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Time varying nonsingular sliding mode control for path tracking of mobile robot

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***Abstract*—This paper is dealing with finite time path tracking control for a nonholonomic mobile robot affected by parametric uncertainties and external disturbances. First, an adaptive kinematic controller that produces velocity command is developed. Then, to remove the reaching phase, a time varying nonsingular terminal sliding mode (T-NTSM) dynamic controller is introduced by incorporation an exponential function into the nonsingular terminal sliding mode (NTSM) manifold. The proposed (T-NTSM) controller guaranties not only fast and finite time error convergence, but also removes the issue of singularity dilemma that conventional terminal sliding mode manifold suffers from. Finally, simulation results confirm the effectiveness of the designed control law.**

***Index Terms*—Mobile robot, Finite time convergence, Dynamic time varying sliding mode control, Adaptive kinematic control, uncertainties and disturbances.**

I. Introduction

Mobile robot is suitable in various applications, such as in inaccessible terrains like underground tunnels [1], in military activities [2] and in mine operations [3]. The working condition could be extremely uncertain because of change payload and variation of the external environment. Accordingly, robot control under the above mentioned condition is a crustal problem to overcome.

Sliding mode control (SMC) has been widely used owing to its consistent performance to disturbances as well as parameter variations, and its simplicity. In the SMC strategy a linear sliding hyperplane is considered as sliding surface, and the error converge asymptotically to zero when the system reaches the sliding mode [4], [5]. However, the equilibrium point is reached in infinite time. With the focus of achieving finite time convergence, terminal sliding mode (TSM) control, which add a nonlinear function to the sliding surface, is developed [6], [7]. But, the TSM suffers from the singularity issue as well as the deterioration of performance related to the error states far from the equilibrium. In order to overcome the singularity issue, the nonsingular terminal sliding mode (NTSM) control is introduced [8], [9]. To upgrade the system convergence properties, fast terminal sliding mode (FTSM) is mentionned in [10]. The fusion of these two yields to nonsingular fast terminal sliding mode (NFTSM) control, used in controlling different nonlinear systems [11], [12]. The main disadvantage of NTSM and NFTSM is that the effective tracking is ensured only after the system states attain the sliding surface. During the reaching phase, parameter variation and disturbances are not totally removed, and some time after the beginning of the robot motion is required to obtain good tracking performance. In order to avoid the sensitivity issue in the reaching phase, the concept of time-varying sliding mode control is introduced. This paper deals with trajectory tracking problem of mobile robot. First, a kinematic controller that ensures the estimation of the parameter d is introduced. It is obvious to give importance to the estimation of this parameter as it has great relation with the variation of the robot mass and inertia. Then, based on a newly sliding surface, a T-NTSM controller is designed for finite time convergence. The major contributions can be summarized:

1) Compared with the existing kinematic controllers [13], [14] which are formulated under the assumption that kinematic parameter is well known, an adaptive tuning control law is introduced to estimate the uncertain kinematic parameter.
2) The proposed T-NTSM contains exponential function

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in the sliding surface to avoid infinite time convergence and singularity issues.

3) Unlike FNTSM, in which the robot is sensitive to uncertanties and disturbances on the reaching phase, the proposed control law is apt to remove it. Therefore, good tracking performance is guaranteed, even if the system state is far away from the equilibrium.
4) By using the proposed control method, the convergence rate is improved, small amplitude of the input torques is provided.

The organization of the paper is: In section 2 the model of the system is presented. Kinematic controller design methodology is illustrated in section 3. Dynamic controllers based on terminal sliding mode strategy are explained in section 4. Simulations are described in section 5. Conclusions are drawn in section 6.

II. Problem formulation

The dynamic equation of motion of wheeled mobile robot is described in [8]:

$$\bar{M}(q)\ddot{Z} + \bar{C}(q,\dot{q})\dot{Z} = \bar{\tau} + \bar{\tau}_d \tag{1}$$

$$\dot{q} = J(q)\dot{Z} \tag{2}$$

where

$$J(q) = \begin{bmatrix} \cos\varphi & -d\sin\varphi \\ \sin\varphi & d\cos\varphi \\ 0 & 1 \end{bmatrix} \tag{3}$$

$$\dot{Z} = V = [u \quad w]^T \tag{4}$$

where u and w represents the linear velocity and angular velocity of the robot system, respectively. $\bar{M}(q) = J^T M J$,$\bar{C}(q,\dot{q}) = J^T(M\dot{J} + CJ)$, $\bar{\tau}_d = J^T\tau_d$ and $\bar{\tau} = J^T B\tau$.

Then equation (1) can be expressed as follows:

$$\bar{M}_0(q)\ddot{Z} + \bar{C}(q,\dot{q})\dot{Z} = \bar{\tau} + \Gamma \tag{5}$$

where $\Gamma = \bar{M}_d(q)\ddot{Z} + \bar{C}_d(q,\dot{q})\dot{Z} + \bar{\tau}_d$. Γ is called lumped uncertainty and contains all uncertainties including external disturbances.

Assumption 1. $\bar{M}_0(q)$ is invertible and bounded positive definite matrix. Thanks to assumption the dynamic system 5 considering disturbances and uncertainties is defined as:

$$\ddot{Z} = \bar{M}_0^{-1}(\bar{\tau} + \Gamma - \bar{C}_0\dot{Z}) \tag{6}$$

Assumption 2. The external disturbances and uncertainties are bounded, so Γ is bounded and garantees $\parallel \Gamma \parallel \leq D_\Gamma$ where D_Γ is the unknown maximum of the uncertainty vector.

Two parts will be considered in the design of the controller:

- The first part will involve the design of an adaptive kinematic controller, such that if we have a reference trajectory q_r, the error $e = q_r - q$ converges to zero.
- In the second part, a dynamic controller will be developed based on sliding mode techniques such that it generate the required input torques τ for the robot system.

III. Adaptive kinematic control design

Consider that a reference trajectory described by $q_r(t) = [x_r \quad y_r \quad \varphi_r]^T$ and $V_r = [u_r \quad w_r]^T$ is generated by a reference mobile robot. Then the tracking position errors can be expressed as follows:

$$q_e = \begin{pmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_r - x \\ y_r - y \\ \varphi_r - \varphi \end{pmatrix} \tag{7}$$

The derivative of (7) is given by:

$$\dot{q}_e = \begin{pmatrix} -u + we_2 + u_r\cos e_3 - dw_r\sin e_3 \\ -we_1 + u_r\sin e_3 - dw + dw_r\cos e_3 \\ -w + w_r \end{pmatrix} \tag{8}$$

Then, the velocity controller is designed as:

$$V_d = \begin{bmatrix} u_d \\ w_d \end{bmatrix} = \begin{bmatrix} u_r\cos e_3 + k_1(e_1 + \hat{d}(1 - \cos e_3)) \\ w_r + u_r(e_2 - \hat{d}\sin e_3) + k_2\sin e_3 \end{bmatrix} \tag{9}$$

k_1 and k_2 are positive constants. and the adaptive law for unknown parameter d is given by:

$$\dot{\hat{d}} = (u_r\cos e_3 - u)(1 - \cos e_3) + u_r\sin^2 e_3 \tag{10}$$

We define :

$$L_1 = \frac{1}{2}(e_1 + d(1 - \cos e_3))^2 + \frac{1}{2}(e_2 - d\sin e_3)^2 + (1 - \cos e_3) + \frac{1}{2}\tilde{d}^2 \tag{11}$$

we note $\tilde{d} = d - \hat{d}$ the estimation error of the distance d, The derivative of (11) is:

$$\begin{aligned} \dot{L}_1 &= (e_1 + d(1 - \cos e_3))(\dot{e}_1 + d\dot{e}_3\sin e_3) \\ &+ (e_2 - d\sin e_3)(\dot{e}_2 - d\dot{e}_3\cos e_3) \\ &+ \dot{e}_3\sin e_3 + \tilde{d}\dot{\tilde{d}} \\ &= (e_1 + \hat{d}(1 - \cos e_3))(u_r\cos e_3 - u) + \sin e_3(u_r(e_2 - \hat{d}\sin e_3) \\ &+ (w_r - w)) - \tilde{d}(\dot{\hat{d}} - (u_r\cos e_3 - u)(1 - \cos e_3) + u_r\sin^2 e_3) \end{aligned} \tag{12}$$

The substitution of velocity control law (9) into (12) and the use of the adaptive law (10), we have

$$\dot{L}_1 = -k_1(e_1 + \hat{d}(1 - \cos e_3))^2 - k_2\sin^2 e_3 \tag{13}$$

$\dot{L}_1 \leq 0$. Thus, it is easy to conclude that $q_e \to 0$ as $t \to \infty$. As consequence from (7) that $x_0 \to x_r$, $y_0 \to y_r$ and $\varphi \to \varphi_r$ as $t \to \infty$.

IV. Robust dynamic control with finite time convergence

Define the variable $\dot{Z}_d = V_d$. The tracking velocity error and its derivative have the following forms:

$$\varepsilon_1 = Z_d - Z \tag{14}$$

$$\varepsilon_2 = \dot{Z}_d - \dot{Z} \tag{15}$$

The problem is to find a controller $\bar{\tau}$ such that ε_1 and ε_2 converge to zero in finite time.

A. Nonsingular terminal sliding mode (NTSM)

The nonsingular Terminal Sliding Mode controller (NTSM) is selected as:

$$s(t) = \varepsilon_1 + \lambda^{'}|\dot{\varepsilon}_1|^{p/q} sign(\dot{\varepsilon}_1) \quad (16)$$

where $\lambda^{'} = \lambda^{-p/q}$ is a strictly positive definite constant, p and q are positive odd integers satisfying $1 < p/q < 2$.
The time derivative of the sliding surface (16) is:

$$\dot{s}(t) = \dot{\varepsilon}_1 + \lambda^{'}\frac{p}{q}|\dot{\varepsilon}_1|^{p/q-1}\ddot{\varepsilon}_1 \quad (17)$$

For $s(t) = 0$, the system dynamics are equivalent to :

$$\varepsilon_2 + \lambda^{'}\frac{p}{q}|\varepsilon_2|^{p/q-1}\dot{\varepsilon}_2 = 0 \quad (18)$$

Then, substituting the equation (6) without considering disturbances into (18), we obtain:

$$\dot{s}(t) = \varepsilon_2 + \lambda^{'}\frac{p}{q}|\varepsilon_2|^{p/q-1}(\ddot{Z}_d - \bar{M}_0^{-1}(\bar{\tau} - \dot{Z}\bar{C}_0(q,\dot{q})) \quad (19)$$

The equivalent control law $\bar{\tau}_0$ is given by:

$$\bar{\tau}_0 = -\frac{1}{\lambda^{'}\frac{p}{q}}|\varepsilon_2|^{2-p/q}\bar{M}_0 + \bar{M}_0(q)\ddot{Z}_d + \bar{C}_0(q,\dot{q})\dot{Z} \quad (20)$$

The switching control law is :

$$\bar{\tau}_1(t) = -\bar{M}_0(\eta s + \kappa sign(s)) \quad (21)$$

Thus, the developed control law is :

$$\begin{aligned} \bar{\tau}(t) &= \bar{\tau}_0(t) + \bar{\tau}_1(t) \\ &= -\frac{1}{\lambda^{'}\frac{p}{q}}|\varepsilon_2|^{2-p/q}\bar{M}_0 + \\ &\bar{M}_0(q)\ddot{Z}_d + \bar{C}_0(q,\dot{q})\dot{Z} - \bar{M}_0(\eta s + \kappa sign(s)) \end{aligned} \quad (22)$$

It is important to note that if the sliding surface is achieved, i.e., $s(t) = 0$, the robot dynamics can be represented by:

$$\dot{\varepsilon}_1 = -\lambda^{'-q/p}|\varepsilon_1|^{q/p} sign(\varepsilon_1) \quad (23)$$

B. Nonsingular fast terminal sliding mode NFTSM

A nonsingular fast terminal sliding surface for the robot system can be illustrated by adding one more non linear term to the NTSM sliding surface (16) as

$$s = \varepsilon_1 + \mu|\varepsilon_1|^{\gamma} sign(\varepsilon_1) + \lambda^{'}|\dot{\varepsilon}_1|^{p/q} sign(\dot{\varepsilon}_1) \quad (24)$$

where μ and $\lambda^{'}$ are positive constants, $1 < p/q < 2$, $\gamma > p/q$ and $sig(.)$ is a function.
Considering the sliding surface defined in (24) and according to the sufficient condition for existence of TSM, the NFTSM control law is introduced:

$$\begin{aligned} \bar{\tau} &= \bar{\tau}_0 + \bar{\tau}_1 \\ &= -\frac{1}{\lambda^{'}\frac{p}{q}}|\varepsilon_2|^{2-\frac{p}{q}}\bar{M}_0(1 + \mu\gamma|\varepsilon_1|^{\gamma-1}) sign(\varepsilon_2) \\ &-\bar{M}_0(\eta s + \kappa sign(s)) \end{aligned} \quad (25)$$

When the terminal sliding mode is achieved i.e $s = 0$, the system dynamics is equivalent to

$$\varepsilon_1 + \mu|\varepsilon_1|^{\gamma} sign(\varepsilon_1) + \lambda^{'}|\dot{\varepsilon}_1|^{p/q} sign(\dot{\varepsilon}_1) = 0 \quad (26)$$

The time taken to move from $\varepsilon_1(t_r) \neq 0$ to $\varepsilon_1(t_r + t_s) = 0$ is finite and defined by

$$t_s = -(\frac{1}{\lambda^{'}})^{q/p} \int_{\varepsilon_1(t_r)}^{0} \frac{1}{(\tau - \mu\tau^{\gamma})^{q/p}} d\tau \quad (27)$$

Theorem 1 describes the introduced control law:

Theorem 1. If the system containing parametric uncertainties (mass, inertia) and unknown external disturbances described by (2) and (5) and if the sliding surface is designed as (24) and the control torque is defined as (25), then the robot motion converge to the defined sliding surface in a selected time t_S.

Proof. Consider the following Lyapunov function candidate:

$$L_2 = \frac{1}{2}s^2 \quad (28)$$

By differentiating L_2 and using equation (24),we obtain

$$\dot{L}_2 = s\dot{s} = s(\varepsilon_2 + \mu\gamma|\varepsilon_1|^{\gamma-1}\varepsilon_2 + \lambda^{'}\tfrac{p}{q}\ |\varepsilon_2|^{p/q-1}\ \dot{\varepsilon}_2) \quad (29)$$

The substitution of the dynamic error (15) into (29) yields:

$$\dot{L}_2 = s\dot{s} = s(\varepsilon_2 + \mu\gamma|\varepsilon_1|^{\gamma-1}\varepsilon_2 + \lambda^{'}\frac{p}{q}\ |\varepsilon_2|^{p/q-1}\ (\ddot{Z}_d - \ddot{Z}) \quad (30)$$

By substituting equation (6) and the control law (25) into (30), we obtain

$$\dot{L}_2 = s\lambda^{'}\frac{p}{q}|\varepsilon_2|^{p/q-1}\left(-\bar{M}_0^{-1}\Gamma - \eta s - \kappa sign(s)\right) \quad (31)$$

Then,

$$\dot{L}_2 \leq \lambda\frac{p}{q}|\varepsilon_2|^{p/q-1}(-D_{\Gamma} - \eta - \kappa)|s| \quad (32)$$

We can conclude that the system states achieve the equilibrium point in a precious time.

C. Time varying Nonsingular terminal sliding mode (T-NTSM)

To tackle the drawbacks of The NTFSM controller, a time-varying nonsingular terminal sliding mode (T-NTSM) manifold is introduced :

$$s(t) = \varepsilon_1 + \lambda^{'}|\varepsilon_2|^{p/q} sign(\varepsilon_2) - e^{-\theta t}s_0 \quad (33)$$

$\theta > 0$ is a defined constant, t is the time. $s_0 = \varepsilon_{10} + \lambda^{'}|\varepsilon_{20}|^{p/q} sign(\varepsilon_{20})$ in which ε_{10} and ε_{20} are the initial conditions of ε_1 and ε_2, respectively.
The sliding surface (33), ensures that the surface starts at the initial condition. Accordingly, the reaching phase is removed and the exponential decay term guarantees that the sliding surface will not have an offset. When the initial conditions for the system error are zero, the sliding surface becomes the same as defined in (16).
Using the sliding surface determined by 33, the controller can be introduced :

$$\begin{aligned} \bar{\tau} &= \bar{\tau}_0 + \bar{\tau}_1 \\ &= -\frac{1}{\lambda^{'}\frac{p}{q}}\bar{M}_0|\varepsilon_2|^{1-p/q}\left(\varepsilon_2 + \theta e^{-\theta t}s_0\right) + \\ &\ddot{Z}_d\bar{M}_0 + \dot{Z}\bar{C}_0 - \bar{M}_0(\eta s + \kappa sign(s)) \end{aligned} \quad (34)$$

Theorem 2. The reaching phase is eliminated and global robustness is guaranteed, if the sliding surface is selected as (33) and the control torque is developed as (34), for the system defined by (2) and (5)

Proof. Consider the following Lyapunov function candidate:

$$L_2 = \frac{1}{2}s^2 \tag{35}$$

Differentiating L_2 with respect of time and using equation (33), we obtain

$$\dot{L}_2 = s\dot{s} = s(\varepsilon_2 + \lambda' \frac{p}{q}|\varepsilon_2|^{p/q-1}\dot{\varepsilon}_2 + \theta e^{-\theta t}s_0) \tag{36}$$

By substituting dynamic error (15) and equation 6 in 36, we find

$$\begin{aligned}\dot{L}_2 &= s(\varepsilon_2 + \lambda' \tfrac{p}{q}|\varepsilon_2|^{p/q-1}(\ddot{Z}_d - \ddot{Z}) + \theta e^{-\theta t}s_0) \\ &= s(\varepsilon_2 + \lambda' \tfrac{p}{q}|\varepsilon_2|^{p/q-1}(\ddot{Z}_d - \bar{M}_0^{-1}(\bar{\tau} - \bar{C}_0\dot{Z} + \Gamma)) + \theta e^{-\theta t}s_0)\end{aligned} \tag{37}$$

The substitution of the control law (34), yield

$$\dot{L}_2 = s\lambda' \frac{p}{q}|\varepsilon_2|^{p/q-1}\left(-\bar{M_0}^{-1}\Gamma - \eta s - \kappa sign(s)\right) \tag{38}$$

Then,

$$\dot{L}_2 \leq \lambda \frac{p}{q}|\varepsilon_2|^{p/q-1}\left(-D_\Gamma - \eta - \kappa\right)|s| \tag{39}$$

It is obvious that D_Γ, η and κ are positive, $\dot{L}_2$ in non positive. As consequence $L_2 \equiv 0$ gives $s \equiv 0$ for $t \geq 0$.

V. SIMULATION RESULTS

Simulations studies are used to show the T-NTSM controller efficacy. A comparative study between T-NTSM, NTSM and NFTSM controllers is presented.
The initial conditions are : $q(0) = [x_0, y_0, \varphi_0] = [0, 0, \Pi/3]$.
The control gains in the kinematic controller are $k_1 = 0.19, k_2 = 0.19$. In the NTSM manifold we have $\eta = 50$, $\kappa = 90$, $\lambda' = 15$,$p/q = 7/5$. Identical value of η, κ, λ' and p/q are selected for NFTSM and T-NTSM manifolds. In the NFTSM controller, the parameters μ and γ are selected as $\mu = 30$ and $\gamma = 2.1$. In the T-NTSM the parameter θ is designed as $\theta = 10$.

The reference trajectory is : $x_r(t) = 0.2t + 0.3, y_r(t) = 0.5 + 0.25\sin(0.2\pi t)$
To demonstrate the efficiency of our algorithm, we consider that parameter variation in the dynamic model and external disturbances occurred. Accordingly, their nominal value are increased by an additive variance of 20%, which implies $m_c = m_{c0} + 0.2m_{c0}$, $m_w = m_{w0} + 0.2m_{w0}$, $I_c = I_{c0} + 0.2I_{c0}$, $I_w = I_{w0} + 0.2I_{w0}$ and $I_m = I_{m0} + 0.2I_{m0}$.
The external disturbances are selected as:
$\tau_\mathrm{d} = [10 * \mathrm{rectpuls(t-10,2)}; 10 * \mathrm{rectpuls(t-17,2)}]$;
For better comparison, the performances of NTSM, NFTSM and T-NTSM controllers are quantified and compared in Table I. In this table the integral of the absolute value of the velocity tracking error (IAE) and the integral of the square value (ISV) of the torque input are illustrated.

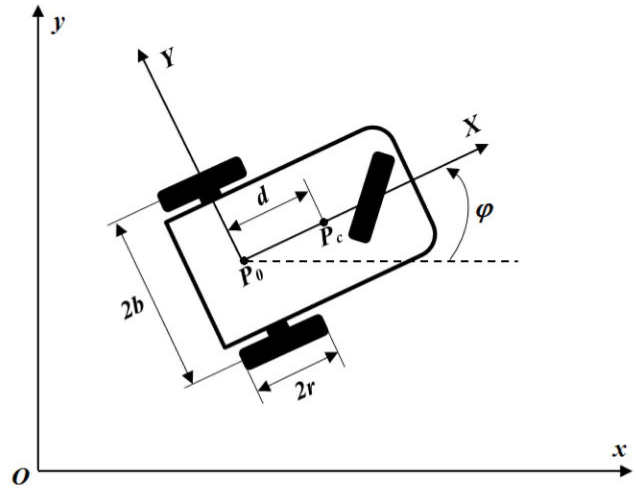


Fig. 1. Mobile robot with two actuated wheels.

$$IAE = \int_0^{t_f} |\varepsilon_2| dt \tag{40}$$

and

$$ISV = \int_0^{t_f} \tau^2(t) dt \tag{41}$$

t_f defines the running time.

The tracking results are shown in Figs 2 and 3 respectively. Figs 4, 5 shows actual and desired velocities. The input torques are illustrated in Fig 6 and sliding manifolds are illustrated in Fig 7.
It can be seen that the T-NTSM controller, has good tracking performance (Fig 2), and the posture tracking errors are lower than those with NTSM and NFTSM (Fig 3). Figs 4, 5 show that significant peaks of actual linear and angular velocities occur under external disturbances (at $t = 10s$ and $t = 17s$) using NTSM and NFTSM controllers. These peaks are successfully removed using the proposed T-NTSM manifold as illustrated in Figs 4-(c), 5-(c). So, we can confirm the indifference of the proposed method toward external disturbances. Moreover, actual linear and angular velocities are too closed to the velocity command. In addition, it can be concluded from the quantitative analysis shown in table I that the designed T-NTSM offers lower values of IAE than the existing control methods.
The input torques produced by the NTSM and NFTSM controllers present a peak when external disturbances occurred (at $t = 10s$ and $t = 17s$). Whereas, the input torques obtained by the developed T-NTSM controller are smooth and the effect of external disturbances is insignificant (Fig 6). Moreover, based on the results of NTSM and NFTSM controllers, we can affirm that the proposed T-NTSM controller produces small control

torques at the beginning of the robot motion (Table I). Fig 7 shows the illustrated controllers good performance in term of fast convergence in a finite time. However, the proposed T-NTSM controller can tackle the effect of external disturbances at $t = 10s$ and $t = 17s$ better than NTSM and NFTSM manifolds.

To summarize, the T-NTSM dynamic controller combined with the adaptive kinematic controller offer robustness to the controlled system even if the system has model uncertainties and disturbances.

TABLE I
QUANTITATIVE ANALYSIS UNDER UNCERTAINTIES AND EXTERNAL DISTURBANCES.

Controllers	IAE		ISV	
	$(u_d - u)$	$(w_d - w)$	τ_l	τ_r
T-NTSM	1.8925	1.8655	1.0355	1.0626
NFTSM	1.0303	2.1725	1.4067	1.7621
NTSM	1.1136	2.6163	1.5296	1.8132

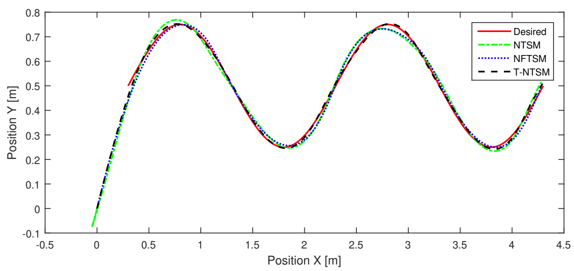
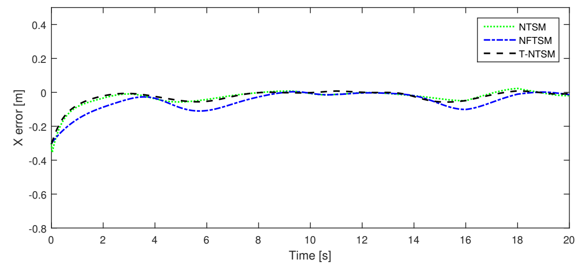
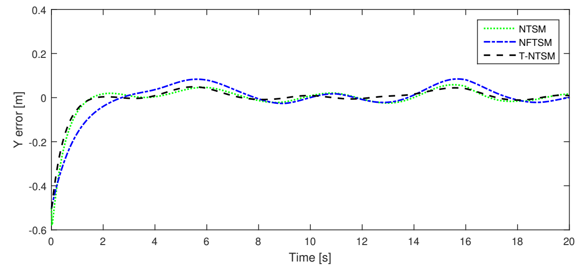


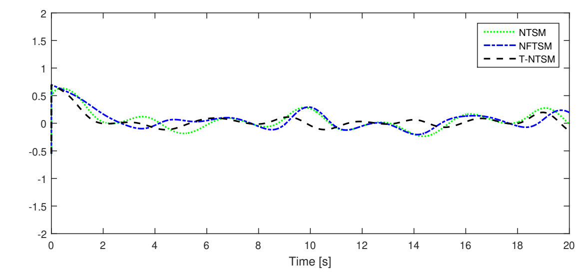
Fig. 2. Trajectory tracking performance.



(a) Tracking error in the X axis



(b) Tracking error in the Y axis



(c) Orientational error

Fig. 3. Comparison of tracking errors.

VI. CONCLUSION

This paper investigates an accurate trajectory tracking control issue of wheeled mobile robot when uncertainties and external disturbances can happen. An adaptive kinematic controller is first developed to generate velocity command such that posture tracking errors reach the zero vector. Then, dynamic controller based on sliding mode techniques and non singularity is designed to produce the required torques for the robot motion. The reaching phase is removed, the robustness performance is guaranteed and the fast convergence rate is obtained, by the proposed T-NTSM method, as compared to the NTSM and NFTSM manifolds. Finally, good performance of the proposed controller is shown thanks to simulation results.

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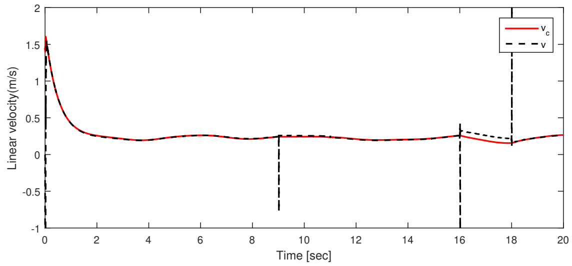
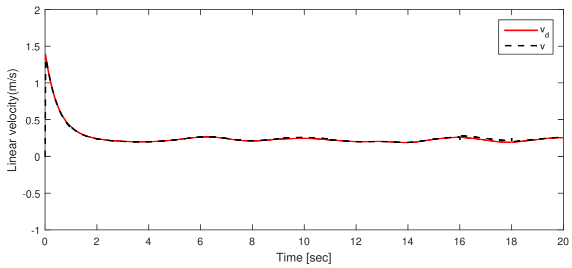
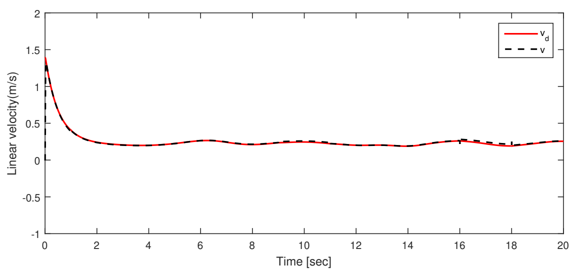


(a) Linear velocity(NTSM)



(b) Linear velocity(NFTSM)



(c) Linear velocity(T-NTSM)

Fig. 4. Desired and actual linear velocity in the presence of system uncertainties and external disturbances.

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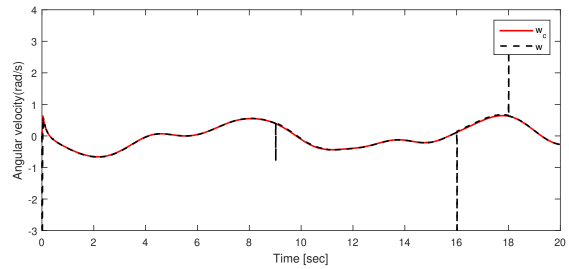
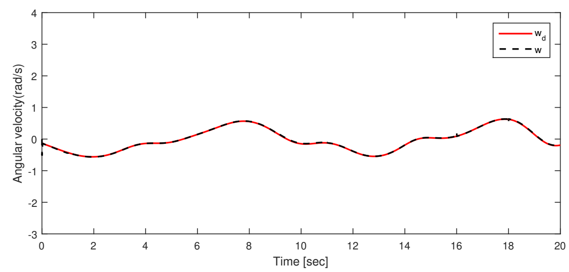
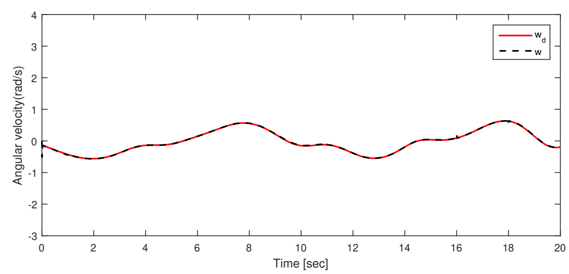


(a) Angular velocity(NTSM)

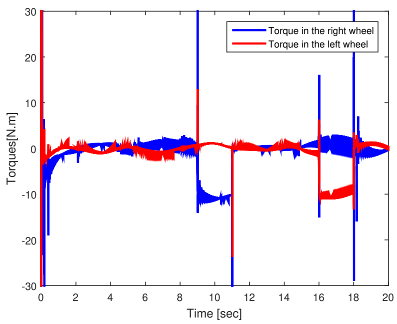


(b) Angular velocity(NFTSM)

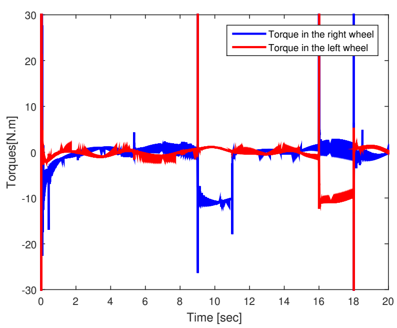


(c) Angular velocity(T-NTSM)

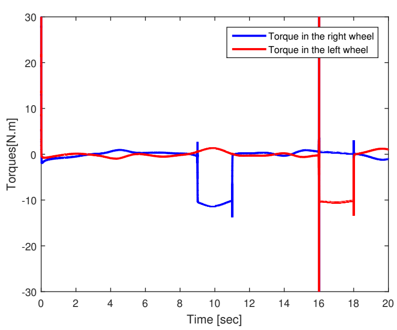
Fig. 5. Desired and actual angular velocity in the presence of system uncertainties and external disturbances.



(a) Input torques(NTSM)

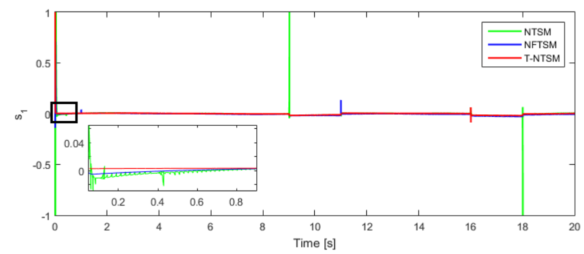


(b) Input torques(NFTSM)

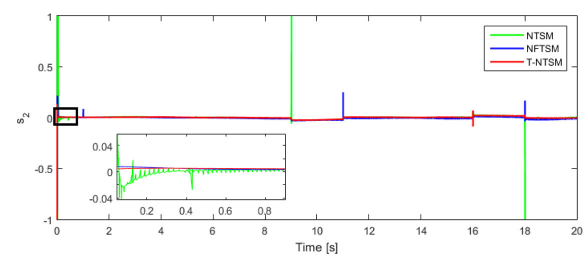


(c) Input torques(T-NTSM)

Fig. 6. Input torques in the presence of system uncertainties and external disturbances.



(a) s_1



(b) s_2

Fig. 7. Sliding manifolds in the presence of system uncertainties and external disturbances.