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Time Delay Estimation-based Adaptive Sliding-Mode Control for Nonholonomic Mobile Robots

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ABSTRACT

In this paper, a new adaptive sliding mode control algorithm combining the adaptive PID sliding mode control with time delay estimation (TDE) technique is proposed for trajectory tracking of nonholonomic mobile robots. Conventional sliding mode control is used to compensate system uncertainties by approximate control, but it is sensitive to chattering because of the high switching gains. TDE technique is efficient to estimate the nonlinear terms in robot dynamics, but it exhibits a pulse-type error due to the discontinuous external disturbance. Integrating the above difficulties, a hybrid control scheme is proposed in this work. Time delay estimation based on adaptive sliding mode control aiming at overcoming the individual weaknesses while retaining the positive advantages. The simulation results demonstrate that the tracking errors under the proposed controller can be guaranteed to be uniformly ultimate bounded with acceptable small bound.

1. Introduction

Nonholonomic mobile robots have received a lot of attentions in the past decades for their feasibility, maneuverability, and wide practicability [1]-[3]. Their broad application domains involve industry, service to military, scientific research and other fields. To perform such complex and demanding tasks, mobile robots are required to follow the desired paths accurately [4]-[6].

The difficulties of controlling mobile robots include inherent nonlinearities, modeling uncertainties, coupling dynamics effects and unknown external disturbance [7]-[8]. Various robust control algorithms have been proposed to solve these problems, including adaptive control[7], [19], fuzzy control [9], [10]neural network [15], [16] time delay control [21], [22], [28], sliding mode control [12], [13]and so on. Among them, adaptive control has fixed structure and variable parameter, which is suitable for application in structural uncertainty, but it can not solve the non-structural uncertainty; Fuzzy control and neural networks control are good at solving nonlinear and uncertain robot dynamics, however, they employ numerous design parameter and complex rules that may be inefficient.

SMC is a representative nonlinear control method, which is an effective way to compensation model uncertainties and external disturbance. It requires a suitable predefined uncertainty bound, if the switching gains of SMC are greater than the upper bound of uncertain terms in the system, it can cover a wide range of uncertainties. However, too large switching gains may cause chattering which will result in serious problems, such as mechanical and electronic damage to mobile robots. During recent years, in order to enhance the tracking performance and suppress the chattering phenomenon, various intelligent algorithms have been combined with SMC, including fuzzy sliding mode control [14], neural sliding mode [11]and so on. Although, these approaches eliminate the requirement for information from dynamics equation, they still have difficulties to get numerous parameters and design fuzzy rules. For this reason, adaptive sliding mode control (ASMC) has been proposed and attracts more and more attentions. Its switching gains are tuned regardless of the upper bound of the uncertainties terms.

Some methods have been used for achieving ASMCs that do not need the upper bound of the uncertainties terms and reduce chattering. In [17]-, the switching gains of sliding mode control are tuned automatically, they are effective on compensating unknown terms. In [17], the switching gains are tuned by just a constant and chattering still happens before reaching the sliding manifold. Then, the boundary layer is proposed to reduce chattering, it has a tradeoff between tracking performance and chattering reduction [18]. As another approach in [19], switching

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gains are tuned automatically through adaptive method based on bound layer, but there is a singular when the sliding variable crosses zero. In [20], the singularity problem is solved by designing a new adaptive law, but the control accuracy is varies with the sliding variables' change. It will be meaningful to design a new adaptive law that can simultaneously improve the accuracy and suppress chattering.

Recently, Time-delay control (TDC) was proposed by combining with ASMC. TDC is a control technique that compensates system uncertainties by using a time-delayed signal of system variables. TDC has simple structure, easy to implement and has a strong robustness. TDC has been widely used to various model, such as underwater vehicles [21]-[23], robot manipulators [19], [20], [24]-[25], and mobile robots [26]-[29]. However TDE technique causes TDE errors because the presence of sampling step. The combination of ASMC and TDE showing better performance compared with [17] and [28].

In this paper, we proposed an ASMC based on TDE technique for tracking control problem of nonholonomic mobile robots. The proposed controller provides robustness against TDE errors [28] without the knowledge of uncertainty bound. The proposed adaptive law guarantees the sliding variables enter an small vicinity of sliding manifold with a finite time and then around it. In addition, the new adaptive law can achieve fast adaptation, and the effective of chattering is reduced obviously. And the posture of a mobile robot is frequently changed, the best switching gains in a particular posture may not suitable for other situations. TDE-based controller with a constant switching gains may show poor tracking performance [21].

The rest part of the paper is organized as follows. Section 2 describes the dynamic model of nonholonomic mobile robot. In Section 3, TDE-based ASMC controller is proposed to improve the tracking performance and present the stability analysis. Simulations and experiments are carried out in Section 4 and Section 5 respectively to verify the effectiveness of the proposed controller. Conclusion is drawn in Section 6.

2. System Modeling

The dynamics of nonholonomic mobile robot can be found in [28]. The robot is driven by two driving wheels of radius r which is separated by distance $2L$. The posture of robot in Cartesian coordinate system is denoted by $q=[x\ y\ \theta]^T$, where, (x,y) denotes the coordinate of the reference point C (center of mass) in Cartesian frame. The coordinate θ denotes angle between local coordinate system $[C\ \ x_c\ \ y_c]$ and Cartesian frame. The force analysis is depicted in Fig.1. The Euler-Lagrange based dynamics equations can be written as follows

$$m\ddot{x}+md(\ddot{\theta}\sin\theta+\dot{\theta}^2\cos\theta)-\frac{1}{r}\cos\theta(\tau_r+\tau_l)-\lambda\sin\theta=0 \quad (1)$$

$$m\ddot{y}-md(\ddot{\theta}\cos\theta-\dot{\theta}^2\sin\theta)-\frac{1}{r}\sin\theta(\tau_r+\tau_l)+\lambda\cos\theta=0 \quad (2)$$

$$I\ddot{\theta}+md(\ddot{x}\sin\theta-\ddot{y}\cos\theta)-\frac{L}{r}(\tau_l-\tau_r)-d\lambda=0 \quad (3)$$

Equations (1)-(3) are written compactly as follows

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+F(\dot{q})+G(q)+\tau_d=B(q)\tau-A^T(q)\lambda \quad (4)$$

where

$$M(q)=\begin{bmatrix} m & 0 & md\sin\theta \\ 0 & m & -md\cos\theta \\ md\sin\theta & -md\cos\theta & I \end{bmatrix},$$

$$C(q,\dot{q})=\begin{bmatrix} 0 & 0 & md\dot{\theta}\cos\theta \\ 0 & 0 & md\dot{\theta}\sin\theta \\ 0 & 0 & 0 \end{bmatrix},\ \tau=\begin{bmatrix}\tau_r \\ \tau_l\end{bmatrix},$$

$$\lambda=-m(\dot{x}\cos\theta+\dot{y}\sin\theta)\dot{\theta},$$

$$B(q)=\frac{1}{r}\begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ -L & L \end{bmatrix},\ G(q)=0,$$

$$A(q)=\begin{bmatrix}-\sin\theta & \cos\theta & -d\end{bmatrix}.$$

m and I are the mass and moment of inertia of the robot respectively. $M(q)\in R^{3\times3}$ is the inertia matrix, $C(q,\dot{q})\in R^{3\times3}$ is a centripetal and Coriolis matrix associated with velocity and position, $F(\dot{q})\in R^{3\times1}$ and $G(q)\in R^{3\times1}$ are static and dynamic friction terms and gravity terms associated with velocity and position respectively, $\tau_d\in R^{3\times1}$ is composed of unmodeled dynamics and bounded disturbances, $B(q)\in R^{3\times2}$ is the input transformation matrix, $\tau\in R^{2\times1}$ is the control input vector, $A\in R^{1\times3}$ is a nonholonomic constraints matrix, and $\lambda\in R$ is a Lagrange multiplier related with the constraints.

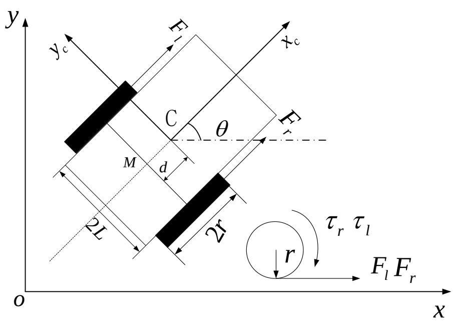

Fig. 1. Schematic force analysis for mobile robot.

The compact equation of (4) can be written in a modified form as follows

$$M(q)=\bar{M}(q)\ddot{q}+H(q,\dot{q},\ddot{q},\lambda)=U \quad (5)$$

where

$$H(q,\dot{q},\ddot{q},\lambda)=[M(q)-\bar{M}(q)]\ddot{q}+C(q,\dot{q})\dot{q}+F(\dot{q})+\tau_d+A^T\lambda \quad (6)$$

$$U=B(q)\tau \quad (7)$$

$H(q,\dot{q},\ddot{q},\lambda)$ also contains unmodeled dynamics and external disturbances in practice. $\bar{M}(q)$ represents the nominal value of the inertia matrix.

3. ASMC with TDE

3.1 Controller design

The control objective is to make the actual position $q(t)$ of robot track the reference position $q_d(t)$ precisely, where $q_d(t)$ represents the desired trajectory. To achieve the control objective, we define a PID sliding variable as follows

$$s(t)=\dot{e}(t)+K_De(t)+K_P\int_0^t e(u)du \quad (8)$$

where $e(t)=[e_1(t),e_2(t),e_3(t)]^T\in R^3$ is error vector, in which $e(t)=q_d(t)-q(t)$, $K_D=diag(k_{D1},k_{D2},k_{D3})\in R^{3\times3}$, and $K_P=diag(k_{P1},k_{P2},k_{P3})\in R^{3\times3}$. It is noted that K_D and K_P in (8) are designed parameters related to stability. With $\dot{s}(t)=0$,

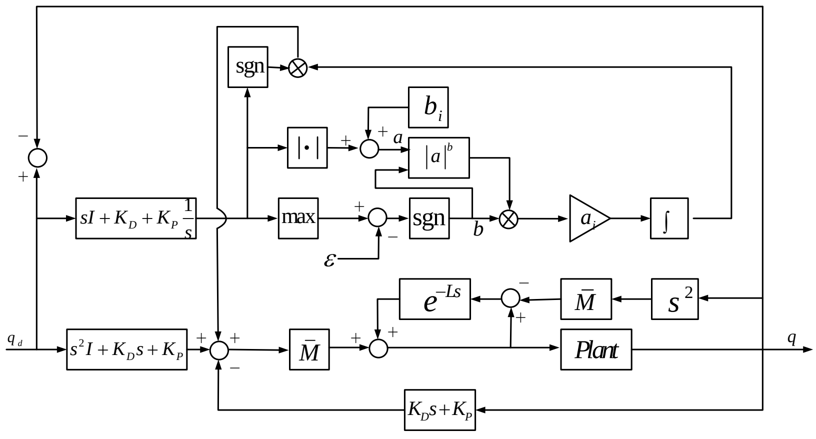

Fig. 2. Schematic diagram of the proposed algorithm.

We can get the system target error dynamics as follows:

$$\ddot{e}(t)+K_D\dot{e}(t)+K_Pe(t)=0 \tag{9}$$

with $\dot{s}(t)=0$, combining equation (5) and (9), the control law can be designed as follows

$$\bar{U}(t)=\bar{M}[\ddot{q}_d(t)+K_D\dot{e}(t)+K_Pe(t)]+\hat{H}(t) \tag{10}$$

where $\hat{H}(t)$ is an estimate of $H(t)$ in (5), using the concept of time delay estimate, and using (5), the estimated value of $H(t)$ is made as follows

$$H(t)\cong\hat{H}(t)=H(t-L)=U(t-L)-\bar{M}\ddot{q}(t-L) \tag{11}$$

where L is a small sampling time.

The method is called TDE, which calculates the unknown dynamics of the system by the estimated function that only needs the values of the immediately past states derivatives and previous control inputs. It is computationally simple and easy to implement. Because time-delayed information is easy to get, we can get easily the estimation of the unknown dynamics of the system and external disturbance.

Substituting (11) into (10), we have

$$\bar{U}(t)=-\bar{M}\ddot{q}(t-L)+U(t-L)+\bar{M}[\ddot{q}_d(t)+K_D\dot{e}\%(t)+K_Pe(t)] \tag{12}$$

Substituting the control input $\bar{U}(t)$ into robot dynamics (5), the system dynamics is

$$\bar{M}[\ddot{e}(t)+K_D\dot{e}(t)+K_Pe(t)]=H(t)-\hat{H}(t) \tag{13}$$

Ideally infinite sampling frequency results infinitesimally small sampling time, hence, $\hat{H}(t)$ is very close to $H(t)$. The system dynamics equation becomes the desired dynamics (9). However, due to sensor response time and computational time, sampling time remains above zero. Based on the reasons, we define a bounded TDE error

$$\varepsilon=H(t)-\hat{H}(t) \tag{14}$$

The TDE error will always exist and it exhibits a pulse-type error due to the discontinuous disturbance. So it is important to suppress this TDE error by using another control algorithm. We propose ASMC and add it to (2), then

$$\begin{aligned}U(t)&=\underbrace{-\bar{M}\ddot{q}(t-L)+U(t-L)}_{\text{TDE}}\\&+\underbrace{\bar{M}[\ddot{q}_d(t)+K_D\dot{e}(t)+K_Pe(t)]}_{\text{desired dynamics}}+\underbrace{\bar{M}(\hat{K}(t)\cdot sgn(s(t)))}_{\text{ASMC}}\end{aligned} \tag{15}$$

The proposed control scheme (see Fig.2) contains three parts: a linear feedback control term that drives the closed-loop system to follow the desired trajectory, TDE term that eliminates the accurate requirement to robot dynamic equation, and a AISMC term that suppresses the TDE error and against parameter variations.

$\hat{K}(t)=diag(k_1,k_2,k_3)\in R^{3\times3}$ is a positive switching gain proposed by

$$\dot{\hat{K}}(t)=a_i\{b_i+|s_i|\}^{\gamma(t)}\cdot\gamma(t) \tag{16}$$

where a_i and b_i are tunable positive gains related to adaptive speed and $\gamma(t)$ is defined as $sgn(\|s(t)\|_\infty-\delta)$ with a positive parameter δ that is related to adaptation speed. The sign function $sgn(x)=[sgn(x_1),sgn(x_2),...,sgn(x_n)]^T\in R^n$ is defined as

$$sgn(x_i)=\begin{cases}1, & if\ x_i(t)\geq0\\-1, & if\ x_i<0\end{cases} \tag{17}$$

The proposed adaptive law does not need the upper bound of the uncertain and unmodeled terms. In the gain dynamics in (16), when $\|s(t)\|_\infty\geq\delta$, the $\dot{\hat{K}}(t)>0$, the switching gain $\hat{k}_i(t)$ increases until $\|s(t)\|_\infty<\delta$. That is to say, when the inequality $\|s(t)\|_\infty\geq\delta$ is satisfied, the switching gain $\hat{k}_i(t)$ keeps increasing, and the sliding variable $s(t)$ is close to the vicinity of the sliding manifold quickly. Once the sliding variable enters the vicinity of the sliding manifold, $\|s(t)\|_\infty<\delta$, the switching gain $\hat{k}_i(t)$ decreases fast because it is inversely proportional to the sliding variable. In general, the proposed adaptive law can achieve better tracking performance and can reduce chattering due to its fast adaption speed.

3.2Stability analysis

The system under the proposed scheme is uniformly ultimately bounded (UUB). Before we show the main analysis result, we give two Lemmas that will be used in the next proof process.

Lemma 1: The TDE error ε_i is bounded by a constant ε_i^+ if the control gain matrix $\bar{M}$ in (15) satisfies the following condition

$$\|I-M^{-1}(q(t))\bar{M}\|<1 \tag{18}$$

Lemma 2: The switching gain $\hat{k}_i(t)$ is upper bounded by a positive constant $\hat{k}_i^*$ as follows

$$\hat{k}_i(t)<\hat{k}_i^* \tag{19}$$

Theorem 1: Considering the mobile robot (5) controlled by (15) and (16), the closed-loop system is UUB if the following condition is satisfied

$$\|s\|_2<\sqrt{\sum_{i=1}^{n}(\delta^2+\eta)} \tag{20}$$

where η is the maximum value of $\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}_i^{-1}\varepsilon_i^{+}-\hat{K}_i)^2$. In addition, the sliding variables enter the vicinity of the sliding manifold within a finite time, and then they are UUB.

Proof: We choose a Lyapunov function as follows

$$V=\frac{1}{2}s^T s+\frac{1}{2}\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}^{-1}\varepsilon_i^{+}-\hat{K}_i)^2 \tag{21}$$

Its time derivative is

$$\dot{V}=s^T\dot{s}-\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}^{-1}\varepsilon_i^{+}-\hat{K}_i)\dot{\hat{K}}_i \tag{22}$$

Substitute (5) and (8) into (22), one yields

$$\begin{aligned}\dot{V}&=s^T[\ddot{q}_d-\bar{M}^{-1}(U-H)+K_D\dot{e}+K_P e]\\&\quad-\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}^{-1}\varepsilon_i^{+}-\hat{K}_i)\dot{\hat{K}}_i\end{aligned} \tag{23}$$

We need to consider two cases: $\|s(t)\|_\infty \ge \delta$ and $\|s(t)\|_\infty < \delta$. In the case of $\|s(t)\|_\infty \ge \delta$, substitute (11), (15) and (16) into (23), we have

$$\begin{aligned}\dot{V}&=\sum_{i=1}^{n}[\bar{M}_i^{-1}\varepsilon_i s_i-\bar{M}_i^{-1}\varepsilon_i^{+}b_i-\bar{M}_i^{-1}\varepsilon_i^{+}|s_i|+\hat{K}_i b_i]\\&\le\sum_{i=1}^{n}[\bar{M}_i^{-1}\varepsilon_i|s_i|-\bar{M}_i^{-1}\varepsilon_i^{+}b_i-\bar{M}_i^{-1}\varepsilon_i^{+}|s_i|\\&\quad+\hat{K}_i b_i]\\&=\sum_{i=1}^{n}[\bar{M}_i^{-1}(\varepsilon_i-\varepsilon_i^{+})|s_i|+b_i(\hat{K}_i-\bar{M}_i^{-1}\varepsilon_i^{+})]\end{aligned} \tag{24}$$

If $\hat{K}_i \le \bar{M}_i^{-1}\varepsilon^{+}$ is satisfied, $\dot{V}<0$. It means that the sliding variable s arrives at the range $|s_i|<\delta$ within a finite time $t_\delta>0$.

Even though within a finite time, the sliding variable arrives at the vicinity of the sliding manifold $|s_i|<\delta$, it may cross the acceptance layer δ since $\dot{V}$ is not guaranteed to be non-positive in this vicinity. If the sliding variable $s(t)$ is in the range $|s_i|\ge\delta$, $\dot{V}$ becomes negative again.

Now, we obtain the upper bound of $\|s\|_2$, which will be satisfied when the sliding variable $s(t)$ enters the region ‖ $\|s(t)\|_\infty<\delta$. It can be seen in (21) the Lyapunov function V is bounded as

$$\frac{1}{2}\|s\|_2^2 \le V \le \frac{1}{2}\|s\|_2^2+\frac{1}{2}\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}_i^{-1}\varepsilon_i^{+}-\hat{K}_i)^2 \tag{25}$$

in which $\frac{1}{2}\sum_{i=1}^{n}\frac{1}{a_i}(\bar{M}_i^{-1}\varepsilon^{+}-\hat{K}_i)^2$ is bounded, because $\bar{M}_i^{-1}\varepsilon^{+}$ is constant and $\hat{K}_i$ is bounded according to Lemma 2. Then one has

$$V<\frac{1}{2}\sum_{i=1}^{n}\delta^2+\frac{1}{2}\sum_{i=1}^{n}\eta \tag{26}$$

According to (25) and (26), one can get

$$\frac{1}{2}\|s\|_2^2<\frac{1}{2}\sum_{i=1}^{n}\delta^2+\frac{1}{2}\sum_{i=1}^{n}\eta \tag{27}$$

which means that

$$\|s\|_2<\sqrt{\sum_{i=1}^{n}\left(\delta^2+\eta\right)} \tag{28}$$

Equation (28) implies that the sliding variable $s(t)$ is UUB. Although the sliding variable moves in and out of the boundary layer, it is guaranteed to be upper-bounded by (28). The proof is completed.

4. Simulation Results

In this section, various computer simulation tests with the nonholonomic mobile robot model are performed to verify the effectiveness of the proposed control law. The control parameters are $\bar{M}$, K_P, K_D, a_i, b_i, δ, for which the values were obtained heuristically Table1.

Gain	Value
$\bar{M}$	$diag(8\ \ 8\ \ 2.5)$
K_P	$diag(8\ \ 8\ \ 8)$
K_D	$diag(100\ \ 105\ \ 110)$
a	$diag(600\ \ 600\ \ 800)$
b	$diag(10\ \ 1.57\ \ 0.15)$
δ	0.015

The desired trajectories are described by $x_r(t)=2\cos(t)$, $y_r(t)=2\sin(t)$, $\theta_r(t)=t$. The initial position vector is chosen as $q_r=[1\ \ 0\ \ 0]^T$. The suffered external disturbance of the mobile robot in the system is $\tau_d=[6\sin(t)\ \ 6\sin(t)]^T$. We perform the simulation and the comparison studies on the system with two approaches: (1) Use the proposed algorithm in this paper; (2) Use the algorithm proposed in [21] (SMC+TDE), where the switching gains are used as constants.

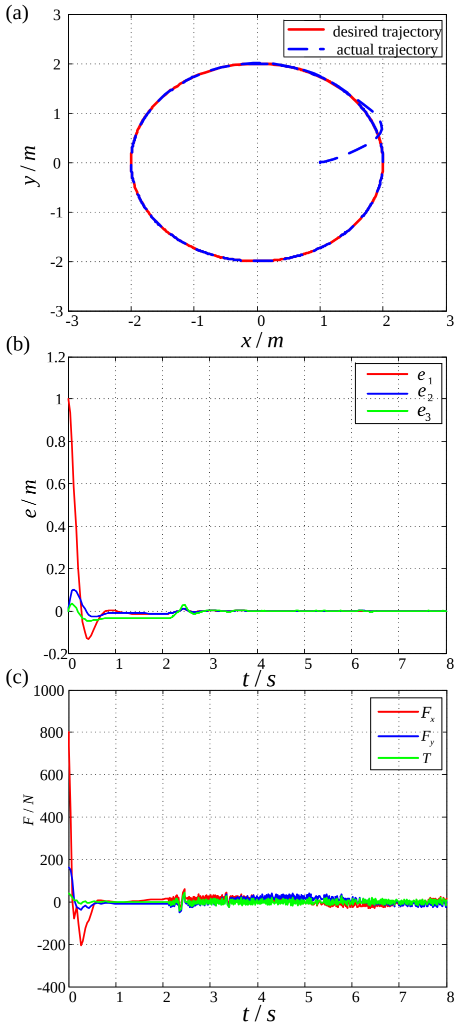

Fig. 3. Tracking trajectory of mobile robot using SMC+TDE in [21]. (a) Tracking trajectory of circular;(b) The tracking errors;(b)The control inputs.

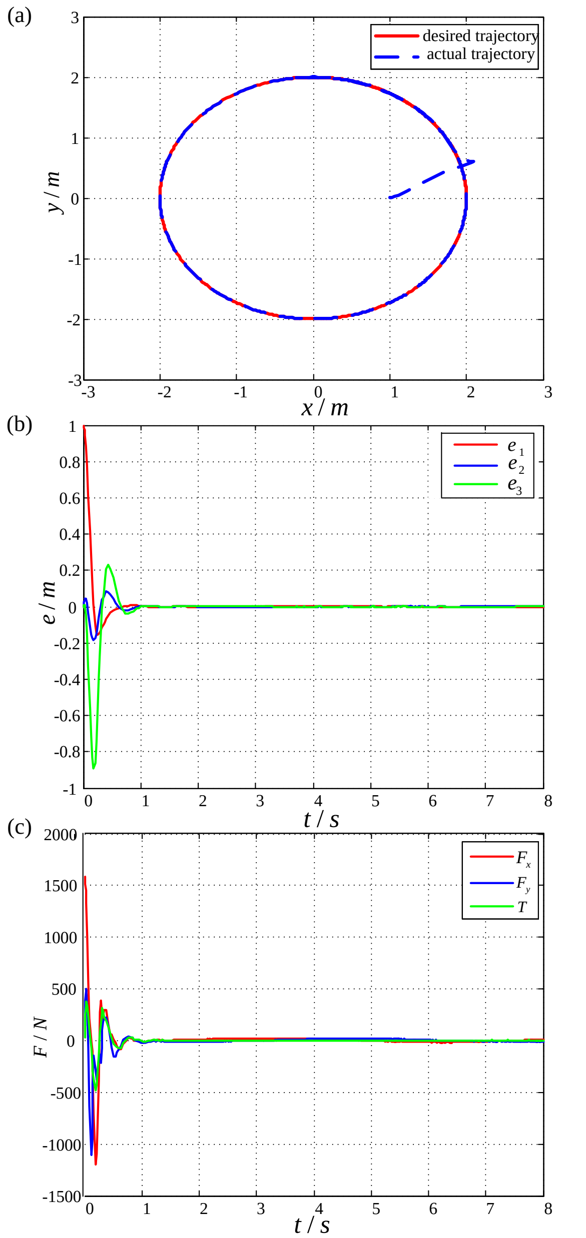

Fig. 4. Tracking trajectory of mobile robot using the proposed algorithm in this paper: (a) Tracking trajectory of circular; (b) The tracking errors; (c) The control inputs.

Fig.3 shows the simulation results of algorithm proposed in [21] (SMC+TDE), and the simulation results using proposed algorithm are shown in Fig.4.

Parameter δ in the adaptive law (16) plays an important role in the tradeoff between chattering reduction and tracking performance. If δ is too small, the chattering will be seriously due to the slow adaptation speed. And if δ is too large, the tracking accuracy will be reduced seriously. The proposed adaptive law of switching gains has fast adaptation speed, it permit more freedom for δ .

Fig.5(a)-(b) show the sliding variables in the two controls. The sliding variables in the proposed ASMC have less chattering when there are disturbance in the process of trajectory tracking.

We can see that the proposed algorithm in this paper have better tracking performance when there are some structure and non-structured by comparing Fig.3 and Fig.4. At the same time, the proposed algorithm eliminated the output force chattering comparing with the algorithm proposed in [21].

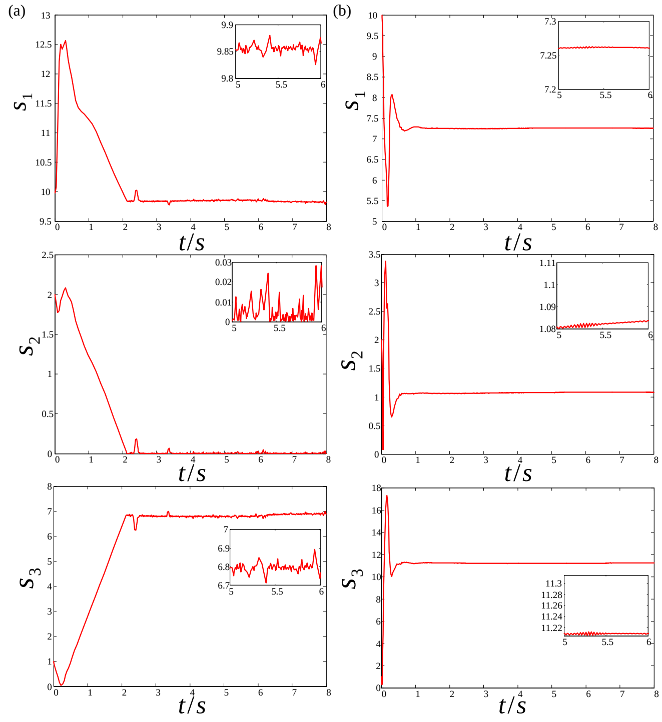

Fig.5. Comparisons of the sliding variables generated by the two controllers. (a) Sliding variables of SMC+TDE controller in [21]; (b) Sliding variables of the proposed controller.

5. Experiments Results

Performance of the proposed controller is verified by two experiments with Makerfire Arduino FPV robot shown as in Fig.6(a). Fig.6(b) shows the diagram of experimental platform. It contains visual positioning subsystem, motion control subsystem, and wireless communication subsystem. We get the position of robot through using image-process software to identify the color paper covered on robots, and transmit the data information to the host computer by wifi. In this paper, we focus on the research of motion control algorithm based on the existing visual positioning and wireless communication mechanism.

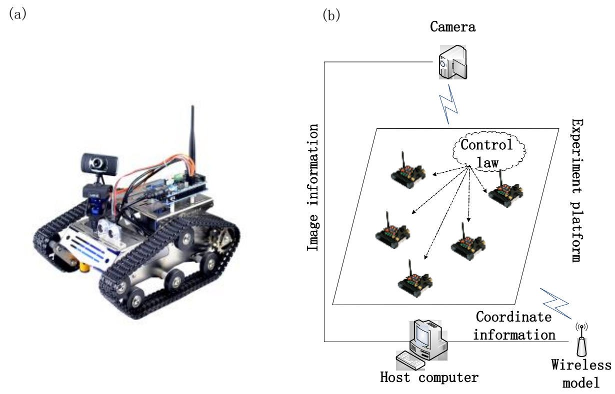

Fig.6. Experimental environment: (a) Makerfire Arduino FPV robot; (b) Diagram of experiment platform.

The circular path tracked by FPV, when two different controllers are employed. The control parameters are chosen to be the same as that in section 4. The experimental results are demonstrated in Fig.7-Fig.10. Particularly, Fig.7 and Fig.9 show some movement screen-shots intercepted from the control software, which describe the motion states of mobile robots in tracking process. Fig.8 and Fig.10 show the trajectory screen-shots from the control software. As it can be seen in the figures, the mobile robots move along the desired trajectory stably after a period of position adjustment. Compared with the trajectory diagram under the SMC based on TDE in Fig.7 and Fig.8, the trajectory diagram under the proposed TDE-based ASMC in this paper, shown in Fig.9 and Fig.10, are obviously superior to the former, and the FPV mobile robot can adjust in time during the process of steering.

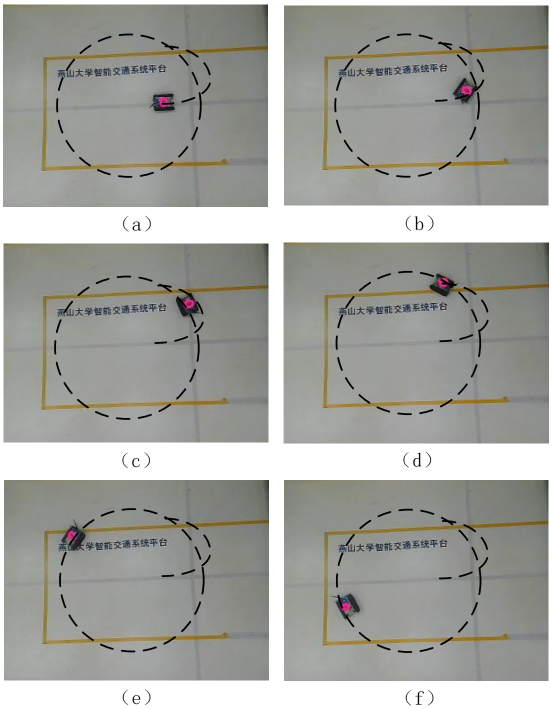

Fig.7. Experimental results under SMC+TDE.

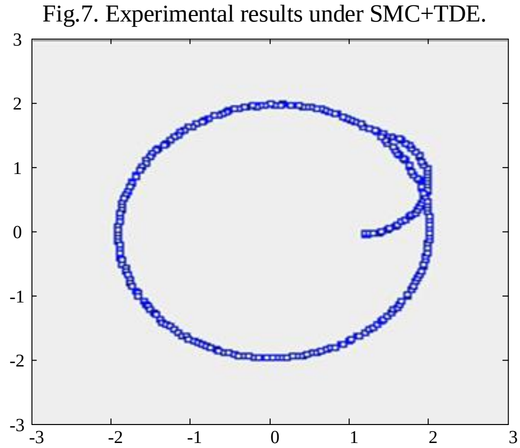

Fig.8. Trajectory diagram under SMC+TDE.

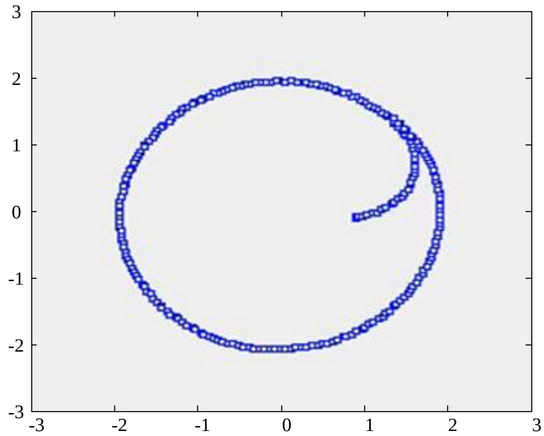

Fig.9. Trajectory diagram under proposed method.

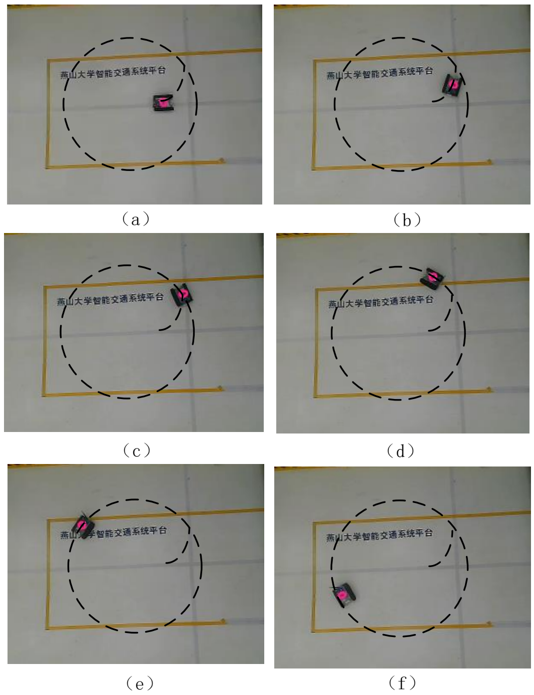

Fig.10. Experimental results under the proposed method.

6. Conclusion

This paper proposes a robust control algorithms using AISMC with the help of TDE and validated through simulation for efficient path tracking of mobile robot. The proposed AISMC algorithm does not require the prior acknowledge of the upper bound of uncertain terms and compensate the TDE errors. The new adaptive law has the characteristics of fast adaptation and chattering reduction. Stability analysis shows that the closed-loop system with the proposed controller is UUB. Finally, the simulation results show good tracking performance by using proposed controller.

Acknowledgements

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