Robust Adaptive Trajectory Tracking Control Based on Sliding Mode of Electrical Wheeled Mobile Robot

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***Abstract*—In this paper, a robust adaptive trajectory tracking controller is proposed for an electrical wheeled mobile robot in the presence of dynamic disturbances. This method, based on the nonlinear dynamic model of the robot and its actuators, guarantees the stability and the convergence of the closed-loop system. Moreover, the developed controller ensures the robustness of the system against the bounded dynamic disturbances, the smoothness of the computing voltage against the chattering phenomenon, and the optimal convergence of the velocity and posture errors. The Lyapunov theory is used to analyze the full stability of the control scheme. The simulation results further illustrate the effectiveness of the developed strategy.**

***Index Terms*— adaptive sliding mode controller, dynamic disturbances, computing voltage, electrical wheeled mobile robot, Lyapunov theory**

I. Introduction

The Wheeled Mobile Robot (WMR) is the typical nonlinear, complex, and non-holonomic dynamic system. Robot's movement and abilities on particular terrain are affected by many factors like geometry and type of locomotion system (wheeled, tracked, hybrid, legged, jumping), properties of effectors, mass properties of a robot, and constraints resulting from characteristics of drives [1]. Trajectory tracking is one of the complex and interesting research problems. Designing a controller that guarantees trajectory tracking and robustness against undesirable effects, due to the environment and modeling uncertainties, is a challenge for researchers [2]. In order to solve the trajectory tracking problem, several studies have been done using the development of computer technology and advanced control theory. In this context, many control strategies are developed based on kinematic and / or dynamic model of the robot platform. These strategies are based on classical techniques and approaches in the control and automation field, such as the back-stepping method [3], the fuzzy logic systems [4]–[7], the sliding mode approach [8]–[11] and the mechanism of neuronal network (NN) [12], [13]. To deal with unmodeled bounded disturbances and/or unstructured dynamics in the robot, the NN controller is used in [12]. Moreover, in [5] and [6], an adaptive fuzzy strategy is employed to approximate the unknown nonlinear function that presents the dynamic disturbances and model uncertainties. In order to estimate the unknown dynamic effects and the model uncertainties the fuzzy logic technique is combined with the backstepping approach [4]. Others, Shojaei et al. ([14]) employ an adaptive backstepping method to guarantee robustness against parametric and non-parametric uncertainties.

In terms of robustness, the Sliding Mode Control (SMC) is the most advantageous. This approach ensures convergence and insensitivity of the system to variations in the state model and to bounded disturbances when the switching gain is large enough. However, the chatter phenomenon is a major drawback of this approach [15]. In order to overcome the chattering problem, the so-called Adaptive Sliding Mode Control (ASMC) has been developed. Focusing on that, the switching gain is adjusted adaptively by using fuzzy logic mechanism [7] , [11], [16], and adaptive theory [8]–[10] in order to reduce the chattering problem effects. Moreover, in [2] and [17] the adaptive strategy (ASMC) is used to estimate the bounded disturbances and uncertainties.

Based on the above discussion, the main contributions of this work are:

(i) Developing the control scheme to ensure the robustness by; compensate and weaken the effects of dynamic disturbance.

(ii) Synthesis of an improved adaptive switching control capable to mitigate the chattering phenomenon and optimize the convergence rate.

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(iii) Analyze the stability of the closed-loop system via Lyapunov criteria and demonstrate the performances of the proposed control scheme using numerical simulations.

The rest of this paper is organized as follows. The kinematic and dynamic models of WMR and actuators are established in section 2. Section 3 presents the closed-loop controller design and stability analysis. Simulation results are shown and discussed in section 4. Finally, conclusion is given in section 5.

II. Modeling of WMR

In this section we present the kinematic and dynamic models of the nonholonomic wheeled mobile robot. As shown in figure "Fig. 1", the considered wheeled mobile robot is a differential vehicle with two wheels independently driven by two dc motors and castor wheel without driving force. The radius of all wheels is defined by r and two driving wheels are separated by 2b. d is the distance between the point C (center of mass) and the geometric midpoint P of the two driving wheels. φ is the angle between the heading direction and the X-axis.

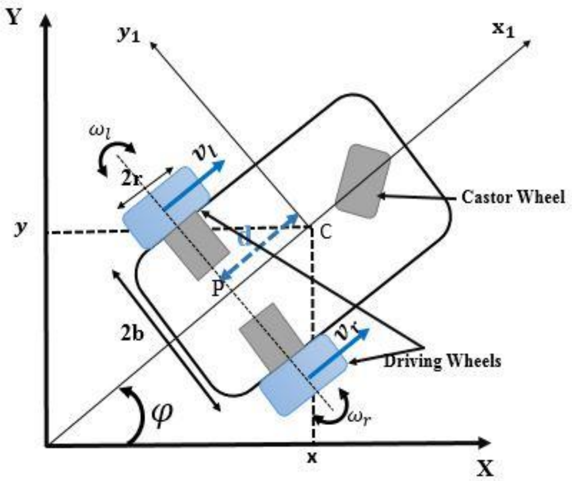

Figure 1. Wheeled Mobile Robot and coordinate systems.

The posture of the robot is defined by: $q = [x, y, \varphi]^T$ in the global coordinate system and by $q_1 = [x_1, y_1, \varphi]^T$ in the local coordinate system fixed to the mobile robot [17].

A. Kinematic Modeling

This subsection presents the description kinematic of WMR. The relationship between q and q_1 is given by [18]:

$$q = R(\varphi)q_1 = \begin{bmatrix} \cos(\varphi) & \sin(\varphi & 0 \\ -\sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix} [x_1, y_1, \varphi]^T \quad (1)$$

Where $R(\varphi)$ is the orthogonal matrix rotation.

Then the so-called nonholonomic constrains are given by $A(q)\dot{q} = 0$ where; $A(q) = [\sin(\varphi), -\cos(\varphi), d]$ and $\dot{q}$ is the time derivative of q. By considering the nonholonomic constraints, the kinematic model of WMR can be expressed as follows [17]:

$$\dot{q} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = T(q)\eta = \begin{bmatrix} \cos(\varphi) & -d\sin(\varphi) \\ \sin(\varphi) & d\cos(\varphi) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \quad (2)$$

Where v and ω are the linear and angular velocities of the WMR, respectively. $T(q)$ is the Jacobian transformation matrix satisfying $A(q)T(q) = 0$.

By principle of the differential motion of the mobile robot, we can write:

$$\begin{cases} v = \frac{v_r+v_l}{2} = \frac{r(\omega_r+\omega_l)}{2} \\ \omega = \frac{v_r-v_l}{2b} = \frac{r(\omega_r-\omega_l)}{2b} \end{cases} \quad (3)$$

Where ω_r and ω_l are the angular velocities of the right and left wheels, respectively.

B. Dynamic Modeling

In this subsection, the dynamic model of mechanical system and dc motors is presented. The state equation describing the dynamic model of the WMR robot is:

$$M\dot{\eta} + A(\eta)\eta = B\tau + F \quad (4)$$

Where: $M = \begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix}$, $A = \begin{bmatrix} 0 & -md\dot{\varphi} \\ md\dot{\varphi} & 0 \end{bmatrix}$,

$B = \begin{bmatrix} \frac{1}{r} & \frac{1}{r} \\ \frac{b}{r} & \frac{-b}{r} \end{bmatrix}$ and $\tau = [\tau_r, \tau_l]^T$. τ_r and τ_l are the right and left torque input of the mobile robot, respectively. m represents the total mass of the robot and I its moment of inertia. The equation (4) becomes:

$$\dot{\eta} = \overline{A}(\eta)\eta + \overline{B}\tau + \overline{F} \quad (5)$$

Where: $\overline{A} = -M^{-1}A, \overline{B} = M^{-1}B, \overline{F} = M^{-1}F$.

To complete the dynamic model, the actuator modeling is included. The WMR is driven by two DC motors assumed to be identical. The electromechanical equations of each motor are defined as follows [19]:

$$\begin{cases} u_i = RI_{ai} + L\frac{dI_{ai}}{dt} + e_i \\ e_i = k_e\omega_{ai} \\ \tau_i = k_\tau I_{ai} \end{cases}, i = r, l \quad (6)$$

Where k_τ and k_e are the torque constant and the back electromotive force constant, respectively. R and L denote the resistance and inductance of the armature circuit of each DC motor, respectively.

By considering the gear ratios N and ignoring the inductance L, the equation (6) becomes:

$$\tau_i = \frac{Nk_\tau}{R}u_i - \frac{N^2k_\tau k_e}{R}\omega_i, i = r, l, \quad (7)$$

Then:

$$\begin{cases} \tau_r = k_1u_r - k_2\omega_r \\ \tau_l = k_1u_l - k_2\omega_l \end{cases} \quad (8)$$

With; $k_1 = \frac{Nk_\tau}{R}$ and $k_2 = \frac{N^2k_\tau k_e}{R}$.

Using (5) and (8), the dynamic model can be described as follows:

$$\dot{\eta} = A_a(\eta)\eta + B_a\tau + F_a \quad (9)$$

Where: $F_a = [f_{a1}, f_{a2}]^T$ presents the disturbances and parameter uncertainties,

$$A_a = \begin{bmatrix} \frac{-2k_2}{r^2 m} & d\dot{\varphi} \\ \frac{-md\dot{\varphi}}{I} & \frac{-2k_2}{I}(\frac{b}{r})^2 \end{bmatrix}, B_a = \begin{bmatrix} \frac{k_1}{rm} & \frac{k_1}{rm} \\ \frac{bk_1}{rI} & \frac{-bk_1}{rI} \end{bmatrix} \text{and}$$

$u = [u_r, u_l]^T$ is the voltage control input.

III. Controller Design and Stability Analysis

In this section, two controllers are designed. The first one is the kinematic controller based on back-stepping approach that was proposed in [20]. The second one is the dynamic algorithm, which is based on the sliding mode control strategy.

A. Kinematic Controller

The objective of this controller is to computing the virtual velocity control law $\eta_c = [v_c, \omega_c]^T$ which converges towards the desired one $\eta_d = [v_d, \omega_d]^T$ in order to ensure the trajectory tracking ($e_p(t \to \infty) \to 0$). In the robot frame, the trajectory error is expressed as:

$$e_p = \begin{bmatrix} e_x \\ e_y \\ e_\varphi \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & -\sin(\varphi & 0 \\ \sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_d - x \\ y_d - y \\ \varphi_d - \varphi \end{bmatrix}$$

Where $e_q = q_d - q = [x_d - x, y_d - y, \varphi_d - \varphi]^T$ denotes the deviation of the robot in the (x,y) plan,
The virtual velocity vector is given by:

$$\begin{cases} v_c = v_d \cos(e_\varphi) + k_x e_x \\ \omega_c = \omega_d + k_y e_y + v_d k_\varphi \sin(e_\varphi) \end{cases} \quad (10)$$

k_x, k_y and k_φ are the positive constants. To study the convergence of this control law the Lyapunov theory is employed. Let V_0 the candidate function defined by ([20]:

$$V_0 = \frac{(e_x{}^2 + e_y{}^2)}{2} + \frac{1-\cos(e_\varphi)}{k_y} \quad (11)$$

The derivative of V_0 is given by the follow equation.

$$\dot{V}_0 = \dot{e_x} e_x + \dot{e_y} e_y + \frac{\dot{e_\varphi} \sin(e_\varphi)}{k_y} \quad (12)$$

By some manipulations, we obtain:

$$\dot{V}_0 = -k_x e_x{}^2 - \frac{v_d k_\varphi \sin(e_\varphi)^2}{k_y} \quad (13)$$

It's clear that $V_0 \geq 0$ and $\dot{V}_0 \leq 0$. Hence, the kinematic controller is asymptotically stable.

B. Dynamic Controller

In this subsection, an adaptive controller based on dynamic sliding mode is designed. This control strategy consists to compute the control law u such that the measured velocity η of the robot converge to the input one η_c. The velocity error is expressed as:

$e_v = [v_c - v, \omega_c - \omega]^T$, the sliding surface is selected as :

$$S(t) = [S_1(t), S_2(t)]^T = e_v + C \int e_v dt \quad (14)$$

With $C = diag(C_1, C_2)$, C_1 and C_2 are the positive constants.

Based on the principle of the sliding mode control method and using the dynamic model defined in (9), the SMC based on the control inputs is given as follows:

$$u = u_{eq} + u_{sw} = B_a{}^{-1}(\dot{\eta}_c + Ce_v - A_a(\eta)\eta + \gamma sgn(S)) \quad (15)$$

Where:

- u_{eq} is the equivalent control law. It is designed by solving the equation $\dot{S} = 0$
- $u_{sw}$is the switching control law, which needs to be properly designed. The classical switch control is given by $u_{sw} = B_a{}^{-1}\gamma sgn(S)$, in which $\gamma = diag(\gamma_1, \gamma_2)$, γ_1 and γ_2 are the positive constants.

In the sliding mode control method (SMC) , the robustness property is derived from the switching item. However, for the important values of γ, the switching of the system around the sliding surface causes the chattering phenomenon. To solve this, an adaptive controller is designed [17]. In the switching control law, the component $\gamma sgn(S)$, is replaced by the function $\sigma(S)$ given as follows.

$$\sigma(S) = \hat{\gamma}^T sgn(S) + \beta S \quad (16)$$

Where $\beta = diag(\beta_1, \beta_2)$, β_1 and β_2 are the positive constants, and $\hat{\gamma}$ is the adaptive gain given as follows:

$$\alpha_1 \dot{\hat{\gamma}} + \alpha_2 \hat{\gamma} = |S| \quad (17)$$

The PI term βS contributes to the optimization of the convergence rate and to the improvement of the precision and robustness of the system [19]. Hence, the proposed controller is given as:

$$u = B_a{}^{-1}(\dot{\eta}_c + Ce_v - A_a(\eta)\eta + \sigma(S)) \quad (18)$$

Consider a Lyapunov candidate function as:

$$V_1 = \frac{1}{2} S^T S \quad (19)$$

The time derivative of V_1 is :

$$\dot{V}_1 = S^T \dot{S} = S^T(\dot{\eta}_c - \dot{\eta} + Ce_v) \quad (20)$$

Inserting (9) and (18) in (20), we obtain:

$$\dot{V}_1 = -S^T \hat{\gamma}^T sgn(S) - S^T \beta S - S^T F_a \quad (21)$$

Assumption 1: Suppose that the dynamic disturbances are bounded and satisfying the condition $|f_{ai}| \leq \delta_i, i = 1,2$ and $\delta_i > 0$.

The equation (21) can be written in the following form:

$$\dot{V}_1 = \sum_{i=1}^{2} [-\hat{\gamma}_i |S_i| - \beta_i S_i{}^2 - S_i f_{ai}] \quad (22)$$

Considering the Assumption 1, we obtain the following inequality:

$$\dot{V}_1 \leq -\sum_{i=1}^{2} |S_i| [\hat{\gamma}_i + \beta_i |S_i| - \delta_i] \quad (23)$$

Suppose that exist $\psi = diag(\psi_1, \psi_2)$ satisfying $\psi_i = \min(\hat{\gamma}_i + \beta_i |S_i| - \delta_i)$, ($i = 1,2$), so the inequality (23) becomes :

$$\dot{V}_1 \leq -\sum_{i=1}^{2} \psi_i \frac{|S_i|}{\sqrt{2}} = -\psi V_1{}^{1/2} \quad (24)$$

According to the Lemma 4.2 in [14], and by selecting properly the control parameters, we get $\dot{V}_1 + \psi \dot{V_1}^{1/2} \leq 0$. As a result, the proposed controller is asymptotically stable.

IV. Simulation Results

In order to evaluate the performance of this controller, numerical simulations are performed in the Matlab/Simulink environment. The inputs of this simulator are; the desired velocities $v_d = 0.3m.s^{-1}$, $\omega_d = 0.1\sin(0.07t)\,rad.s^{-1}$ and the disturbances and parameter uncertainties $F_a = [f_{a1}, f_{a2}]^T$ are shown in figure "Fig. 2". The desired trajectory $q_d(t) = [x_d, y_d, \varphi_d]^T$ (shown in "Fig. 3"), is calculated by the following expression:

$$\begin{cases} x_d(t) = \int (v_d\cos(\varphi_d) - d\omega_d \sin(\varphi_d))dt + x_d(0) \\ y_d(t) = \int (v_d \sin(\varphi_d) + d\omega_d\cos(\varphi_d))dt + y_d(0) \\ \qquad \varphi_d(t) = \int \omega_d\, dt - \varphi_d(0) \end{cases}$$

And $q_d(0) = [0,0,0]^T$. The robot's initial posture (position and orientation) is $q(0) = [0.3, 0.4, 0]^T$.

The simulation parameters are defined in Table I.

TABLE I. Simulation Parameters

Kinematic parameters	$d = 0.15m$, $b = 0.09m$, $r = 0.03m$
Dynamic parameters	$m = 4Kg$, $I = 2Kgm^{-1}$
Actuator parameters	$N = 34$, $R = 5\Omega$, $k_e = k_\tau = 0.08N.m^{-1}$
Controller parameters	$C = diag(50,50)$, $\alpha_1 = 0.1$, $\alpha_2 = 10$, $\beta = diag(30,30)$, $k_x = 1$, $k_y = 1$, $k_\varphi = 1.5$

As illustrated in figures "Fig. 4", "Fig. 5" and "Fig. 6", all signals are bounded. The speed and posture errors converge to zero and the effects of the disturbances are attenuated (figures "Fig. 4"and "Fig. 5"). The computed voltages (right and left) are presented in figure "Fig. 6". It can be seen that the proposed controller eliminates the chattering phenomenon.

Moreover, the robustness and stability of the system is improved and increase for the high values of β. The adaptive switching function that contributes to correct and compensate the effect of dynamic disturbances is presented in "Fig. 7".

From a quantitative point of view, we consider the integral of the absolute value of the error (IAE) defined by:

$$\mathrm{IAE_i} = \int_0^{t_f} |e_{vi}|dt\, , i = 1,2 \tag{25}$$

In this study, $\mathrm{IAE_1} = 0.1122$ And $\mathrm{IAE_2} = 0.1201$.

In this work, the convergence time and the problem related to singularities are not studied in this work. In addition, the speed of the system depends on the input speeds while stability and precision depend on the choice of command parameters.

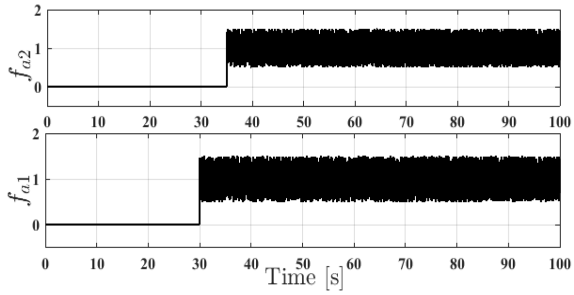

Figure 2. Disturbances and uncertainties

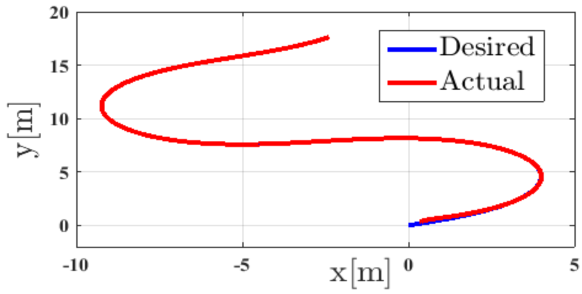

Figure 3. Desired and robot's trajectories.

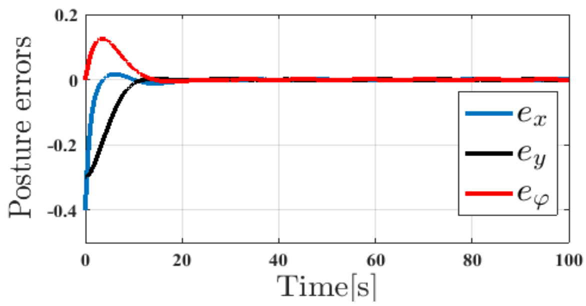

Figure 4. Position and orientation errors.

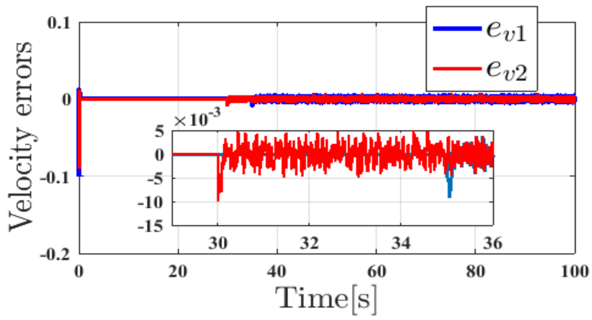

Figure 5. Linear and angular velocity errors.

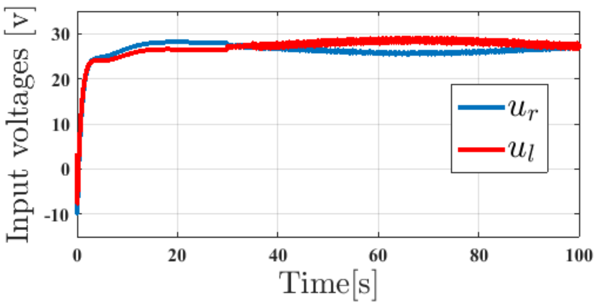

Figure 6. Right and left voltage inputs.

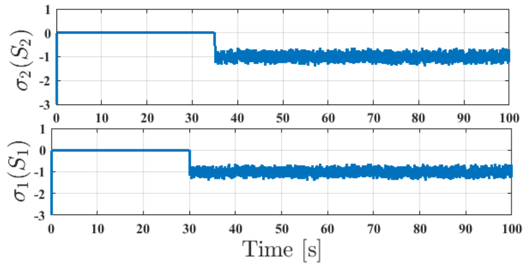

Figure 7. Corrective switching function.

V. CONCLUSION

In this paper, an adaptive trajectory tracking controller of an electrically wheeled mobile robot is discussed. The kinematic model is used to compute the virtual velocity which converges to the desired velocity. Based on the dynamic model of the robot and its actuators, an adaptive sliding mode controller is developed to compute the electrical inputs (voltages). The proposed control strategy is capable to: suppress the chatter phenomenon, attenuate the disturbances and uncertainties, and improve the convergence of the posture and speed errors in terms of precision ($\text{IAE}_1 = 0.1122$ And $\text{IAE}_2 = 0.1201$). The proposed controller is asymptotically stable according to Lyapunov theory. The simulation results illustrate the performances of this method. The next work will be dedicated to implementing this algorithm in a mobile robot platform.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The first author analyzed and wrote the manuscript. The second and third author conducted, analyzed, and revised the paper. all authors had approved the final version.

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