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Adaptive sliding mode control for uncertain wheel mobile robot

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ABSTRACT

In this paper a simple adaptive sliding mode controller is proposed for tracking control of the wheel mobile robot (WMR) systems. The WMR are complicated systems with kinematic and dynamic model so the error dynamic model is built to simplify the mathematical model. The sliding mode control then is designed for this error model with the adaptive law to compensate for the mismatched. The proposed control scheme in this work contains only one control loop so it is simple in both implementation and mathematical calculation. Moreover, the requirement of upper bounds of disturbance that is popular in the sliding mode control is cancelled, so it is convenient for real world applications. Finally, the effectiveness of the presented algorithm is verified through mathematical proof and simulations. The comparison with the existing work is also executed to evaluate the correction of the introduced adaptive sliding mode controller. Thoroughly, the settling time, the peak value, the integral square error of the proposed control scheme reduced about 50% in comparison with the compared disturbance observer based sliding mode control.

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1. INTRODUCTION

Wheel mobile robot (WMR) is one of the important branches of mobile robot with widely applications such as agriculture, service industry, and manufacture industry [1]–[5]. WMRs are classified into two main types, holonomic and nonholonomic robots [6], [7]. In comparison with holonomic type, the nonholonomic robots are more difficult in control because they are underactuated systems. In addition, the working of WMR is affected by many factors such as the surface of the floor, the working load, or the slips of the wheels. These challenges are the motivations for researchers to investigate to the controller design for nonholonomic wheel mobile robots to track the desired trajectory under the effect of the uncertainties, wheel slips, and external disturbances.

Recently, many efforts have been introduced to solve the problem of tracking control for WMR including backstepping control [8]–[11], adaptive control [12]–[15], sliding mode control (SMC) [16]–[24], and intelligent control [25]–[28]. In these, the sliding mode control is one of the popular control algorithms to deal with the problems of nonholonomic WMRs. In [16], an enhanced variable structure based on sliding mode is developed for tracking system of the nonholonomic WMR. The sliding surface is designed firstly, then the sliding controller is established based on the kinematic model. This control structure ensures the small error of a pose and controllable linear velocity and angular speed. However, the disturbances and uncertainties are not analyzed in this work. In [17]–[19], the adaptive sliding mode controls are introduced for kinematic control of wheeled mobile robot. All control schemes ensure good performance with reducing computation time. Despite these advantages, the mentioned adaptive SMCs do not consider dynamic uncertainties and disturbances. On the contrary, the SMC algorithms in [20], [21] only consider unknown dynamics and disturbances. The uncertainties and disturbances in the kinematic are not investigated in those. The nonsingular recursive-structure sliding mode controller is introduced in [22] for tracking control of the WMR. The disturbance is observed by a fixed-time observer and the upper bound of the observation error is adapted by an adaptive law. The control scheme in [22] guarantees the finite-time stability of the sliding surface but the tracking errors only converges to a small region of the origin. In [23], the sliding mode control is combined with a disturbance observer to deal with the multiple types of uncertainties. With this combination, the compensating error is eliminated, and the performances of the system are improved. However, in this scheme, it is assumed that the wheel slips and disturbances are only appeared in the dynamic loop. The WMR system in [24] is controlled by an adaptive SMC to track the reference trajectory with considering disturbances and inertia uncertainties. The control scheme achieves finite-time convergence of two subsystems, avoids explosion of calculation. Despite of these contributions, the given control algorithm does not consider the wheel slips which are typical in WMR. In parallel with the adaptive SMC, the combination of SMC with intelligent techniques including neural network and fuzzy logic are also widely applied for WMR. The work in [25] employs the fuzzy controller for dynamic control loop of WMR system to face with the dynamic disturbances and uncertainties. By combining with the adaptive law, this fuzzy adaptive SMC guarantees the robust property for the dynamic closed loop system. However, the stability of the cascade system including kinematic control loop and dynamic control loop is not proven mathematically. In [26], the fuzzy logic technique is applied to both kinematic and dynamic control loops. For the kinematic control loop, the fuzzy logic controller based on a lookup table is introduced to force the sliding surface toward zero. This control scheme guaranties good performances for WMR system under the effect of disturbances and uncertainties, but the stability is also proven for each loop separately.

In this paper, an adaptive SMC (ASMC) is proposed for the tracking control of the nonholonomic wheel mobile robot. The disturbances, the wheel slips, and the uncertainties are compensated by an adaptive law, so the system achieve the robust ability. The advantages of the proposed control scheme can be listed as the following: i) the introduced control scheme consists of only one control loop instead of two as in [16]–[24] then the complexity in mathematical proof as well as implementation is greatly reduced; ii) the proposed ASMC compensate for the unknown components acting on the whole system (the simulation is setup with the presence of the wheel slips, the external disturbances, and the parameter uncertainties) instead of considering only kinematic disturbances as in [17]–[19] or dynamic disturbances as in [20], [21]; and iii) the upper bound of the disturbance is not required as in almost conventional SMCs.

2. ADAPTIVE SLIDING MODE CONTROLLER DESIGN FOR WMRs

2.1. Modelling of WMR

The considered WMR system in this work is a three-wheel nonholonomic mobile robot. Figure 1 is the block diagram of the system. In considering to the wheel slips and input disturbance, the kinematic and dynamic of the WMR in the coordinate of Figure 1 is expressed as (1) and (2) [29], [30]:

$$\begin{bmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} cos\,\theta & -sin\,\theta & 0 \\ sin\,\theta & cos\,\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sigma \\ \dot{\rho} \\ \omega \end{bmatrix} \tag{1}$$

$$\dot{v} = -M^{-1}(Bv + Q\ddot{\gamma} + C\dot{\eta} + G\ddot{\eta} + \tau_d) + M^{-1}\tau \tag{2}$$

where ρ is the lateral slip factor along the wheel shaft, σ and ω are the forward velocity and the angular velocity of the WMR at point R, respectively, $v = [\dot{\phi}_R \quad \dot{\phi}_L]^T$, τ_d is the input disturbance, $\gamma = [\gamma_L\ \gamma_R]^T$. σ and ρ are calculated as:

$$\sigma = \frac{r(\dot{\phi}_R + \dot{\phi}_L)}{2} + \frac{\dot{\gamma}_R + \dot{\gamma}_L}{2}, \quad \rho = \frac{r(\dot{\phi}_R - \dot{\phi}_L)}{2b} + \frac{\dot{\gamma}_R - \dot{\gamma}_L}{2b}$$

in which γ_L and γ_R are longitudinal slip factors of the right and left driving wheels, respectively, $\dot{\phi}_L$ and $\dot{\phi}_R$ are the angular velocities of the right and the left wheel, respectively.

$$C = m_G \frac{r}{2} \omega \begin{bmatrix} 1 \\ 1 \end{bmatrix}, G = m_G \frac{ar}{2b} \begin{bmatrix} 1 \\ -1 \end{bmatrix}, M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, m_{22} = m_{11}, m_{21} = m_{12}$$

$$m_{11} = m_G\left(\frac{r^2}{4}+\frac{ar^2}{4b^2}\right)+\frac{r^2}{4b^2}(I_G+2I_D)+2m_w r^2+I_w,\ m_{12} = m_G\left(\frac{r^2}{4}-\frac{a^2r^2}{4b^2}\right)-\frac{r^2}{4b^2}(I_G+2I_D)$$

$$B = m_G\frac{r^2}{2b}\omega\begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix},\ Q=\begin{bmatrix}Q_1 & Q_2\\ Q_2 & Q_1\end{bmatrix},\ Q_{1,2} = m_G\frac{r}{4}\left(1\pm\frac{a^2}{b^2}\right)\pm\frac{r}{4b}(I_G+2I_D)$$

The position error between the points $R(x_R, y_R)$ and $D(x_D, y_D)$ in the $RX'Y'$ coordinate is as (3).

$$e_p = \begin{bmatrix}e_{p1}\\ e_{p2}\end{bmatrix} = \begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}x_D - x_R\\ y_D - y_R\end{bmatrix} = \begin{bmatrix}\cos\theta\,(x_D - x_R) + \sin\theta\,(y_D - y_R)\\ -\sin\theta\,(x_D - x_R) + \cos\theta\,(y_D - y_R)\end{bmatrix} \quad (3)$$

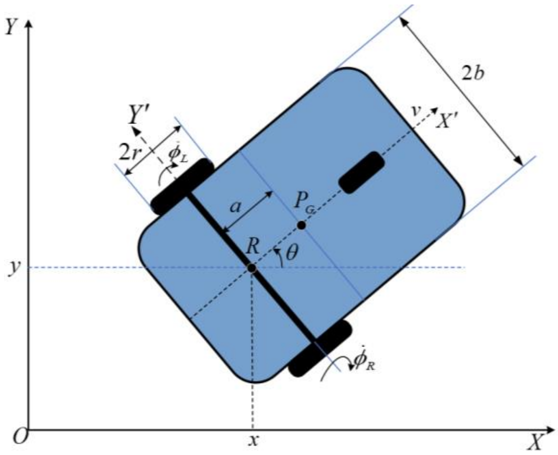


Figure 1. Block diagram of the studied WMR

Next, the error dynamic of the position error will be determined for the control design purpose. Derivative both sides of (3) with considering the wheels slip, external disturbances. The following results are obtained [29]:

$$\dot{e}_p = \begin{bmatrix}\left(\frac{e_{p2}}{b}-1\right)\frac{r}{2} & -\left(\frac{e_{p2}}{b}+1\right)\frac{r}{2}\\ -\frac{e_{p1}r}{2b} & \frac{e_{p1}r}{2b}\end{bmatrix}v + \begin{bmatrix}\left(\frac{\dot{\gamma}_R-\dot{\gamma}_L}{2b}\right)e_{p2} - \frac{\dot{\gamma}_R+\dot{\gamma}_L}{2}\\ -\left(\frac{\dot{\gamma}_R-\dot{\gamma}_L}{2b}\right)e_{p1} - \dot{\eta}\end{bmatrix} + \begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}\dot{x}_D\\ \dot{y}_D\end{bmatrix}$$
$$= hv + d_1 \quad (4)$$

where

$$h = \begin{bmatrix}\left(\frac{e_{p2}}{b}-1\right)\frac{r}{2} & -\left(\frac{e_{p2}}{b}+1\right)\frac{r}{2}\\ -\frac{e_{p1}r}{2b} & \frac{e_{p1}r}{2b}\end{bmatrix},\ d_1 = \begin{bmatrix}\left(\frac{\dot{\gamma}_R-\dot{\gamma}_L}{2b}\right)e_{p2} - \frac{\dot{\gamma}_R+\dot{\gamma}_L}{2}\\ -\left(\frac{\dot{\gamma}_R-\dot{\gamma}_L}{2b}\right)e_{p1} - \dot{\eta}\end{bmatrix} + \begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}\dot{x}_D\\ \dot{y}_D\end{bmatrix}$$

2.2. Adaptive sliding mode controller design

Define variables $x_1 = e_p$; $x_2 = \dot{x}_1 + kx_1$ where k is a positive scalar. The derivative of x_2 along with time using (2) and (4) is obtained as (5):

$$\begin{aligned}\dot{x}_2 &= \ddot{x}_1 + k\dot{x}_1\\ &= h\dot{v} + \dot{h}v + \dot{d}_1 + k(hv + d_1)\\ &= -hM^{-1}Bv + hM^{-1}\tau + hd_2 + \dot{h}v + \dot{d}_1 + khv + kd_1\\ &= P_1 v + F\tau + d_3\end{aligned} \quad (5)$$

where $P_1 = -hM^{-1}B, F = hM^{-1}, d_3 = hd_2 + \dot{h}v + \dot{d}_1 + khv + kd_1$. Replace v from (4) into (5) leading to (6):

$$\dot{x}_2 = Px_2 - kPx_1 + F\tau + d \tag{6}$$

in which $P = h^{-1}P_1 = M^{-1}B, \quad d = d_3 - P_1 h^{-1} d_1$.

The error dynamics are written in the state space form as (7).

$$\begin{cases} \dot{x}_1 = x_2 - kx_1 \\ \dot{x}_2 = Px_2 - kPx_1 + F\tau + d \end{cases} \tag{7}$$

Define the sliding surface.

$$s = \dot{x}_1 + (n+k)x_1 \tag{8}$$

where n is a scalar which satisfies $(n+k)>0$.

Choose the Lyapunov function.

$$V_1 = \tfrac{1}{2}x_1^T x_1 + \tfrac{1}{2}s^T s \tag{9}$$

The time derivative of V_1 using (7) and (8) is obtained as (10).

$$\begin{aligned} \dot{V}_1 &= x_1^T \dot{x}_1 + s^T \dot{s} = x_1^T(x_2 - kx_1) + s^T(n\dot{x}_1 + \dot{x}_2) \\ &= x_1^T x_2 - kx_1^T x_1 + s^T[n(x_2 - kx_1) + \dot{x}_2] \\ &= x_1^T x_2 - kx_1^T x_1 + s^T[n(x_2 - kx_1) + Px_2 - kPx_1 + F\tau + d] \\ &= x_1^T x_2 - kx_1^T x_1 + s^T[(nI+P)x_2 - k(nI+P)x_1 + F\tau + d] \end{aligned} \tag{10}$$

where I is the identify matrix. In (10), the unknown component d still exists so it can not conclude that time derivative of Lyapunov function is negative.

In the next part, the uncertain disturbance d is estimated by an adaptive component $\hat{d}$ with the estimated error $\tilde{d} = d - \hat{d}$. Choose the second Lyapunov function.

$$V_2 = V_1 + \frac{1}{2\alpha}\tilde{d}^T\tilde{d} \tag{11}$$

Assume that the disturbance d is slow change along with time. The time derivative of V_2 is as (12).

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 - \frac{1}{\alpha}\tilde{d}^T\dot{\hat{d}} \\ &= x_1^T x_2 - kx_1^T x_1 + s^T\left[(nI+P)x_2 - k(nI+P)x_1 + F\tau + \tilde{d} + \hat{d}\right] - \frac{1}{\alpha}\tilde{d}^T\dot{\hat{d}} \\ &= x_1^T x_2 - kx_1^T x_1 + s^T[(nI+P)x_2 - k(nI+P)x_1 + F\tau + \hat{d}] - \tfrac{1}{\alpha}\tilde{d}^T(\dot{\hat{d}} - \alpha s) \end{aligned} \tag{12}$$

Choose the controller and adaptive law as (13):

$$\tau = -F^{-1}[(nI-P)(x_2 - kx_1) + \hat{d} + \varepsilon\, sgn(s)] \tag{13}$$

$$\dot{\hat{d}} = \alpha s \tag{14}$$

where ε is a positive scalar.

Substitute (13) and (14) into (12) leading to result as (15).

$$\dot{V}_2 = x_1^T x_2 - kx_1^T x_1 - \varepsilon|s| \tag{15}$$

Define the auxiliary variables:

$$X = \begin{bmatrix} x_1 \\ x_2^T \end{bmatrix}; \qquad Z = \begin{bmatrix} \frac{k}{2} & \frac{k}{2} \\ -1 & 0 \end{bmatrix}$$

then:

$$X^T Z X = -x_1 x_2 + k x_1^T x_1 \tag{16}$$

Sompare (15) and (16), it is easy to see that:

$$\dot{V}_2 = -X^T Z X - \varepsilon|s| \tag{17}$$

Since k>0 then Z is positive definite or $\dot{V}_2 < 0$. This means that by using controller (13) and adaptive law (14) the system (7) is stable as the time goes to infinite.

3. SIMULATION RESULTS

In this section, the effectiveness of the proposed adaptive SMC is validated on the WMR system with parameters as the following: weight of the platform (m_G): 10 kg; weight of each wheel (m_W): 2 kg; inertial moment of the platform (I_G): 4 kgm^2; inertial moment of each wheel (rotation axis-I_W): 0.1 kgm^2; inertial moment of each wheel (diameter axis-I_D): 0.05 kgm^2; distance between the R and P_G (a): 0.2 m; radius of the wheel shaft (b): 0.3 m; radius of the wheel (r): 0.15 m.

The simulation is executed under conditions that the system parameters are uncertain (increasing 20% from nominal value), the wheel slips $[\dot{\gamma}_R \quad \dot{\gamma}_L \quad \dot{\eta}]^T = [1 + \sin t \quad 1 + \cos t \quad \sin t]^T$ (m/sec), and the input disturbances $\tau_d = [1 + \sin(0.2t) \quad 1 + \cos(0.2t)]$ (N.m). The control parameters are designed as: k=8.3, n=1.7, ε=10, α=10.

The simulation is done with two types of reference trajectory: curved trajectory and trifolium trajectory. In each scenario, the responses of the proposed adaptive SMC (ASMC) are compared with the observer-based SMC (OSMC) in [23] to demonstrate the advantages of the given control scheme.

Scenario 1: the reference trajectory is expressed by (18).

$$x_D = -t; \quad y_D = \sin(0.5t) + 0.5t + 1 \tag{18}$$

The initial position of the robot in this case is $[x_R y_R \theta] = [0.5 0 - \pi/4]$. The simulation results of the ASMC and OSMC with the presence of the wheel slips and input disturbances are illustrated in Figures 2, 3(a), and 3(b).

In Figure 2, two WMRs have the same initial position which is not in the reference trajectory. The robot with the proposed ASMC rapidly archives the desired trajectory without oscillation; meanwhile, the robot controlled by OSMC also tends to reference path but swings around the desired curve before tracking. As the results, in Figure 3, the tracking errors in x-axis and y-axis of two system are almost zero at steady state; however, at transient time, the ASMC provides better responses with faster reaching time and smaller tracking error.

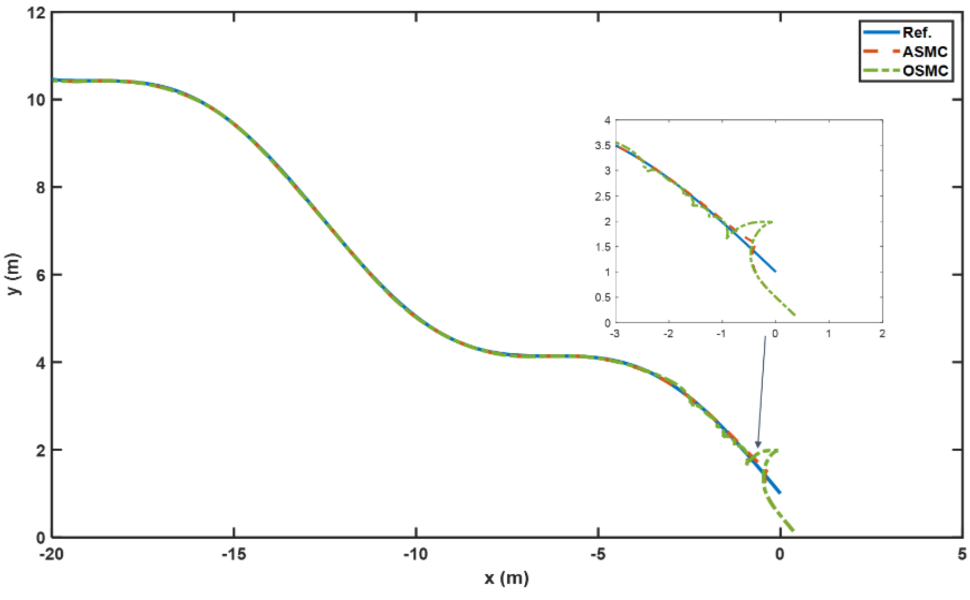
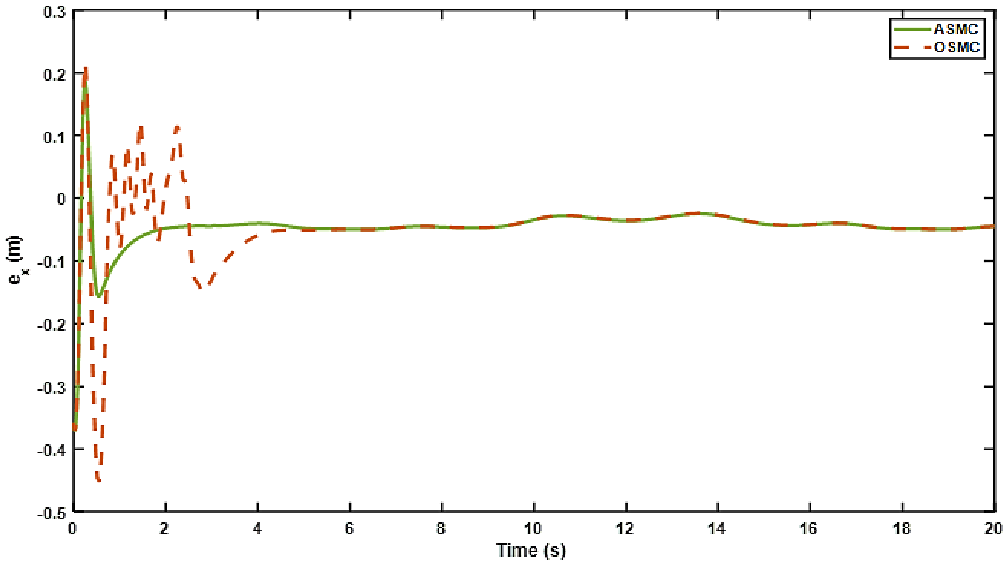
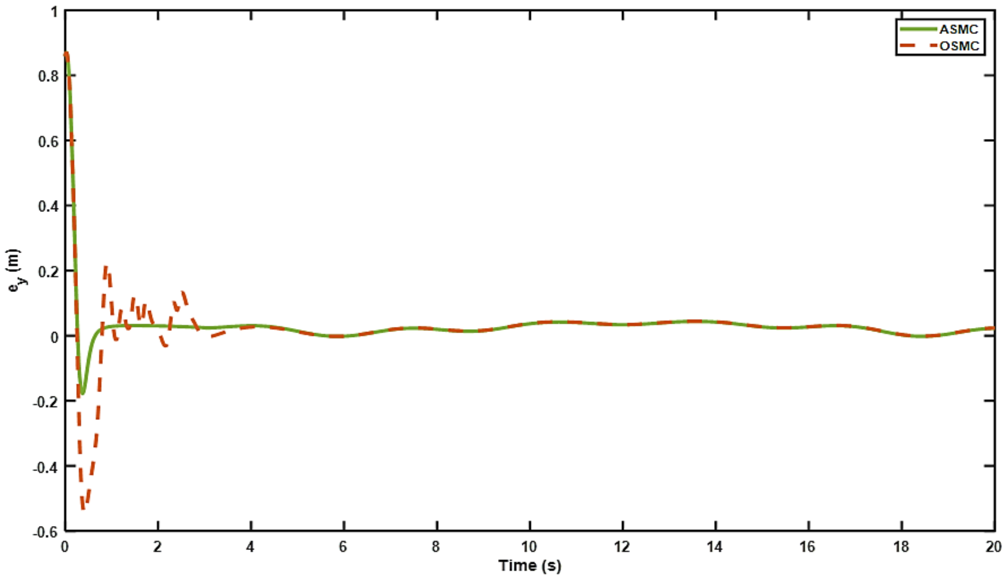


Figure 2. Trajectory tracking of the proposed ASMC and the OSMC with the curved trajectory



(a)



(b)

Figure 3. Tracking error of the proposed ASMC and the OSMC with the curved trajectory (a) *x*-axis error and (b) *y*-axis error

Scenario 2: the reference trajectory is trifolium which is formulated as (19):

$$x_D = 5\,cos\left(\frac{\pi}{10}t\right)cos\left(\frac{\pi}{30}t\right); \quad y_D = 5\,sin\left(\frac{\pi}{10}t\right)sin\left(\frac{\pi}{30}t\right) \tag{19}$$

The initial position of the robot for this case is $[x_R y_R \theta] = [5 - 1\pi/2]$.The simulation results of tracking a trifolium trajectory by means of the proposed ASMC and the OSMC are depicted in Figures 4-5. In Figure 3, both controllers have good responses at steady state, the real trajectories track the desired trajectory. However, the WMR which is controlled by the proposed ASMC reaches the target smoothly while the OSMC makes the system oscillate at initial time before tracking the reference path. These results are reflected clearly in Figure 3 with tracking errors in *x*-axis and *y*-axis. In Figures 5(a) and 5(b) the waveform of e_x and e_y of the ASMC is smoother than the OSMC's waveform at the first 4s. The numerical comparisons of the proposed ASMC and OSMC are concluded in Table 1. As shown in Table 1, the responses of the proposed ASMC are better than the OSMC in both scenarios.

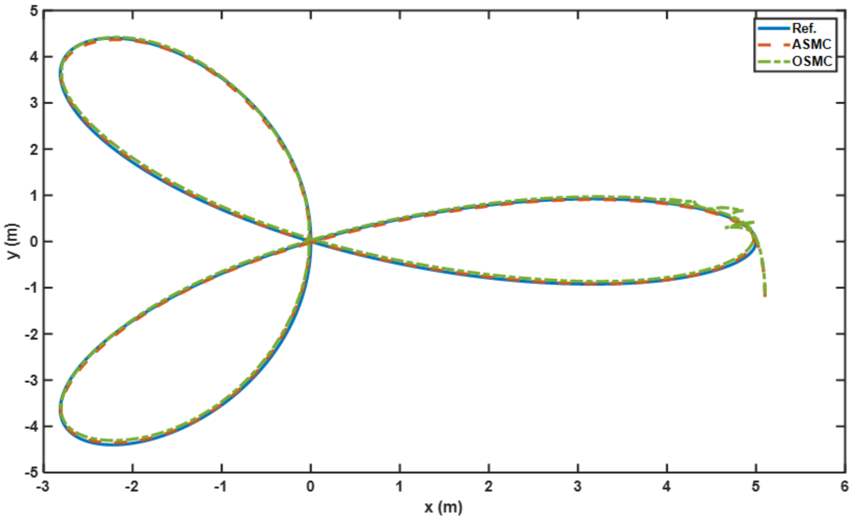
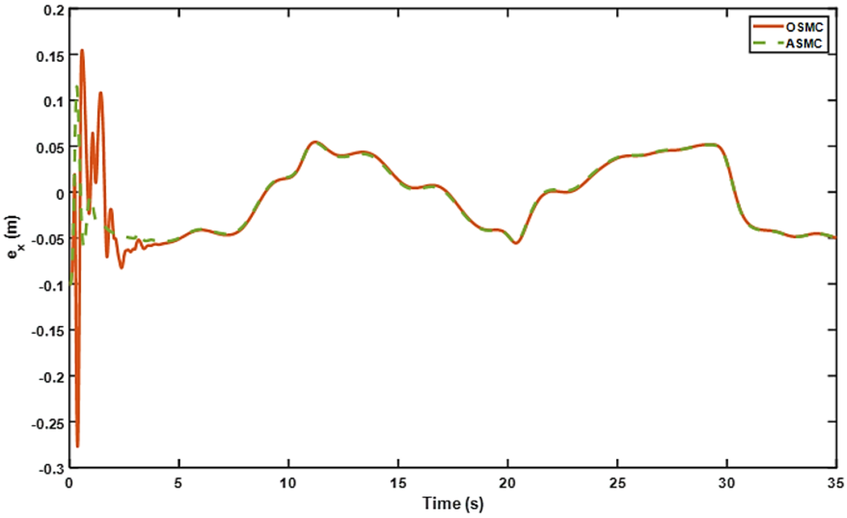


Figure 4. Trajectory tracking of the proposed ASMC and the OSMC with the trifolium trajectory



(a)

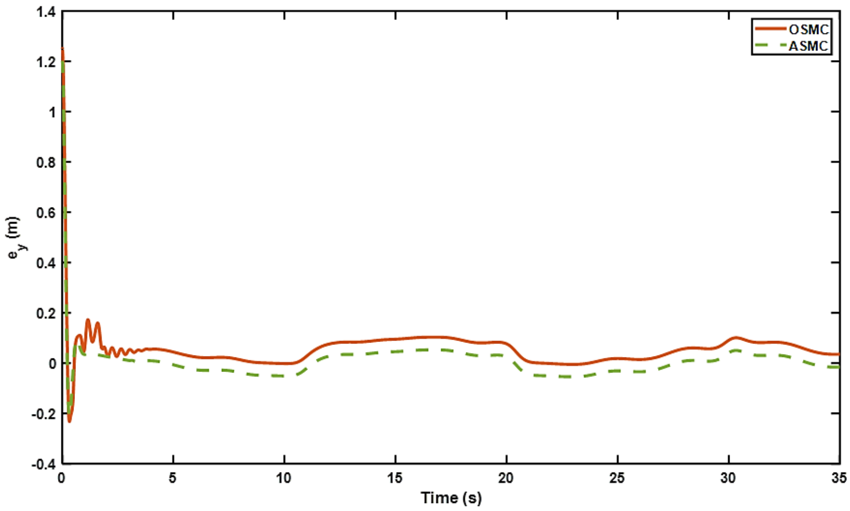


Figure 5. Tracking error of the Proposed and ASMC and the OSMC with the trifolium trajectory (a) *x*-axis error and (b) *y*-axis error

Table 1. Numerical comparisons

		Proposed ASMC	OSMC
Scenario 1	Settling time x-axis (s)	2	5
	Settling time y-axis (s)	1	4
	Peak error x-axis (m)	0.21	0.45
	Peak error y-axis (m)	0.2	0.55
	ISE x-axis	0.061	0.111
	ISE y-axis	0.123	0.213
Scenario 2	Settling time x-axis	none	none
	Settling time y-axis	none	none
	Peak error x-axis	0.12	0.27
	Peak error y-axis	1.2	1.3
	ISE x-axis	0.042	0.071
	ISE y-axis	0.136	0.275

4. CONCLUSION

An adaptive sliding mode controller is introduced in this paper for tracking control of the nonholonomic WMR with considering wheel slips and disturbances. The error state space model of the system is built from kinematic and dynamic models firstly. Next, the sliding mode control is designed to guarantee the stability of the system. The wheel slips and unknown components in the system are compensated by a simple adaptive law. The proposed control scheme consists of only one control loop instead of two loops as usual, so it is very simple in both calculation and implementation. Moreover, the proposed adaptive SMC does not require the upper bound of the unknown components, so it is convenient for real life applications. Finally, the simulations are executed with two types of the trajectory under conditions of existing wheel slips and input disturbances. The comparisons are also employed with the observer based sliding mode control to demonstrate the advantage of the proposed adaptive sliding mode control. The simulation results show that the presented ASMC has the better transient response in comparing with the OSMC.

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