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Terminal Sliding Mode Controller for Tracking a Wheeled Mobile Robot

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Abstract

In this paper, reference path tracking based on terminal slip mode control for a wheeled mobile robot is presented and the proposed method is practically simulated on a mobile robot. The wheeled actuator is a nonlinear system with two inputs for controlling and three state variables and a nonlinear constraint. To control this system in this paper, first by converting the equations of the non-holonomic system into a chain form, the equations of a wheeled mobile robot are extracted for generalized chain equations. Then the limited time terminal sliding model control method is presented to control the reference path tracking of this system. It could be run using a graphical simulation environment in MATLAB software. The proposed method for the wheeled mobile robot used in the laboratory is simulated. The simulation results in the graphical environment show the efficiency of the proposed method in comparison with the classical sliding mode control method. Finally, the practical results of the controller simulation to follow the reference path provided on the mobile robot are shown. The results of the practical simulation show well the proper performance of the proposed method.

Keywords: Non-Holonomic Systems, Sliding Mode Control, Terminal Sliding Mode Controller, Graphic Simulation.

1. INTRODUCTION

In some mechanical and robotic systems, there are certain types of additional conditions that restrict movement, which are generally called constraints. Non-integral constraints are called non-holonomic constraints. Non-holonomic will restrict the movement of robots and it will be difficult to control the robot. Under these conditions, the robot will usually not be able to move in any direction [2, 1]. For example, wheeled mobile robots, surface watercraft, and space robots are examples of non-holonomic systems. Such systems do not behave linearly around any of their equilibrium points and could not

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be stabilized by continuous, time-independent derivative feedback. The issue of stabilization and reference path tracing in such systems has attracted the attention of many researchers in recent years [4, 3].

As mentioned, wheeled mobile robots are an example of a non-holonomic system in which the motion of these robots is achieved by actuators that determine the torque applied to the wheel and the direction of motion of the wheel axis [4]. Wheeled mobile robots have three degrees of freedom to move on the surface while having only two controllable inputs [6, 5]. One of the problems in controlling non-holonomic mobile robots is the uncertainty in modeling this system. Uncertainty in the robot is due to the inherent characteristics of the mobile wheeled robot, including the actual dynamics of the robot, inertia and power limitations of operators, and the positioning error of the robot, and therefore the equations of this system could not be described as a simplified mathematical model [5].

Many controllers are dedicated to the design of closed-loop stabilizer controllers for non-holonomic mobile robots. In this case, the position of the robot must be exactly known at all times, but this assumption is very unrealistic for robotics experts, because it is possible that a mobile robot may be driven in motion. As a result, their exact location is not possible by blind navigation alone [7]. To control a mobile robot, we face two issues, which include finding a predetermined path and stabilizing around the desired position. In recent years, the issue of guiding mobile wheeled robots with non-holonomic constraints has attracted a lot of attention in the field of robotics [8-23]. Early research on mobile robots was conducted in the 1960s, and expanded in the 1990s. For tracking problem in this system, various methods have been proposed, including the appropriate controller. Derivative-integral traction [8], Sliding mode control [9, 6, 5] Adaptive control [10], Neural control [11, 2], Fuzzy control [12, 2], and Combined controllers [16-13] Appeared. In addition, based on Bracket's theorem [15], researchers have shown that systems with three degrees of freedom and two inputs could be controlled as open loops. But it could not be stabilized by the law of state feedback control, continuous and time-independent derivative. Much research has been done to solve this problem, including the design of time-varying feedback [16] and the design of nonlinear continuous mode feedback [17].

One of the most effective ways to control a wheeled mobile robot is to control the sliding mode. Sliding mode control is an effective robust technique that has been used effectively to control linear and nonlinear systems. This method has been widely used in systems with uncertainty due to its convenient features such as simplicity of design, good consistency, reduction of order, and easy implementation. Slip mode control and its combinations are considered as a way to control robust systems [3, 5, 6, 9, 20, and 23]. Reference [5] presents a robust control method for asymptotic stabilization of the non-holonomic mobile robot and shows that the designed sliding mode controller is resistant to limited external disturbances. In the reference [9], a sliding mode control law was introduced to stabilize and follow the reference path in non-holonomic systems, which has become a chain form. For limited time convergence, the terminal slip mode control method was proposed for this system. In reference [20], sliding mode control was used to stabilize the wheeled mobile robot system. Reference [21] provides a limited time tracking controller for non-holonomic systems in extended chain form. In the method proposed in this reference, the technique of relay switching and control of terminal sliding mode with limited time convergence has been used to design the controller. In reference [22], a recursive terminal slip mode control method is proposed to track non-holonomic systems that have become a chain form. In reference [23] based on the fast terminal slip mode control method presented in references [25, 24], limited time tracking in non-holonomic systems is presented in the form of a chain.

In this paper, inspired by previous works, the reference path for a wheeled mobile robot is presented and the proposed method is implemented on a wheeled mobile robot. In this regard, first by combining the cinematic and dynamic equations, equation of the wheeled mobile robot is extracted in the form of chain equations. Then the terminal slip mode control method is presented to control the reference path tracking for the obtained model. The proposed method for the wheeled mobile robot is then simulated using a graphical simulation environment. It should be noted that at each stage of the simulation, the terminal slip mode control method is compared with the conventional slip mode control method. Graphic simulation has the advantage that the adjustable parameters in the tested robot are very high and using the graphical environment, the robot parameters are easily adjusted and there is no need to use the trial and error method, which is very time consuming in practical testing. The structure of this article is as follows: The second part includes a combination of cinematic and dynamic model of a wheeled mobile robot and the whole problem is stated. The design method of the terminal slip mode controller for the robot is given in the third section. The fourth part of this paper includes the simulation results of the proposed method on the tested robot. Finally, the conclusion of the research is presented.

2. TWO-WHEELED MOBILE ROBOT MODEL AND PROBLEM EXPRESSION

Assuming that the sliding wheels are negligible when the mobile robot is moving, the dynamic model of the wheeled mobile robot in Figure (1) could be expressed as (1) [23].

$$\begin{aligned} \dot{x} &= v\cos(\theta) \\ \dot{y} &= v\sin(\theta) \\ \dot{\theta} &= \omega \\ m\dot{v} &= F \\ I\dot{\omega} &= N \end{aligned} \tag{1}$$

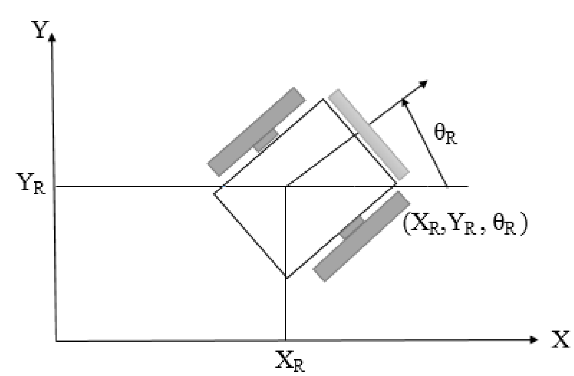


Fig. 1. Schematic of a mobile robot in Cartesian coordinates [23].

Equation (1), represents the position of the robot in Cartesian coordinates and θ indicates the direction of movement of the robot relative to the x-axis, m indicates the mass of the robot, I represents the inertia of the robot, v and ω express the linear velocity and angular velocity of the robot, F represents the tensile force and N is steering torque.

2.1. Cinematic Model

First consider the coordinate conversion as relation (2), [23]:

$$\begin{aligned} x_1 &= \theta \\ x_2 &= x\cos(\theta) + y\sin(\theta) \\ x_3 &= x\sin(\theta) - y\cos(\theta) \end{aligned} \tag{2}$$

Considering the conversion of coordinates as (2) and defining the new control inputs as (3), the form of the cinematic transformed chain of the mobile robot is obtained as (4).

$$\begin{aligned} u_1 &= \omega \\ u_2 &= v - x_3\omega \end{aligned} \tag{3}$$

$$\begin{aligned} \dot{x}_1 &= u_1 \\ \dot{x}_2 &= u_2 \\ \dot{x}_3 &= x_2 u_2 \end{aligned} \tag{4}$$

which $x = (x_1, ..., x_n)^T$ are mode vectors, u_1 and u_2 are two control inputs.

The cinematic equations of the mobile robot have a simple form and are of the third order without drift and show the main features of non-holonomic systems. This system could not be controlled linearly around any of its equilibrium points. Although the cinematic control of mobile robots has been extensively studied in various studies, this system is not able to consider both the cinematics and the dynamics of the system, while for most practical applications, it is better to have a complete model including dynamics and cinematics of the systems, which is considered practical.

2.2. Dynamic Model

Control inputs for system (1) are defined as:

$$\begin{aligned} v_1 &= \dot{\omega} = \frac{N}{I} \\ v_2 &= \dot{v} - \frac{N}{I}x_3 - \omega^2 x_2 \end{aligned} \tag{5}$$

By applying the coordinate change according to Equation (2) for the system states and changing the variable according to (5), the dynamics of the mobile robot defined as (1) could be converted to (6).

$$\begin{aligned} \ddot{x}_1 &= v_1 \\ \ddot{x}_2 &= v_2 \\ \ddot{x}_3 &= x_2 v_2 \end{aligned} \tag{6}$$

With this change in coordinates, Equation (6) includes the cinematics and dynamics of a wheeled mobile robot. The inputs of this system include two inputs which are the tensile force and the steering torque of the robot wheels.

2.3. Stating the Problem

The purpose of this paper is to provide a collaboration that allows the tested wheeled mobile robot to follow the given paths without error. To achieve this goal, equations (6) are first taken to the polar coordinates and formed into a simpler chain form. It is then obtained by designing a suitable controller for the form of stabilization chains and tracing the reference path.

3. DESIGN OF TERMINAL SLIDING MODE CONTROLLER

3.1. Main Results of Tracking Problem

The proposed method for designing the terminal sliding mode controller inspired by reference [21] is presented in this section. For this purpose, first, the design method for a system with 3 modes is presented. Assume $x_d = (x_{1d}, ..., x_{3d})^T$ that the desired path is (7).

$$\begin{aligned} \dot{x}_{1d} &= u_{1d} \\ \dot{x}_{2d} &= u_{2d} \\ \dot{x}_{3d} &= x_{2d} u_{1d} \end{aligned} \tag{7}$$

which u_{1d} and u_{2d} are two reference control inputs.

Chain form tracking problems (7) could be applied to mechanical systems, including wheeled mobile robots. Therefore, system (4) with two control inputs is considered as (8).

$$\begin{aligned} \dot{u}_1 &= v_1 \\ \dot{u}_2 &= v_2 \end{aligned} \tag{8}$$

In Equation (8), v_1 and v_2 control inputs are dynamic models. Therefore, the purpose of control is to design a controller in such a way that with two control inputs, v_1 $v_2 x(t)$ it follows the desired path $x_d(t)$ according to the system (7). The transformed equations of the mobile robot chain form and its reference model could be expressed as (9) and (10):

$$\begin{aligned} \dot{x}_1 &= u_1 \\ \dot{x}_2 &= u_2 \\ \dot{x}_3 &= x_2 u_1 \\ \dot{u}_1 &= v_1 \\ \dot{u}_2 &= v_2 \end{aligned} \tag{9}$$

$$\begin{aligned} \dot{x}_{1d} &= u_{1d} \\ \dot{x}_{2d} &= u_{2d} \\ \dot{x}_{3d} &= x_{2d} u_{1d} \\ \dot{u}_1 &= v_1 \\ \dot{u}_2 &= v_2 \end{aligned} \tag{10}$$

The tracking error is defined $x_{ie} = x_i - x_{id}$ for (9) and (10) and $(i = 1, ..., 3)$ therefore the system error equations are (11).

$$\begin{aligned} \dot{x}_{1e} &= u_1 - u_{1d} \\ \dot{x}_{2e} &= u_2 - u_{2d} \\ \dot{x}_{3e} &= x_{2e} u_{1d} + x_2 (u_1 - u_{1d}) \\ \dot{u}_1 &= v_1 \\ \dot{u}_2 &= v_2 \end{aligned} \tag{11}$$

The goal of the design is to converge the tracking error to zero in a limited time. Equations (11) could be divided into two independent sub-equations (12).

$$\begin{aligned} \dot{x}_{1e} &= u_1 - u_{1d} \\ \dot{u}_1 &= v_1 \\ \dot{x}_{3e} &= x_{2e} u_{1d} + x_2 (u_1 - u_{1d}) \\ \dot{x}_{2e} &= u_2 - u_{2d} \\ \dot{u}_2 &= v_2 \end{aligned} \tag{12}$$

Using the terminal sliding mode control method for tracking, we first consider the subsystem (12). The control law for the equation of the above first-order system is considered as (13).

3.2. Main Results of TSMC

Assumption 1: Let the tracking errors be as: $e_i = x - x_d$.

Assumption 2: In general, consider the constraints on the disturbance and uncertainty as:

$$\left| f(x(\tau)) \right| \leq \alpha_1 \ , \ \left| d(\tau) \right| \leq \alpha_2 \tag{13}$$

where α_1 and α_2 denote positive unknown constants.

Assumption 3: Suppose $x = x_d$ implies that $\lim_{\tau \to \infty} e_i(\tau) = 0$.

Consider the nonlinear system with external disturbance as

$$\dot{x}(\tau) = f(x(\tau), \tau) + g(x(\tau), \tau)u(\tau) + d(x(\tau), \tau). \tag{14}$$

where $x(\tau) = \left[x_m(\tau),\ x_s(\tau) \right]^T$ is the states' vector, $u(t)$ is the input signal, $g(x(\tau))$, and $f(x(\tau))$ are the nonlinear functions with known bounds, and is the disturbance of the system satisfying $| d(x(\tau)) | \leq \sigma$, where σ is a positive constant. The control goal is to make the nonlinear system track the trajectories of (14) reference system $x_{im}(\tau)$, so that the reference paths $x_{is}(\tau)$ would follow paths $x_{im}(\tau)$ for $i = 1, ..., 4$. Then, the tracking error trajectories are formed as

$$e_i(\tau) = x_i(\tau) - x_{id}(\tau) \tag{15}$$

Assumption 4: $f(x(\tau), \tau),\ g(x(\tau), \tau),\ d(x(\tau), \tau)$, which are nonlinear functions, change over time.

The sliding surface for System (14) is described as:

$$\delta(\tau) = \tanh^2 \left(\int_0^t \xi \dot{e}(\tau) d\tau + \int_0^t \xi (f(x(\tau)) + \dot{x}_m(\tau)) d\tau \right) \tag{16}$$

By combining Equations (14) and (15) and deriving from (16), the time–derivative of the sliding surface is found as:

$$\dot{\delta}(\tau) = \left(\xi \dot{e}(\tau) + \xi e(\tau) \right) \operatorname{sech}^4(\tanh(\delta)) \tag{17}$$

Lemma 1: Consider the equation of error (15). If we consider the sliding surface as (17), system modes are converged in finite time to the origin, and we will have finite-time synchronization.

Theorem 1: Consider the general nonlinear equation (14). Considering the error equation (15) if we have a fast terminal SMC (FTSMC) low as follows:

$$\begin{aligned} u(\tau) = (\xi B)^{-1} \big(& \xi \dot{x}_{im}(\tau) - \psi_1 \delta(\tau) \\ & - sign\left(\delta(\tau) \right) \left(\psi_2 + \Theta_1 \left\| \xi \right\| \right. \\ & \left. \left. + \Theta_2 \left\| \xi \right\| \psi_3 e^{-\left\| x_{im} \right\|} \right) \right) \end{aligned} \tag{18}$$

where $\xi \in R^{i \times 1}$, $\psi_1, \psi_2, \psi_3 \in R^{1 \times 1}$ are the real constants, $B \in R^{i \times 1}$ is the control gain, and Θ_1, Θ_2 are defined as follows:

$$\begin{aligned} \dot{\Theta}_1 &= k_1 \left\| \delta \right\| \left\| \xi \right\| \operatorname{sech}^4(\tanh(\delta)) \\ \dot{\Theta}_2 &= k_2 \left\| \delta \right\| \left\| \xi \right\| \psi_3 e^{-\left\| x_{im} \right\|} \operatorname{sech}^4(\tanh(\delta)) \end{aligned} \tag{19}$$

Proof: The Lyapunov candidate function can be considered as follows:

$$\vartheta(\tau) = 0.5\delta^T(\tau)\delta(\tau) \tag{20}$$

By deriving from the Lyapunov candidate function (20), we will have:

$$\begin{aligned}\dot{\vartheta}(\tau) &= \delta^T(\tau)\dot{\delta}(\tau) \\ &= \delta^T(\tau)\left(\xi\dot{e}(\tau) - \xi f(e(\tau) + \xi\dot{x}_m(\tau)\right) \\ &\qquad \cosh^4(\tanh(\delta(\tau)))\end{aligned} \tag{21}$$

By placing Equation (14) in differentiating the Lyapunov function (21), we will have

$$\begin{aligned}\dot{\vartheta}(\tau) &= \delta^T(\tau)\left(\left(\xi g(e(\tau))u(\tau)\right) + \xi d(\tau)\right. \\ &\qquad \left. + \xi\dot{x}_m\right)\text{sech}^4(\tanh(\delta(\tau)))\end{aligned} \tag{22}$$

Placing Controller (18) into Equation (22) results in:

$$\begin{aligned}\dot{\vartheta}(\tau) &= \left\{\delta^T(\tau)\left(-\psi_1\delta(\tau) - sign(\delta(\tau))\right)\left(\psi_2 + \Theta_1\|\xi\| + \Theta_2\|\xi\|\psi_3 e^{-\|x_m(\tau)\|}\right) + \xi d(\tau)\right\} \\ &\qquad \times \text{sech}^4(\tanh(\delta(\tau)))\end{aligned} \tag{23}$$

The upper limit of Equation (23) can be written as follows:

$$\begin{aligned}\dot{\vartheta}(\tau) \le &\left\{-\psi_1\|\delta(\tau)\|^2 - \|\delta(\tau)\|\left(\psi_2 + \Theta_1\|\xi\| + \Theta_2\|\xi\|\psi_3 e^{-\|x_m(\tau)\|}\right)\right. \\ &\left. + \|\delta(\tau)\|\|\xi\|\left(\Theta_2\psi_3 e^{-\|x_m(\tau)\|}\|e(\tau)\| + \Theta_1\right)\right\} \times \text{sech}^4(\tanh(\delta(\tau)))\end{aligned} \tag{24}$$

Thus, we will have:

$$\begin{aligned}\dot{\vartheta}(\tau) \le &\left\{-\psi_1\|\delta(\tau)\|^2 - \psi_2\|\delta(\tau)\|\right. \\ &- \|\delta(\tau)\|\|\xi\|\Theta_1 \\ &- \|\delta(\tau)\|\|\xi\|\psi_3 e^{-\|x_m(\tau)\|}\|e(\tau)\| \\ &\left. + \Theta_2\right\} \times \text{sech}^4(\tanh(\delta(\tau)))\end{aligned} \tag{25}$$

By placing Equation (19) into Equation (25), we can write:

$$\begin{aligned}\dot{\vartheta}(\tau) \le &-\psi_1\|\delta(\tau)\|^2 - \psi_2\|\delta(\tau)\| \\ &\text{sech}^4(\tanh(\delta(\tau)))\end{aligned} \tag{26}$$

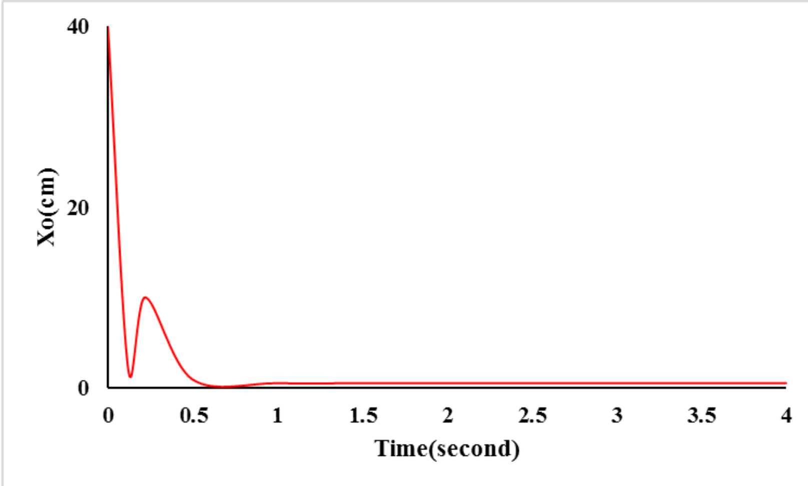
with $\psi_1 > 0,\ \psi_2 > 0$, the derivative of the Lyapunov function (26) is decreased gradually, and the sliding surface converges to the origin in the finite time. Consequently, this completes the proof.

Remark 1: Controller (18) will be used to tracking errors in a finite-time.

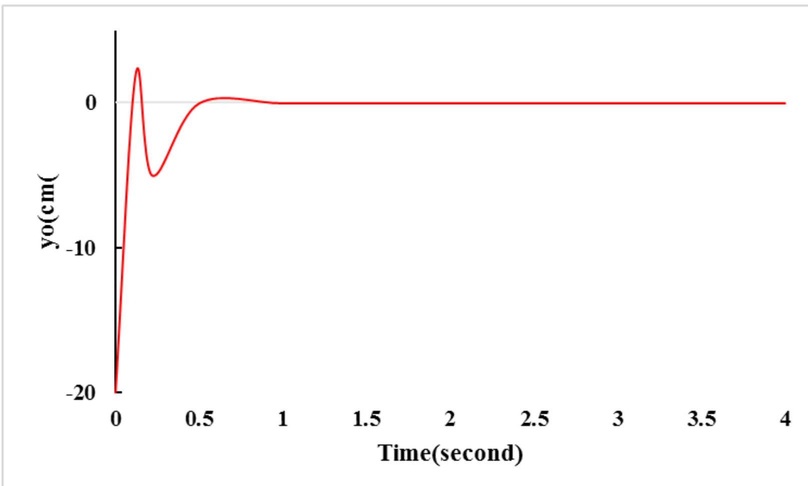
In this system, in order to design the controller of the TSMC, we first consider the system in general and for this purpose, equations (14) are considered.

4. SIMULATION

In this section, the method presented in the previous section is first simulated in MATLAB environment with the help of Simulink and graphical simulation to provide the necessary parameters for practical implementation on the tested robot and then the method is implemented on the robot and tested. At each stage, the simulation results of the conventional sliding mode control method are presented. For this purpose, the



(a)



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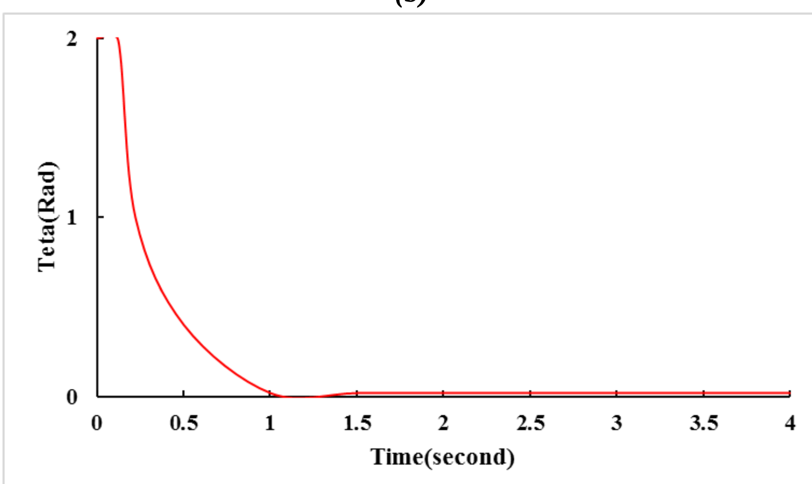
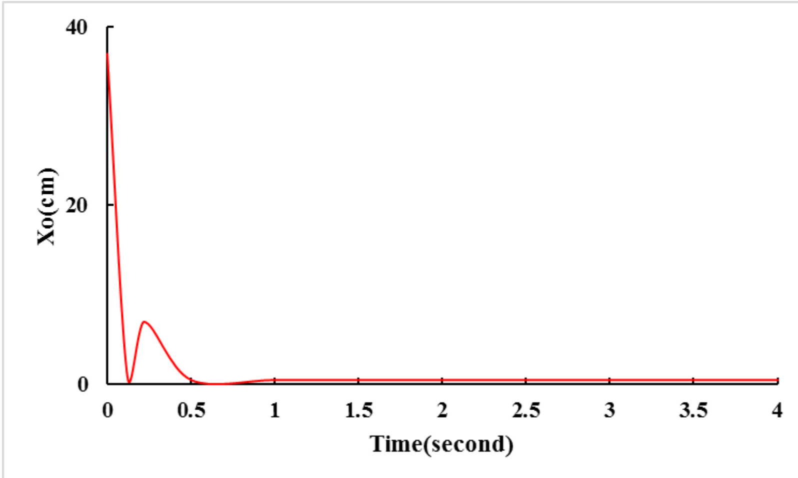
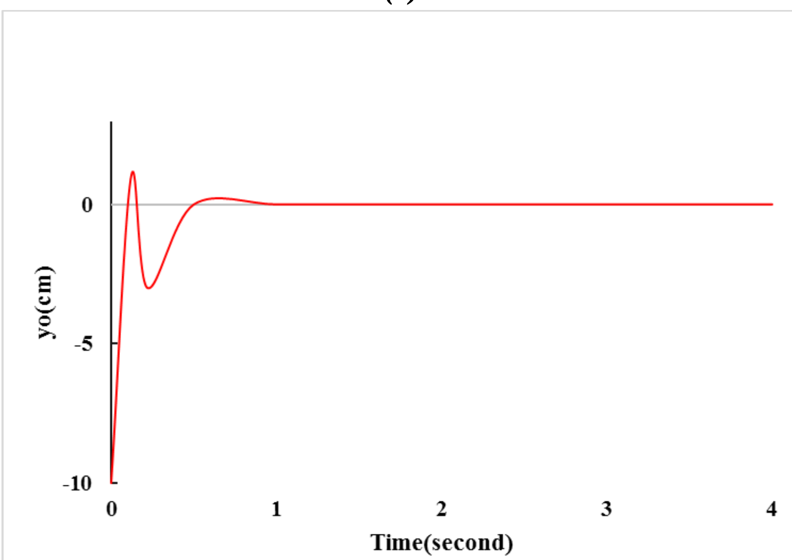


(c)

Fig. 2. Position and error direction for a wheeled mobile robot with a classic sliding mode controller.



(a)



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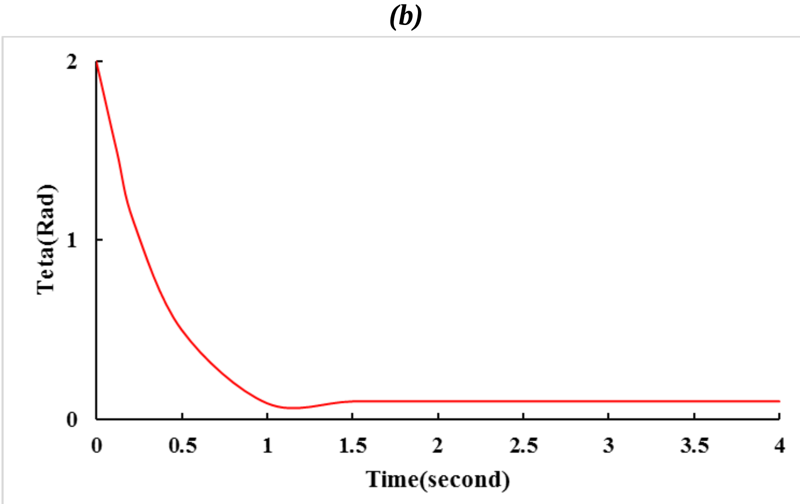

(c)

Fig. 3. Position and error direction for wheeled mobile robot with terminal slip mode controller.

conventional sliding mode control according to the reference [26] for system (1) is considered. In this reference, the slip level and the control law are considered as (27):

$$\begin{aligned} s_e &= \dot{x}_e + k_1 x_e \\ v &= -k_2 s_e \end{aligned} \tag{27}$$

In this reference, it is shown that the slip surface converges to zero and the system is stable.

4.1. Simulation Result

In this section, the simulation results of slip mode control and terminal slip mode control in MATLAB simulator environment for moving the robot towards a certain fixed point are presented. In all simulations, the parameters of the classic sliding mode controller are selected as follows:

$$k_1 = 4, k_2 = 10 \tag{28}$$

The parameters of the terminal sliding mode controller are selected as follows:

$$\begin{aligned} &(\beta, \beta_1, \beta_2, k_0, k, p_0, q_0, p_1 \\ &\quad , q_1, p_2, q_2, p_3, q_3, m, n) = \\ &(5, 1, 97.13, 10, 61, 17, 7, 213 \\ &\quad , 175, 137, 39, 269, 111, 9, 11) \end{aligned} \tag{29}$$

In the first step, controlling the position and direction of the (1.1) robot in moving from the origin to the target point, the starting point is proposed using two methods. Position and direction error in tracking the point reference path for each slip model control method and terminal slip mode control are shown in Figures 2 and 3, respectively. As could be seen, the convergence rate in the slip mode control method is less than the slip mode control method.

Table (1) shows the comparison of the absolute value error $(IAE = \sum_{n=1}^{\infty} |e|)$ for each of the system state changes and Table (2) shows the final error of each state variable in percentage relative to the maximum error. As shown in these two tables, the error from the slip mode control method is less than the error from the slip mode control method.

Table 1. ***Absolute value of the error obtained from the slip mode control method and terminal slip mode control.***

IAE / Parameter	Terminal sliding mode control	Sliding mode control
X	52.667	60.786
Y	15.455	20.132
θ	2	2.576

Table 2. ***Percentage of final error obtained from the slip mode control method and terminal slip mode control.***

IAE / Parameter	Terminal sliding mode control	Sliding mode control
X	3e-7	5e-6
Y	0	0
θ	0	0

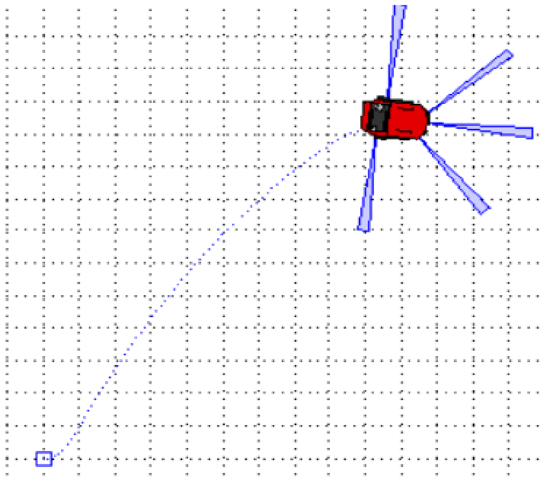

Fig. 4. Graphic simulation of the movement of a mobile robot to move from the origin to the point (1,1) with sliding mode control.

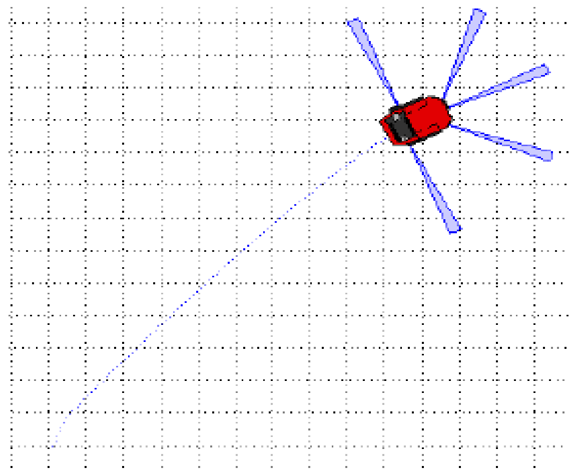

Fig. 5. Graphic simulation of a wheeled mobile robot with a slider model controller for moving to a point (1,1).

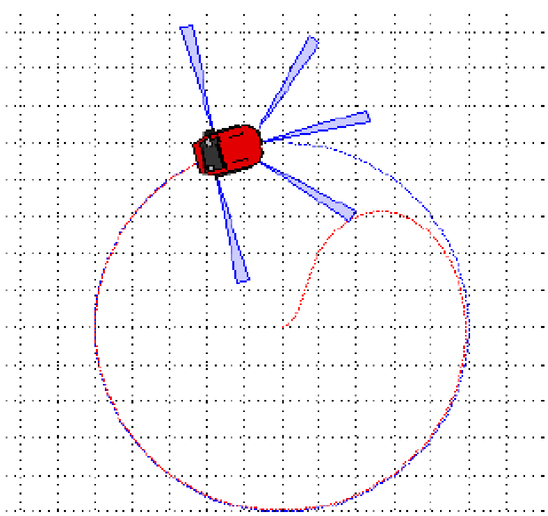

Fig. 6. Graphic simulation of a wheeled mobile robot with a sliding mode controller to track the circular path.

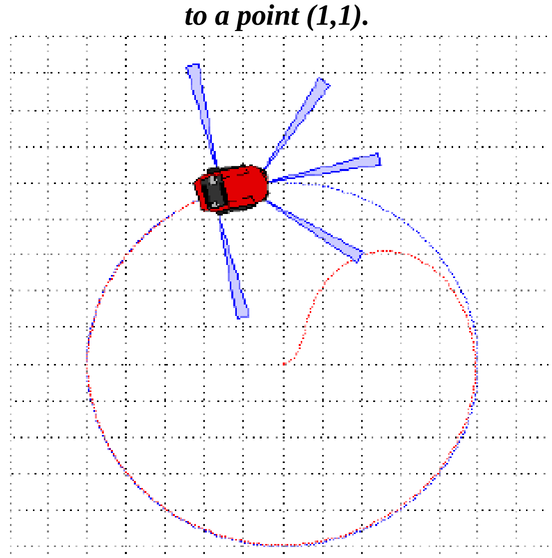

Fig. 7. Graphic simulation of a wheeled mobile robot with a terminal sliding mode controller to track circular paths.

4.2. Graphic Simulation

In this section, the performance of two controllers in the simulator environment is graphically simulated. For implementation in this section, both direct path and circular path are considered for the robot. The simulation results for direct movement of the robot are shown in Figure 4 for the slip mode control method and in Figure 5 for the terminal slip mode control method. The simulation results of the mobile robot moving around a circular reference path with a radius of 1 m and center (0, 0) in slip mode control and terminal slip mode are shown in Figures 6 and 7, respectively.

5. CONCLUTION

In this research, a controller based on the controlled sliding method was designed for a non-holonomic mobile wheeled robot. The simulation results showed the optimal performance of the controller design. Practical results showed that the controllers presented in practice were able to perform good follow-up in the sample reference. At each stage, the simulation results of the traditional sliding mode control were also presented. According to the results of practical implementation, it is observed that as expected, the anti-slip controller of the terminal has better performance and less tracking error in finding the desired target point, while the follow-up error of the classical creep mode controller is higher and the welding time is higher. It is longer. It should be noted that the method of calculating the position of the robot from speed inputs is based on the counting of encoder pulses and the analysis with the help of Eddie and Terry, which itself is sensitive to the accumulation of position calculation error over time. Slippage in a mobile robot can also cause errors, which could make a difference in the different configurations of a mobile robot with a single controller, but what matters overall is the stable and proper performance of each of the controllers. It follows the reference path that was observed in both the classic slip controller design and the terminal anti-slip model. Therefore, both controllers for the mobile robot could be used to track different time reference paths due to their convenient operation and at the same time simple structure and adjustable parameters. For the purposes of the point where the robot is directed to a specific point, the use of a terminal slider mode controller could demonstrate better performance of the robot.

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