PD Terminal Sliding Mode Control Using Fuzzy Genetic Algorithm for Mobile Robot in Presence of Disturbances

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Walid Benaziza, Noureddine Slimane, Ali Mallem

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Abstract:
This paper presents a new approach in the field of trajectory tracking for nonholonomic mobile robot in presence of disturbances. The proposed control design is constructed by a kinematic controller, based on PD sliding surface using fuzzy sliding mode for the angular and linear velocities disturbances, in order to tend asymptotically the robot posture error to zero. Thereafter a dynamic controller is presented using as a sliding surface design, a fast terminal function (FTF) whose parameters are generated by a genetic algorithm in order to converge the velocity errors to zero in finite time and guarantee the asymptotic stability of the system using a Lyapunov candidate. The elaborated simulation works in the case of different trajectories confirm the robustness of the proposed approach.

Keywords: *mobile robot, fast terminal function, PD sliding surface, fuzzy system, genetic algorithm, Lyapunov stability.*

1. Introduction

The mobile robots are widely used in different fields and are known as nonholonomic system [1]. Different works are done in the field of trajectory tracking of mobile robots taking into account the model uncertainties [2]. Therefore, many researchers have done to use kinematic and dynamic model to control the motion of wheeled mobile robot [3]. The unicycle robot is generally used for the control design to track the reference trajectory in a plane [4]. The control of mobile robot has been studied in different ways for instance, point stabilization, trajectory tracking, path-following etc.

Sliding mode control has shown its robustness against the uncertainties and external disturbances [5], but conventional sliding mode control is known with the discontinuity, and the last one creates, in high oscillations, the chattering phenomenon. Many works have been proposed to resolve this kind of problem [6], [7], [8] and another suggests a fuzzy logic to reduce the effect of this phenomenon [9], [10] and [11]. However the sliding mode control displayed the problem of chattering, which is the high problem of their real implementation.

Recently, many robust controllers are proposed for the trajectory tracking and obstacle avoidance, using dynamic model [12], [13], [14] and [15].

A recent method suggests an adaptive fuzzy terminal sliding mode control for nonlinear system with non-singularity in presence of external disturbances in order to achieve a fast convergence [16], [17], [18] and [19].

A robust control using PD sliding surface for robotic system is introduced to stabilize the closed loop system and compensate the effect of the disturbances and reduce the tracking errors [20], another work used genetic sliding mode in order to achieve the optimal parameters is presented in [21] for a servo system and in [22] for a manipulator arm.

Based on the previous works using PD sliding mode control, the contribution of this paper aims to suggest a new kinematic controller for the linear and angular velocities using PD and fuzzy logic. The selected PD sliding surface is used for the angular velocity in order to accelerate the orientation error to converge to zero in short time. The added fuzzy system permits to avoid the effect of the disturbances presented in the kinematic model by selecting the appropriate value of the gain parameter. A conventional sliding mode controller used for the linear velocity aims to converge the robot position error to zeros and guarantee the asymptotic stability of the system.

A dynamic controller based on terminal sliding mode with genetic algorithm is proposed. The genetic algorithm is used in order to select the optimal values of the controller parameters, which permit to the controller to converge the dynamic velocity error to zero and guarantee the asymptotic stability by using the Lyapunov stability.

The new trajectory tracking controller is proposed, based on fuzzy logic and genetic sliding mode for mobile robot. The approach gives mainly an asymptotic stability by using Lyapunov theory.

The proposed control law can tend the tracking error and velocity error to zero in very short time with asymptotic stability by taking into account the disturbances and the system uncertainty.

The paper is organized as follow. The first section presents the kinematics and dynamic model. The second section consists to propose a kinematic controller based on PD terminal sliding mode control with fuzzy logic. The third section presents a new dynamic controller using fast terminal function (FTF) with genetic algorithm [23] into the sliding surface design by including a saturation function in order to reduce the chattering problem by taking into account the disturbances.

2. Kinematics and Dynamic Modelling

2.1. Kinematic Model

Consider the differential drive which is indicated in Fig 1. The robot has two wheels and the speed of each wheel is given as follows:

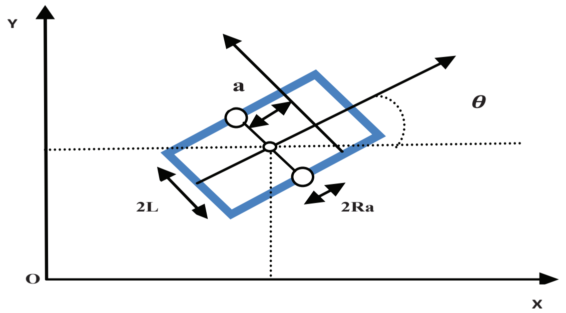

Fig. 1. The mobile robot model

The linear velocity is given as:

$$v = R_a\left(\frac{\dot{\varphi}_r + \dot{\varphi}_l}{2}\right) \quad (1)$$

The angular velocity of the mobile robot is:

$$\omega = \frac{R_a}{2L}(\dot{\varphi}_r - \dot{\varphi}_l) \quad (2)$$

The Kinematic model for a mobile robot is given by:

$$\dot{p} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix}\gamma \quad (3)$$

where $\gamma = (v \quad \omega)^T$.

Consider the posture error of mobile robot $p_e = (x_e \quad y_e \quad \theta_e)^T$ the reference posture is given as: $p_r = (x_r \quad y_r \quad \theta_r)^T$.

The vector of the desired velocity is: $\gamma_r = (v_r,\ \omega_r)^T$.

The position error of the mobile robot is given as:

$$p_e = \begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \quad (4)$$

The derivative of the trajectory tracking error is expressed as:

$$\dot{p}_e = \begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{\theta}_e \end{bmatrix} = \begin{bmatrix} y_e\omega + v_r\cos\theta_e - v \\ -x_e\omega + v_r\sin\theta_e \\ \omega_r - \omega \end{bmatrix} \quad (5)$$

Consider the kinematic model (3) with disturbances [24], [25]:

$$\dot{p} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix}(\gamma + \Psi) \quad (6)$$

Therefore, the vector Ψ presents the disturbances in the two velocities:

$$\Psi = (\tilde{v} \quad \tilde{\omega}) \quad (7)$$

Where:

$$|\tilde{v}| \le \varepsilon_v,\ |\tilde{\omega}| \le \varepsilon_\omega$$

The derivative of model error becomes as follows:

$$\dot{p}_e = \begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{\theta}_e \end{bmatrix} = \begin{bmatrix} v_r\cos\theta_e - (v + \tilde{v}) + y_e(\omega + \tilde{\omega}) \\ v_r\sin\theta_e - x_e(\omega + \tilde{\omega}) \\ \omega_r - (\omega + \tilde{\omega}) \end{bmatrix} \quad (8)$$

The proposed control law of the two velocities must take the tracking error to zero while t tends to infinity by considering:

$$|v|''\ v_{\max},\ |\omega| \le \omega_{\max}.$$

2.2. Dynamic Model

When dynamic model of the robot is described as [26, 27]:

$$M(q)\dot{V} + V(q,\dot{q})V + F(\dot{q}) + G(q) + \tau_d = \beta(q)\tau + \tilde{D}(t) \quad (9)$$

Where:

$V = (v\ \omega)^T$ is the vector of velocities and v and ω are the linear and angular velocities respectively, $[\tau_1 \quad \tau_2]^T$ is the vector of torque of the wheels of the mobile robot τ_1 and τ_2 are the torques of the right and left wheel.

Where

$$M(q) = \begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix},\ \beta(q) = \frac{1}{R_a}\begin{bmatrix} 1 & 1 \\ L & -L \end{bmatrix}$$

m is the mass of the robot.
I is the moment inertia of the robot.
L is the distance between the two wheels.
R_a is the radius of the wheel.
$\tilde{D}(t)$ represents the disturbance.
$V(q,\dot{q})$ is the vector of centripetal and Coriolis forces.
$F(\dot{q})$ represents the friction matrix.
$G(q)$ represents the gravitational vector.
τ_d is an unknown disturbance.

Eq. (6) of the robot is used in order to control the movement of the robot by using fuzzy genetic sliding mode control in presence of the disturbances. Hence, the posture error of the robot must tend asymptotically to zero:

$$\lim_{t\to\infty} p_e = \lim_{t\to\infty}\|p_r(t) - p(t)\| = 0 \quad (10)$$

3. Controller Design

3.1. Kinematic Controller Design

1) Angular Velocity Control

Each By using PD sliding surface, the selection of switch function is given as:

$$s_1 = \rho_1 e_1 + \rho_2 \dot{e}_1 \quad (11)$$

Where $e_1 = \theta_e$

The derivative of the first sliding surface is:

$$\dot{s}_1 = \rho_1 \dot{e}_1 + \rho_2 \ddot{e}_1 \quad (12)$$

Appling the reaching control law:

$$\dot{s}_1 = -k_1 sign(s_1) \quad (13)$$

In order to attenuate the chattering problem, the discontinue function is replaced by saturation function:

$$\dot{s}_1 = -k_1 sat(s_1) \quad (14)$$

The control law of the angular velocity is given as:

$$\dot{\omega} = \frac{1}{\rho_2}(\rho_1\omega_r - \rho_1\omega + \rho_2\dot{\omega}_r + k_1 sat(s_1)) \quad (15)$$

This control law can make θ_e converges to zero and, $\omega_r \approx \omega$. Therefore, in order to eliminate the effect of angular disturbances, the fuzzy system is applied.

2) Fuzzy Sliding Mode Control

The parameter k_1 is chosen with fuzzy system in order to delete the effect of disturbances and reduces the chattering problem [28].

To select the value of k_1, the relation between k_1 and the sliding surface s_1 must be determined. So, at this case, the inputs of fuzzy system will be s_1 and $\dot{s}_1$ and the output will be k_f.

The fuzzy sets of the inputs and output can be given as:

S_1= {NP, NM, ZE, PS, PL}

$\dot{S}_1$ = {NP, NM, ZE, PS, PL}

K_f = {NP, NM, ZE, PS, PL}

The control law (15) is becoming as follows:

$$\dot{\omega}_k = \frac{1}{\rho_2}(\rho_1\omega_r - \rho_1\omega_k + \rho_2\dot{\omega}_r - k_f sat(s_1)) \quad (16)$$

3) Linear Velocity Control

Now, to design the control of linear velocity, the sliding mode control is applied.

When the orientation error tends to zero, the error model (7) becomes as follows:

$$\dot{x}_e = \omega_r y_e - v + v_r + \tilde{v} \quad (17)$$

$$\dot{y}_e = -\omega_r y_e \quad (18)$$

The second sliding surface is selected as:

$$s_2 = x_e - y_e \quad (19)$$

Using a sliding mode control which is given by:

$$\dot{s}_2 = -k_2\frac{s_2}{|s_2| + \delta_1} \quad (20)$$

By combination of the equation (13) and (14), the obtained result is:

$$\dot{s}_2 = \dot{x}_e - \dot{y}_e = \omega_r y_e + \omega_r x_e + v_r - v_c \quad (21)$$

By introducing (17) and (18), the control law can be obtained as:

$$\dot{s}_2 = \dot{x}_e - \dot{y}_e = v_r + \omega_r x_e + \omega_r y_e - v = -k_2\frac{s_2}{|s_2| + \delta_1} \quad (22)$$

$$v_k = v_r + \omega_r x_e + \omega_r y_e + k_2\frac{s_2}{|s_2| + \delta} \quad (23)$$

The selected switching surfaces are given as:

$$s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} \rho_1 e_1 + \rho_2\dot{e}_1 \\ x_e - y_e \end{bmatrix} \quad (24)$$

The obtained control law is:

$$\begin{bmatrix} v_k \\ \dot{\omega}_k \end{bmatrix} = \begin{bmatrix} v_r + \omega_r x_e + \omega_r y_e + k_2\frac{s_2}{|s_2| + \delta} \\ \frac{1}{\rho_2}(\rho_1\omega_r - \rho_1\omega_k + \rho_2\dot{\omega}_r - k_f sat(s_1)) \end{bmatrix} \quad (25)$$

Proof 1: to guarantee the stability of the system, the Lyapunov candidate is selected as:

$$v = \frac{1}{2}s_1^2 \quad (26)$$

The derivative of this equation is given as:

$$\dot{v} = s_1\dot{s}_1 = -s_1(k_f sat(s_1)) = -s_1 k_f sat(s_1) \quad (27)$$

k_f is positive and $s_1 sat(s_1) \geq 0$

Then,

$$\dot{v} \leq 0 \quad (28)$$

3.2. Dynamic Control Using Terminal Function

In this section, it is interesting to design the robot control torque in order to converge asymptotically the velocities error to zero.

Considering the dynamic model (9) and taking into account that the gravitational, centripetal, Coriolis, friction matrices and unknown disturbances are equal zero.

The dynamic model (9) becomes as follows:

$$M(q)\dot{V} = \beta(q)\tau + \tilde{D}(t) \quad (29)$$

Hence, the dynamic control is based on terminal function; therefore the design of the control law consists, firstly, in the choice of the sliding surface which is the error between the velocities of the robot:

$$E_v = [e_v \quad e_\omega]^T = \begin{bmatrix} v_k - v \\ \omega_k - \omega \end{bmatrix} \quad (30)$$

The derivative is given as:

$$\dot{E}_v = \begin{bmatrix} \dot{v}_k - \dot{v} \\ \dot{\omega}_k - \dot{\omega} \end{bmatrix} \quad (31)$$

The sliding surfaces are choosing as:

$$S = \begin{bmatrix} s_3 \\ s_4 \end{bmatrix} = \begin{bmatrix} v_k - v \\ \omega_k - \omega \end{bmatrix} \quad (32)$$

The derivative of the sliding surfaces is given as:

$$\dot{S} = \begin{bmatrix} \dot{s}_3 \\ \dot{s}_4 \end{bmatrix} = \begin{bmatrix} \dot{v}_k - \dot{v} \\ \dot{\omega}_k - \dot{\omega} \end{bmatrix} \quad (33)$$

Secondly, by using the fast terminal function (FTF), the form of the proposed sliding surface [23] is:

$$\dot{s} + \lambda_1 s^{\eta_1} + \lambda_2 s^{\eta_2} = 0 \quad (34)$$

Where, $0 \prec \eta_1 \prec 1,\ \eta_2 \succ 1,\ \eta_1,\ \eta_2 \in \Re$.

The above equation can be written as:

$$\dot{s} = -\lambda_1 s^{\eta_1} - \lambda_2 s^{\eta_2} \tag{35}$$

The time derivative of the first sliding surface is:

$$\dot{s}_3 = -\lambda_1 s_3^{\eta_1} - \lambda_2 s_3^{\eta_2} \tag{36}$$

Using the sliding mode:

$$\dot{s}_4 = -k_3 \frac{s_4}{|s_4| + \sigma} \tag{37}$$

The control law is obtained as:

$$\tau_1 = \frac{R_a}{2}(I\dot{\omega}_k + Ik_3 \frac{s_4}{|s_4|+\sigma} + m\dot{v}_k + m\lambda_1 s_3^{\eta_1} + m\lambda_2 s_3^{\eta_2}) \tag{38}$$

$$\tau_2 = \frac{R_a}{2}(-I\dot{\omega}_k - Ik_3 \frac{s_4}{|s_4|+\sigma} + m\dot{v}_k + m\lambda_1 s_3^{\eta_1} + m\lambda_2 s_3^{\eta_2}) \tag{39}$$

This control law can be written as follows:

$$\tau = \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} = \frac{R_a}{2} A \begin{pmatrix} \dot{v}_k \\ \dot{\omega}_k \end{pmatrix} + B \begin{pmatrix} \lambda_1 s_3^{\eta_1} + \lambda_2 s_3^{\eta_2} \\ k_3 \frac{s_4}{|s_4|+\sigma} \end{pmatrix} \tag{40}$$

Where:

$$A = \begin{pmatrix} I & m \\ m & -I \end{pmatrix},\ B = \begin{pmatrix} m & I \\ m & -I \end{pmatrix}$$

Proof 2: To ensure the stability of the system, the Lyapunov function is selected as:

$$V_2 = \frac{1}{2} S^T S \tag{41}$$

The time derivative of the Lyapunov function is:

$$\dot{V}_2 = s_3\dot{s}_3 + s_4\dot{s}_4 \tag{42}$$

$$\dot{V}_2 = S^T\dot{S} = -\lambda_1 s_3^{\eta_1+1} - \lambda_2 s_3^{\eta_2+1} - k_3 \frac{s_4^2}{|s_4|+\sigma} \le 0 \tag{43}$$

So, the system is asymptotically stable.

The selection of λ_1, λ_2 are done by genetic algorithm, in order to achieve optimal values and accelerate the nonlinear equation (34) to converge to the origin.

1) Parameters Selection Using Genetic Algorithm

A genetic algorithm (GA) is a robust search method used to find approximate solutions in research problem optimization [29].

The diagram of control system is given in Fig. 2.

The structure of genetic algorithm (GA) is given as:

1. Produce casual population of chromosomes that is given an appropriate solution.
2. Reform the fitness of any chromosome of population.
3. Produce a novel population by repeating the steps until the new population is complete.
4. Choosing two parents of chromosomes from a population depending to their fitness.
5. Crossover the parents to a novel offspring and if the condition is not satisfied, the offspring is the same of the parents.
6. Mutate the novel offspring at each position.
7. Make the novel offspring in the new population.

Finally, use the new parent populations, and if the final condition is verified, stop and return to the perfect solution of population.

The precedent operation is repeated till the condition is verified [30].

A flow chart of the general scheme of the implementation of the technique is shown in Fig. 3.

In this work, the interested parameters to optimize are (λ_1, λ_2). So that the controlled system can achieve a good overall performance in the slide mode control design. It is desirable to have the fast reaching velocity into the switching hyper plane during the reaching phase and the corresponding state slides to the origin.

By using GA, firstly we selected a fitness function with two variables (λ_1, λ_2) to achieve optimal values.

$$f_n = f_n(\lambda_1, \lambda_2) \tag{44}$$

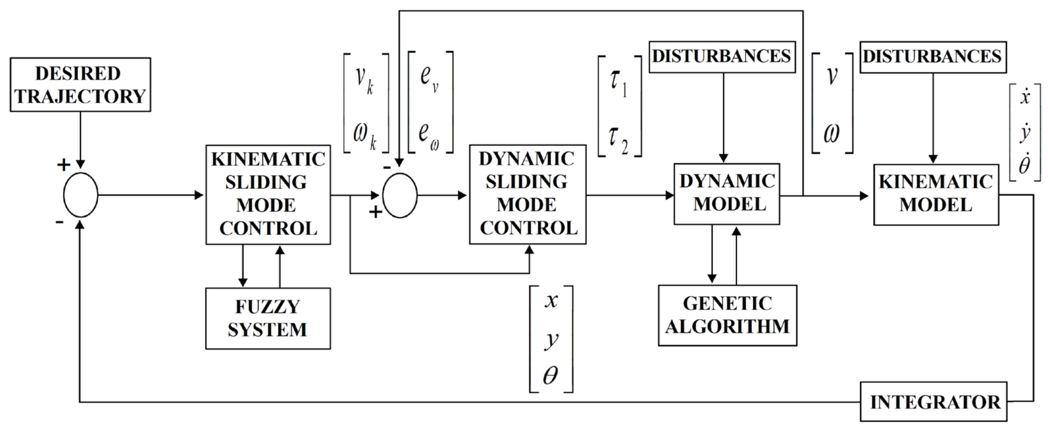

Fig. 2. Structure of the control system

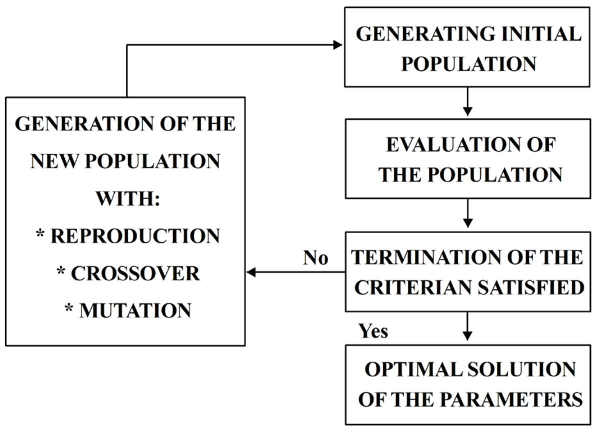

Fig. 3. Flow chart of the genetic algorithm

When the fitness function is defined, the GA prospection search will depend on the requirement of this function. The choice of the defined fitness function is an important step, which permit to the system to attain the desired performance.

The gain parameters (λ_1, λ_2) of dynamic controller will be optimally chosen in order to tend the function f_n to zero.

The fitness function that will be used is:

$$f_n(\lambda_1,\lambda_2)=\dot{s}_3+\lambda_1 s_3^{\eta_1}+\lambda_2 s_3^{\eta_2} \tag{45}$$

Choosing two intervals of the parameters $\lambda_1 = [\lambda_{11}, \lambda_{12}]$ and $\lambda_2 = [\lambda_{21}, \lambda_{22}]$, we obtain the optimal values (λ_{1opt}, λ_{2opt}), that minimize the fitness function and tend rapidly f_n (λ_1, λ_2) = 0.

By selecting optimal parameters λ_{1opt} and λ_{2opt}, the design control law τ is given as follows:

$$\tau=\begin{pmatrix}\tau_1\\ \tau_2\end{pmatrix}=\frac{R_a}{2}A\begin{pmatrix}\dot{v}_k\\ \dot{\omega}_k\end{pmatrix}+B\begin{pmatrix}\lambda_{1opt}s_3^{\eta_1}+\lambda_{2opt}s_3^{\eta_2}\\ k_3\dfrac{s_4}{|s_4|+\sigma}\end{pmatrix} \tag{46}$$

Proof 3: To verify the stability of the system, new parameters are chosen, therefore the derivative of Lyapunov function is given as:

$$\dot{V}_2=S^T\dot{S}=-\lambda_{1opt}s_3^{\eta_1+1}-\lambda_{2opt}s_3^{\eta_2+1}-$$
$$-k_3\frac{s^2{}_4}{|s_4|+\sigma}\le 0 \tag{47}$$

4. Results and Discussion

The software MATLAB/SIMULINK is selected in order to simulate the proposed control, and illustrate the behavior motion of the mobile robot. In this section, we evaluate through computer simulation, the ability of the proposed controller to stabilize the mobile robot trajectories. Different trajectories as sinusoidal, circular and specific are taken in consideration. In the simulation, the desired angular and linear velocities are chose as $v_r = 2$, $\omega_r = 1$, and the parameters of the kinematic controller are taken manually:

$k_2 = 25$, $\rho_1 = 20$, $\rho_2 = 0.1$, $\rho_3 = 0.9$

The parameters of the mobile robot are chosen as: $m = 4$ kg; $I = 3$ kg/m^2; Ra = 0.03 m; $L = 0.15$ m;
The kinematic disturbance is implemented in time $3 < t < 4$ seconds into the velocity of the mobile robot which is given as follows:

$$\tilde{\omega}=1.5\sin(t-\pi)u(t)$$

$$\tilde{v}=1.5\sin(t-\pi)u(t)$$

Where:

$$u(t)=\begin{cases}1 & for\ 3\prec t\prec 4\\ 0 & elsewhere\end{cases}$$

The parameters of dynamic controller are given as:

$k_3=25,\ \sigma=0.95,\ \eta_1=0.9,\ \eta_2=3.5,$

$\lambda_{1opt}=30,\ \lambda_{2opt}=30.$

The dynamic disturbances are inserted in time $7 < t < 8$ are given as:

$$\tilde{D}(t)=\left[2\sin(t)p(t)\quad 2\sin(t)p(t)\right]$$

Where:

$$p(t)=\begin{cases}1 & \text{for } 7\prec t\prec 8\\ 0 & elsewhere\end{cases}$$

The initial position and orientation error is: $(2\,\text{m}, 3\,\text{m}, \frac{\pi}{3}\,\text{rad})$

The membership of the inputs and output are shown in the Fig. 4, Fig. 5 and Fig. 6.

By using the kinematic and dynamic controllers of the equations (25) and (46), the circular trajectory tracking is shown in Fig. 7.

Figure 9 shows the tracking errors and the inputs control v and ω is indicated in Fig. 8.

Figure 11 indicates the torques control and Fig. 12 shows the velocity error.

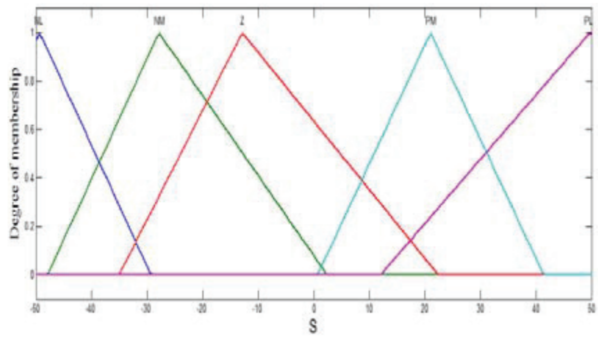

Fig. 4. Membership function of S_1

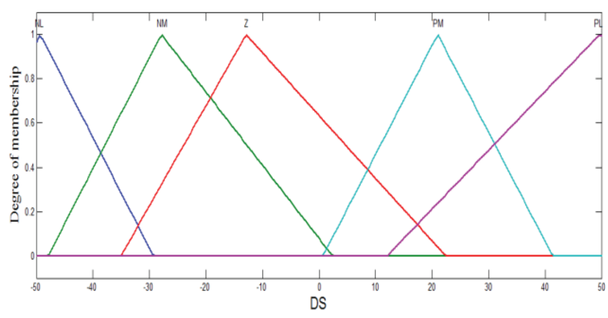

Fig. 5. Membership function of $\dot{S}_1$

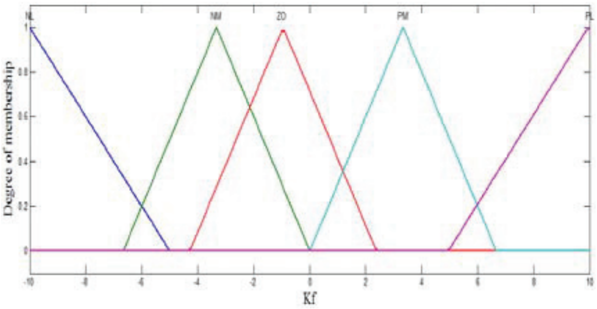

Fig. 6. Membership function of kf

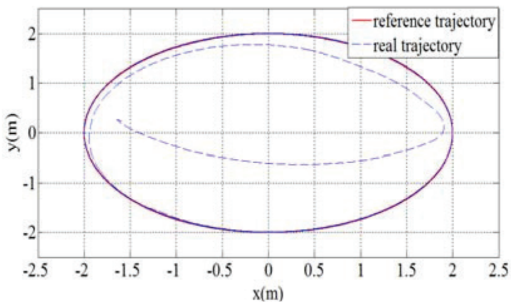

Fig. 7. Circular trajectory tracking

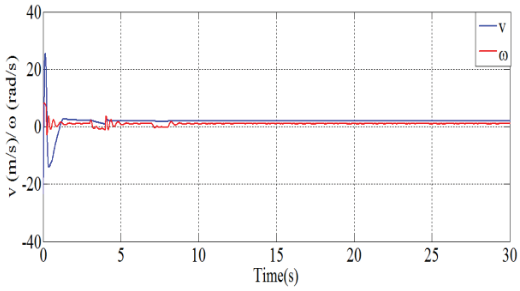

Fig. 8. The control v and ω

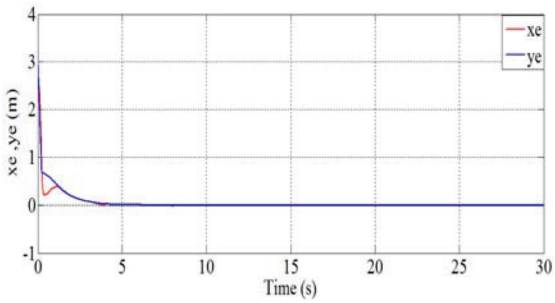

Fig. 9. Tracking errors

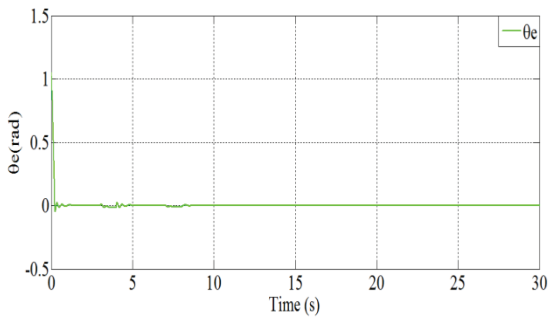

Fig. 10. Error orientation

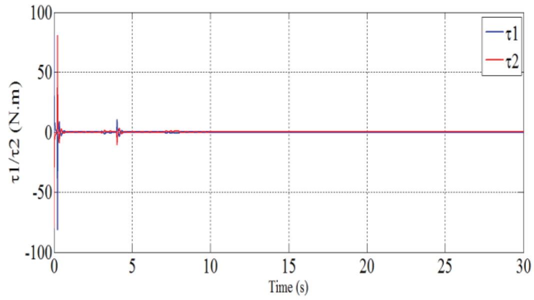

Fig. 11. Torques control

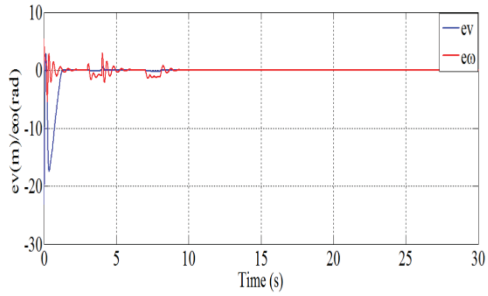

Fig. 12. Velocity error

With an initial error: $(1\,\text{m}, 1\,\text{m}, \frac{\pi}{6}\,\text{rad})$, Fig. 13 shows the sinusoidal trajectory tracking:

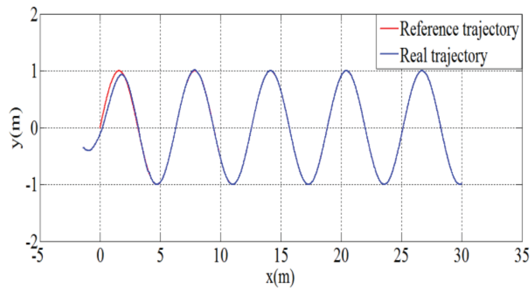

Fig. 13. Sinusoidal trajectory tracking

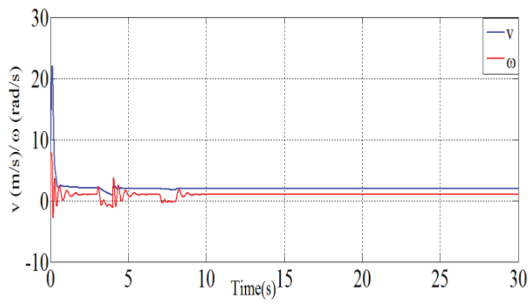

Fig. 14. The control v and ω

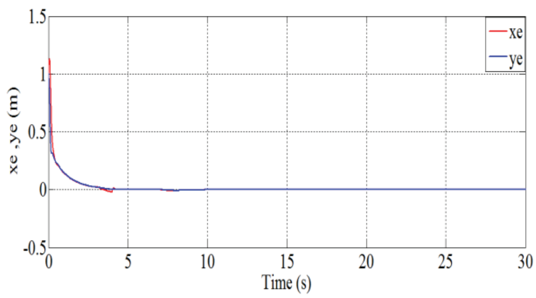

Fig. 15. Position errors

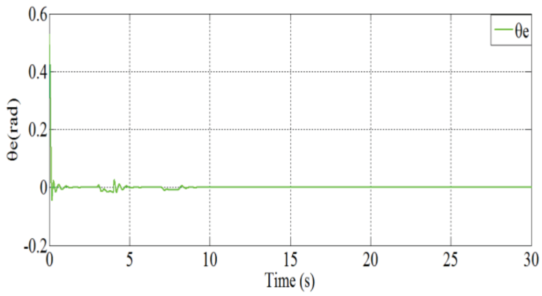

Fig. 16. Orientation error

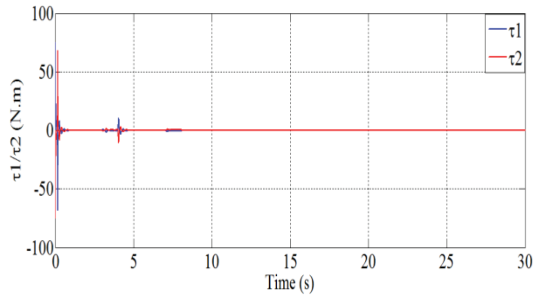

Fig. 17. Torques control

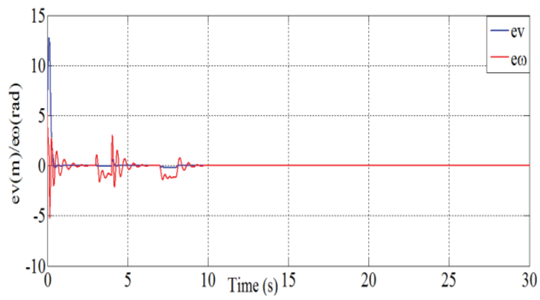

Fig. 18. Velocity error

With an initial error: $\left(1\,\mathrm{m}, 1\,\mathrm{m}, \frac{\pi}{6}\,\mathrm{rad}\right)$, Fig. 19 shows the specific trajectory tracking:

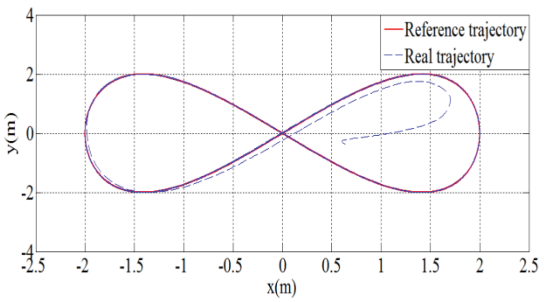

Fig. 19. Specific trajectory tracking

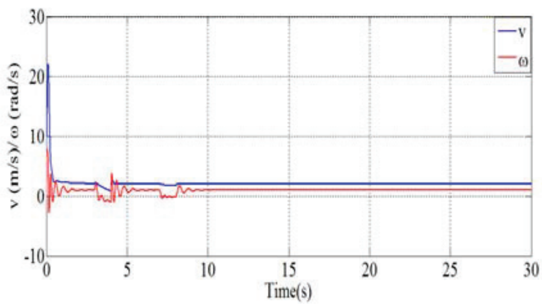

Fig. 20. The control v and ω

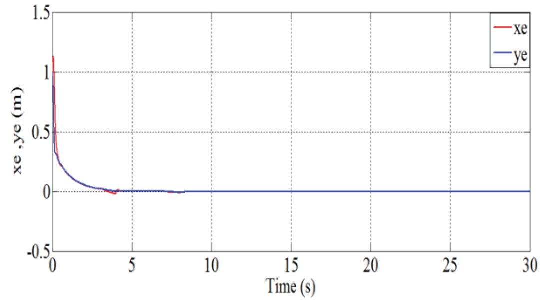

Fig. 21. Position error

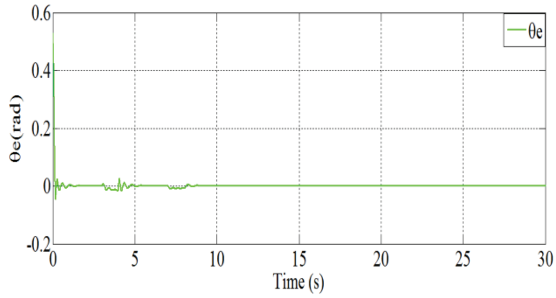

Fig. 22. Orientation error

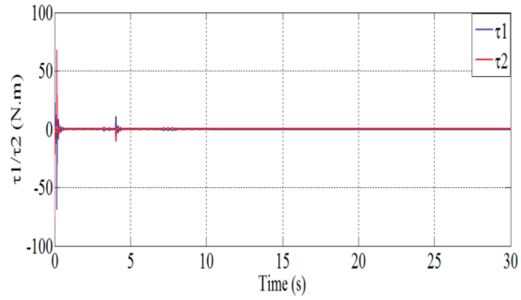

Fig. 23. Torques error

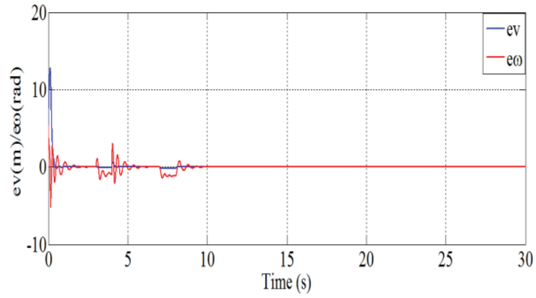

Fig. 24. Velocity error

The simulation results show the effectiveness of the proposed control laws for the dynamic and kinematic model of the three trajectories (circular, sinusoidal, specific).

Hence, in the Fig. 7 the mobile robot can achieve the circular trajectory rapidly in short time among $t = 4$ s after inserting the kinematic disturbances and in the time $t = 9$ s after inserting the dynamic disturbances, therefore the asymptotic stability of the robot is assured and the tracking errors can converge to zero.

Moreover, in the Fig. 13 and Fig. 19 the mobile robot can attain the sinusoidal and specific trajectory in the time among $t = 4$ s after implementing the kinematics disturbances and in the time $t = 10$ s after inserting the dynamic disturbances, therefore the tracking errors and velocity errors of the robot converge asymptotically to zero.

The general control law can assure the convergence of the tracking errors to zero and guarantee the asymptotic stability of the system regarding to some kind of perturbation due to the robot wheeled slipping, however the robot can follow the reference trajectory rapidly.

5. Conclusion

In this work, a new control law is proposed for trajectory tracking of nonholonomic mobile robots. The control law is divided in two parts. Firstly, the control law for the kinematic model is proposed by using PD sliding surface and fuzzy system in order to avoid the disturbances inserted in the system. Therefore the control can bring the error state of the robot to zero rapidly in short time. However, the stability of system is guaranteed and the system is asymptotically stable. Secondly the control law for the dynamic model is proposed based on classical sliding mode and fast terminal function (FTF). This control law converge the velocity error to zero and the asymptotic stability is proved.

The general control law has the ability to maintain the robot in the reference trajectory in the presence of the disturbances, which are presented in both models, dynamic and kinematic, respectively. The simulation works show the robustness of the proposed control law regarding to the different desired trajectory using for the robot, thus the convergent time from the initial state to zero is very short.

AUTHORS

Walid Benaziza*, Noureddine Slimane, Ali Mallem – Advanced Electronic laboratory, University of Batna 2, Batna, Algeria. E-mails:
w.benaziza@univ-batna2.dz,
Slimane_doudi@yahoo.fr,
Ali_mallem@hotmail.fr.

* Corresponding author

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