+e^{-c'_2(|s|-1)}}|s|^{\beta+1} < 0 \tag{37}$$

Thus, the reachability condition of the sliding mode surface could be met.

Suppose $s(0) > 1$, the reaching process could be divided two stages: from $s(0)$ to $s = 1$ and from $s = 1$ to $s = 0$.

$$\dot{s} = \frac{-2k_1}{1+e^{-c'_1(s-1)}}s^{\alpha} + \frac{-2k_2 e^{-c'_2(s-1)}}{1+e^{-c'_2(s-1)}}s^{\beta} \tag{38}$$

$$\int_{s(0)}^{0} \frac{1}{\frac{-2k_1}{1+e^{-c'_1(s-1)}}s^{\alpha} + \frac{-2k_2 e^{-c'_2(s-1)}}{1+e^{-c'_2(s-1)}}s^{\beta}}ds = \int_0^{t'_1} dt \tag{39}$$

For the first stage, from $s(0)$ to $s = 1$, the first term in Eq.(38) plays the major role:

$$\begin{aligned} t'_1 &= \int_1^{s(0)} \frac{1}{\frac{2k_1}{1+e^{-c'_1(s-1)}}s^{\alpha} + \frac{2k_2 e^{-c'_2(s-1)}}{1+e^{-c'_2(s-1)}}s^{\beta}}ds \\ &< \int_1^{s(0)} \frac{1}{k_1 s^{\alpha}}ds = \frac{1-s(0)^{1-\alpha}}{k_1(\alpha-1)} \end{aligned} \tag{40}$$

For the second stage, from $s = 1$ to $s = 0$, the second term in Eq.(38) plays the major role:

$$\begin{aligned} t'_2 &= \int_0^{1} \frac{1}{\frac{2k_1}{1+e^{-c'_1(s-1)}}s^{\alpha} + \frac{2k_2 e^{-c'_2(s-1)}}{1+e^{-c'_2(s-1)}}s^{\beta}}ds \\ &< \int_0^{1} \frac{1}{k_2 s^{\beta}}ds = \frac{1}{k_2(1-\beta)} \end{aligned} \tag{41}$$

Therefore, the sum time t' could be calculated as:

$$t' = t'_1 + t'_2 < \frac{1-s(0)^{1-\alpha}}{k_1(\alpha-1)} + \frac{1}{k_2(1-\beta)} \tag{42}$$

Likewise, If $s(0) < -1$, the reaching process also could be divided two stages: from $s(0)$ to $s = -1$ and from $s = -1$ to $s = 0$. The sum time t'' could be calculated as:

$$t'' = t''_1 + t''_2 < \frac{1-(-s(0))^{1-\alpha}}{k_1(\alpha-1)} + \frac{1}{k_2(1-\beta)} \tag{43}$$

In conclusion, for the any initial state $s(0)$, the system could converge to the equilibrium point $(0, 0)$ in a finite-time t:

$$t < \frac{1-|s(0)|^{1-\alpha}}{k_1(\alpha-1)} + \frac{1}{k_2(1-\beta)} \tag{44}$$

In this paper, the improved reaching law above is used to control the attitude of the vehicle. Suppose $e_v = v - v_d$ and $e_\theta = \theta - \theta_d$. The two sliding mode surfaces could be defined as:

$$s_3 = c_0 e_v + \dot{e}_v \tag{45}$$

$$s_4 = c_1 e_\theta + c_2 \dot{e}_\theta + \ddot{e}_\theta \tag{46}$$

where, the coefficients c_0, c_1 and c_2 meet the Hurwitz condition.

$$\begin{aligned} \dot{s}_3 &= c_0 \dot{e}_v + \ddot{e}_v \\ &= c_0 \dot{v} - c_0 \dot{v}_d - \frac{2k_e}{rk_T S_v}v - \frac{k_R}{k_T}\dot{v} + \frac{1}{k_T S_v}u'_1 - \ddot{v}_d \end{aligned} \tag{47}$$

$$\begin{aligned} \dot{s}_4 &= c_1 \dot{e}_\theta + c_2 \ddot{e}_\theta + \dddot{e}_\theta \\ &= c_1 \dot{\theta} - c_1 \dot{\theta}_d + c_2 \ddot{\theta} - c_2 \ddot{\theta}_d \\ &\quad - \frac{k_e l}{rk_T S_\theta}\dot{\theta} - \frac{k_R}{k_T}\ddot{\theta} + \frac{1}{k_T S_\theta}u'_2 - \dddot{\theta}_d \end{aligned} \tag{48}$$

Thus,

$$\begin{aligned} u'_1 &= \frac{-2k_1 k_T S_v}{1+e^{-c'_1(|s_3|-1)}}|s_3|^{\alpha}\mathrm{sgn}(s_3) \\ &\quad + \frac{-2k_2 k_T S_v e^{-c'_2(|s_3|-1)}}{1+e^{-c'_2(|s_3|-1)}}|s_3|^{\beta}\mathrm{sgn}(s_3) \\ &\quad - c_0 k_T S_v \dot{v} + c_0 k_T S_v \dot{v}_d + \frac{2k_e}{r}v + S_v k_R \dot{v} + k_T S_v \ddot{v}_d \end{aligned} \tag{49}$$

$$\begin{aligned} u'_2 &= \frac{-2k_1 k_T S_\theta}{1+e^{-c'_1(|s_4|-1)}}|s_4|^{\alpha}\mathrm{sgn}(s_4) \\ &\quad + \frac{-2k_2 k_T S_\theta e^{-c'_2(|s_4|-1)}}{1+e^{-c'_2(|s_4|-1)}}|s_4|^{\beta}\mathrm{sgn}(s_4) \\ &\quad - c_1 k_T S_\theta \dot{\theta} + c_1 k_T S_\theta \dot{\theta}_d - k_T S_\theta c_2 \ddot{\theta} \\ &\quad + k_T S_\theta c_2 \ddot{\theta}_d + \frac{k_e l}{r}\dot{\theta} + k_R S_\theta \ddot{\theta} +_1 k_T S_\theta \dddot{\theta}_d \end{aligned} \tag{50}$$

Define lyapunov function as:

$$V = \frac{1}{2}s_3^2 + \frac{1}{2}s_4^2 \tag{51}$$

So,

$$\begin{aligned} \dot{V} &= s_3 \dot{s}_3 + s_4 \dot{s}_4 \\ &= \frac{-2k_1 k_T S_v}{1+e^{-c'_1(|s_3|-1)}}|s_3|^{\alpha+1} + \frac{-2k_2 k_T S_v e^{-c'_2(|s_3|-1)}}{1+e^{-c'_2(|s_3|-1)}}|s_3|^{\beta+1} \\ &\quad + \frac{-2k_1 k_T S_\theta}{1+e^{-c'_1(|s_4|-1)}}|s_4|^{\alpha+1} \\ &\quad + \frac{-2k_2 k_T S_\theta e^{-c'_2(|s_4|-1)}}{1+e^{-c'_2(|s_4|-1)}}|s_4|^{\beta+1} \\ &\le 0 \end{aligned} \tag{52}$$

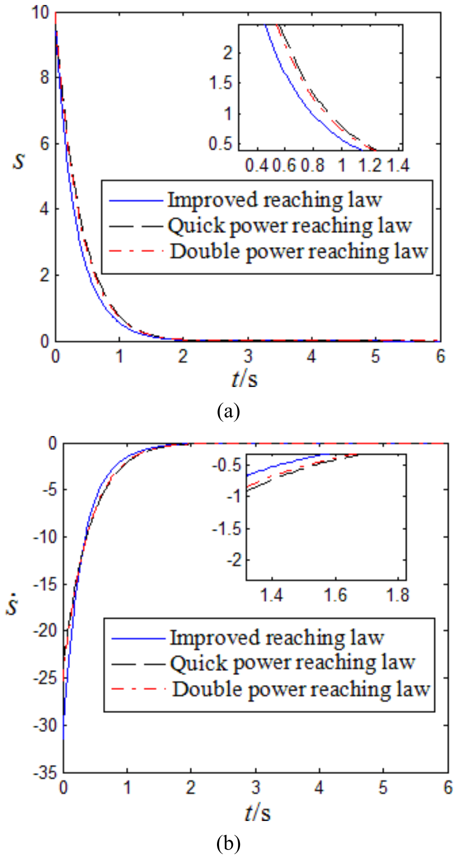

FIGURE 4. The changes of the system states. (a) The response of the state s. (b) The response of the state $\dot{s}$.

where, the equalit y holds up if and only if $s = 0$. Thus, the reachability of the sliding mode surface could be proved.

From Eq.(36), If $c'_1 = c'_2 = 0$, the improved reaching law would become the double power reaching law. Therefore, c'_1 and c'_2 are the key parameters of the reaching law. The larger the parameters, the faster the convergence. Therefore, the parameters should be designed within the constraints of the fast response and the engineering feasibility

IV. SIMULATION EXPERIMENTS

A. THE REACHING SPEED

The performance of the improved reaching law in Eq.(36) is compared with the quick power reaching law in Eq.(34) and the double power reaching law in Eq.(35).

The parameters are set as: $\alpha = 1.02$, $\beta = 0.9$, $k_1 = 1.5$, $k_2 = 1.2$, $c'_1 = 1.2$ and $c'_2 = 1.4$. The changes of the system states, s and $\dot{s}$, are shown in Fig. 4.

From Fig. 4, the reaching speed of the double power reaching law is slightly faster than that of the quick power reaching law, and the reaching speed of the improved reaching law is significantly faster than that of the double power reaching law. Therefore, the sliding mode control method based on the improved reaching law could quicken the response of the system.

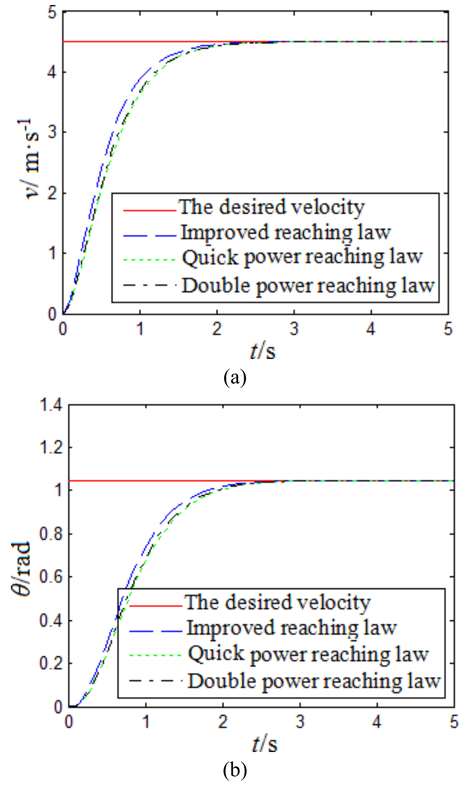

FIGURE 5. The attitude control results of the vehicle. (a) The velocity control results. (b) The attitude angel control results.

B. THE ATTITUDE CONTROL

The sliding mode control methods based on the three reaching laws above are separately designed to control the attitude of the vehicle. The parameters of AGV are set as: r = 0.1m, l = 0.8m, J = 0.005kgm^2, M = 20kg, m = 1kg, and $J_z = 6.4$kgm^2. The control results are shown in Fig. 5.

From Fig.5, the control method based on the improved reaching law has much faster response than the method based on the double power reaching law or the quick power reaching law. The improved reaching law could quicken the state of the system to the sliding mode surface, so the response of the attitude control could be accelerated. Therefore, the sliding mode control method based on the improved reaching law could be used in the inner loop to control the attitude of the vehicle.

C. THE TRAJECTORY TRACKING CONTROL

The trajectory tracking of AGV could be controlled by the double closed-loop control above. Three desired trajectories, the straight line trajectory, the sinusoidal trajectory and the given function trajectory, are given as:

$$\begin{cases} x_d = t + 1 \\ y_d = t \end{cases} \tag{53}$$

$$\begin{cases} x_d = t \\ y_d = \sin t \end{cases} \tag{54}$$

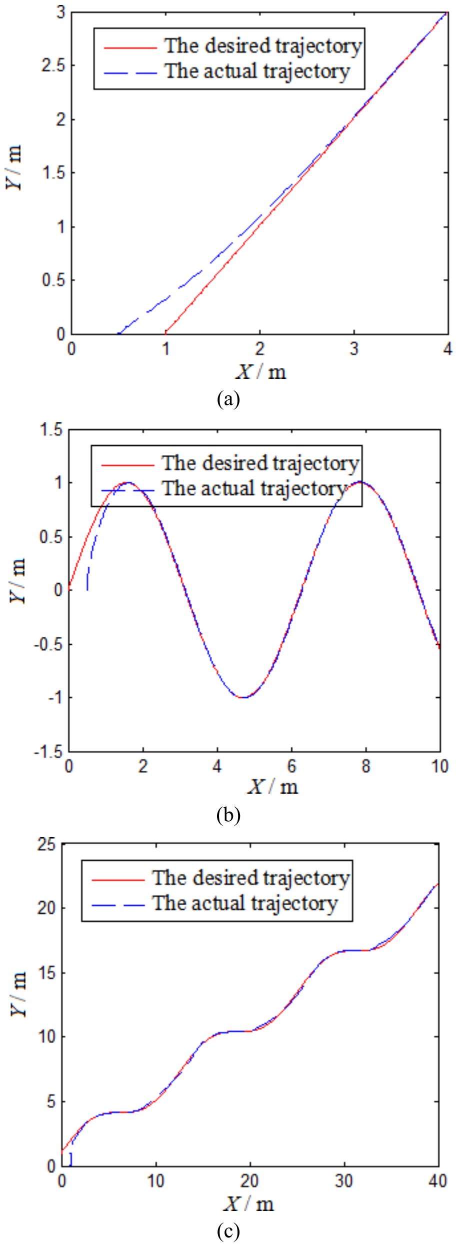

FIGURE 6. The trajectory tracking results. (a) The straight line trajectory. (b) The sinusoidal trajectory. (c) The given function trajectory.

$$\begin{cases} x_d = t \\ y_d = \sin(0.5t) + 0.5t + 1 \end{cases} \tag{55}$$

The tracking results for the straight line trajectory, the sinusoidal trajectory and the given function trajectory, are shown in Fig.6.

From Fig. 6, AGV could rapidly adjust its attitude to track the different given trajectories by the double closed-loop control method. The sliding mode control method based on the improved reaching law in the inner loop could control the angle and velocity of AGV to the desired values which are given by the outer-loop controller. So, even if the trajectory is complex, AGV still could track the given trajectory effectively.

V. CONCLUSION

A double closed-loop control method is designed to control AGV to track the given trajectory. The outer loop controller outputs the desired velocity and the desired attitude angle for the inner loop control sub-system, and a sliding mode control method based on a new reaching law is designed as the inner loop controller to control the attitude of AGV. The improved reaching law could make the system have faster response than the double power reaching law. Therefore, the control performance of the attitude sub-system could be improved by the sliding mode control method based on the improved reaching law, and the trajectory tracking could be effectively performed by the double closed-loop control method. Furthermore, the design of the high-order sliding mode control with the improved reaching law would be the subsequent research direction and deserves our further exploration.

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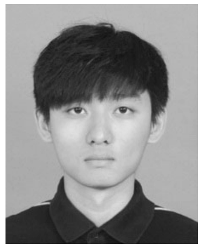

YUXING HAN received the B.S. degree in communication engineering from Beijing Information Science and Technology University, in 2009, and the M.S. degree in software engineering from the Beijing Institute of Technology, in 2013, where he is currently pursuing the Ph.D. degree in software engineering.

From 2013 to 2018, he was a Software Engineer with the China North Industries Group Corporation Ltd., Information Center. He participated in the construction of Beidou Satellite Ground Enhancement System and the development of related navigation applications. His major research interests include the unmanned driving technology and the intelligent logistics technology.

YI CHENG received the Ph.D. degree in navigation, guidance, and control from Harbin Engineering University, Harbin, China, in 2009. Her research interests include system modeling and artificial intelligent.

GUOWEI XU received the M.Sc. degree in motor and electrical professional from the Shenyang University of Technology, Shenyang, China, in 2000, and the Ph.D. degree in the textile engineering from Tianjin Polytechnic University, Tianjin, China, in 2015. His research interests include sliding mode control, neural networks, and artificial intelligence.