Optimization of Higher-Order Sliding Mode Control Parameter using Particle Swarm Optimization for Lateral Dynamics of Autonomous Vehicles

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Abstract— **In this paper, we develop a strategy for lateral control of an autonomous vehicle using a higher-order sliding mode control by the super-twisting algorithm. We minimize the lateral displacement of the autonomous vehicle to a reference trajectory. And more particularly we used a Particle Swarm Optimization (PSO) algorithm to optimize the Control parameters of the higher-order Sliding Mode. In the simulation, We have followed two scenarios, the first is to optimize the sliding surface parameter and the second scenario based on the optimization of the control parameters. In this system the command input is the steering angle and the output is the lateral error. The simulation show that the control results by higher-order sliding mode control with parameters optimization PSO are better than those of the control by sliding mode control random.**

Keywords— Lateral Dynamics; Autonomous Vehicles; SMC; PSO.

I. INTRODUCTION

The scientific community develops an intelligent vehicle capable of overcoming problems caused by driver, infrastructure or vehicle. Many actors (car manufacturers,…) are working on autonomous car projects to overcome the major vehicle disadvantage (accidents).

The Defense Advanced Research Projects Agency (DARPA) of the U.S. organized three competitions (2004, 2005 and 2007) [1], which aroused media interest and public curiosity has stimulated research for the development of autonomous vehicles. This is an area of growing research.

Driving autonomous at high speed is the major challenge today.

Autonomous vehicle driving consists in three stages:

- The perception of the environment. It consists of detecting obstacles, the road and other vehicles.
- The trajectory generation. It consists in generating and choosing one trajectory in the navigable space.
- Vehicle control. It consists of controlling the vehicle by actuators such as the accelerator, the brake and the steering wheel to follow the reference trajectory.

This document studies vehicle control, And more precisely, the lateral control of the autonomous vehicle. The lateral control of a vehicle allows the autonomous vehicle to be steered automatically to follow the reference trajectory. The controller must be robust to disturbances caused by wind, the coefficient of friction of the road, and capable of handling variations in parameters and the uncertainties encountered in automotive applications.

During these last few years, Considerable researches have been conducted to provide lateral guidance of autonomous vehicles. In [2] the lateral dynamics of vehicles has been studied. Several control strategies have been developed in literature: In [3], nested PID controller is proposed. In [4], the neural network PID control is used. In [5], controller based on state feedback control is developed. In [6], [7], [8], and [25] the H_∞ control is used. In [9], controller based on adaptive control is presented. While the paper [10] has developed a lateral controller based on fuzzy control. The techniques of artificial intelligence used in [11]. H_∞ fault-tolerant control problem for active suspension systems with actuator failure has been used in [23,24]. A controller synthesis based on antiwindup for steer-bywire system performances in vehicle has been investigated in [26].

Sliding mode control (SMC) method has been used for controlling the maximum power point tracking process in photovoltaic pumping systems [12]. In [13-14], the fuzzy sliding mode control has been used for three tank system. The higher order SMC has been applied to vehicle dynamic in [15]. The strategy of lateral control by sliding mode makes it possible to provide small displacement errors when the speed increases. In addition, it provides better results than linear controllers [16]. Also, it is robust to uncertainties (variations in model parameters) and to disturbances existing in automotive systems. Lateral control by sliding mode makes it possible to produce control laws of low complexity and simpler compared to other robust control methods [17]. And their main drawback is chattering. To reduce this chattering phenomenon, the higher order sliding mode is used.

A control method by the integration of PSO and SMC is proposed in [27], PSO is used to optimize the forces acting on the force sensors which are attached to the vehicle body.

A controller based on the higher order sliding mode and more precisely the super- twisting algorithm used in this article, to provide lateral control at high speed of an autonomous vehicle. SMC parameters are optimized using Particle Swarm Optimization in order to both track a reference trajectory and maximizing the system accuracy and speed. The simulations validate the robustness, accuracy and speed of the proposed method using MATLAB.

This work is a continuation of the research on the lateral control of the autonomous vehicle carried out by Mr. G. Tagne from the article "Higher-Order Sliding Mode Control for Lateral Dynamics of Autonomous Vehicles, with Experimental Validation" [15], in our work we added an optimization algorithm to optimize the controller parameters instead of choosing them randomly, and from the simulation results obtained it appears the efficiency and improvement of the results.

This paper is organized as follows. Sections II presents the dynamic models of the vehicle that we used. In Section III, we develop our control strategy by optimizing their parameters. Section IV presents the results and the evaluation of robustness. Section V presents the conclusions, remarks and future work directions.

II. DYNAMIC MODELS OF VEHICLE

The automobile model used in this work is the bicycle model.

The dynamic bicycle model [5] is used to represent the lateral behavior of the vehicle, See Fig. 1.

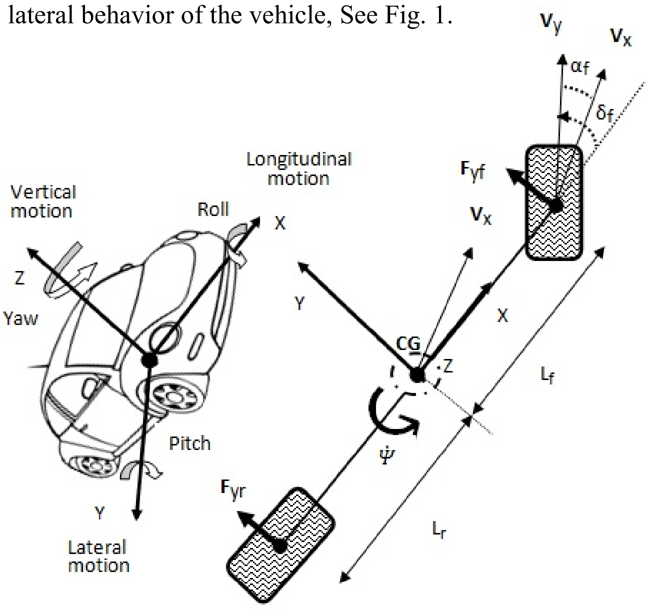

Fig. 1. Vehicle body motions and *Bicycle model* vehicle

Assume that the vehicle is symmetrical and that the sideslip angles on the same axle are equals. The pitch and roll dynamics are neglected and the angles are assumed to be small (direction, yaw, sideslip), the longitudinal speed Vx is considered to be a variable parameter.

Using a linear tire force model, the bicycle model becomes a variable linear parameter model (LPV) composed of lateral dynamics and yaw represented as follows:

$$\begin{cases} \ddot{y} = -\frac{(C_f+C_r)}{mV_x}\dot{y} - \left(\frac{L_fC_f-L_rC_r}{mV_x} + V_x\right)\dot{\psi} + \frac{C_f}{m}\delta \\ \ddot{\psi} = -\frac{L_fC_f-L_rC_r}{I_zV_x}\dot{y} - \frac{{L_f}^2C_f+{L_r}^2C_r}{I_zV_x}\dot{\psi} + \frac{L_fC_f}{I_z}\delta \end{cases} \quad (1)$$

with y and ψ represent respectively the lateral position and the yaw angle of the vehicle. The nomenclature and the parameters of the vehicle. Are presented in table I.

TABLE I: VEHICLE NOMENCLATURE AND PARAMETERS (BICYCLE MODEL)

Parameter	Unit	Meaning	Value
$\dot{y}$	[m/s]	Lateral velocity	-
$\dot{\psi}$	[rad/s]	Yaw rate	-
δ	[rad]	Steering wheel angle	-
V_x	[m/s]	Longitudinal velocity	-
m	[kg]	Mass	1719
L_f	[m]	Front axle-CG distance	1.195
L_r	[m]	Rear axle-CG distance	1.513
C_f	[N/rad]	Comering stiffness of the front tire	170550
C_r	[N/rad]	Comering stiffness of the rear tire	137844
I_z	[kgm^2]	Yaw moment of inertia	3300

III. CONTROL STRATEGY

The sliding mode technique consists of bringing the state trajectory of a system towards the sliding surface and forcing it to reach the equilibrium point while remaining on this surface.

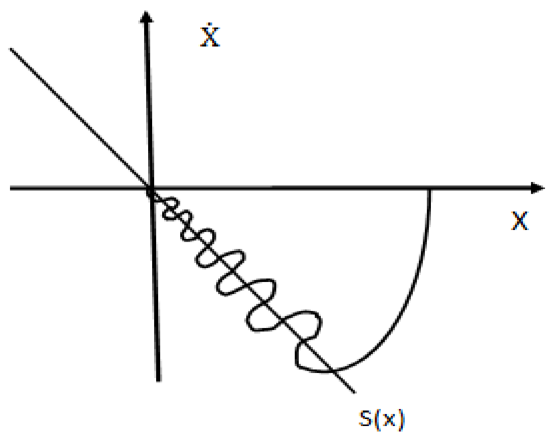

Fig. 2. SMC principle

The major drawback of SMC is the ‘chattering’, to mitigate this phenomenon three approaches were proposed [18]:

- The use of smooth functions instead of the discontinuous function sign,
- The use of an approach based on observers,
- The use of higher order sliding mode.

A. Super-twisting algorithm

This algorithm only applies to systems of relative degree 1. Its interest lies in the reduction of chattering, due to the continuity of the control signal [19], [20].

The system (1) can be rewritten as follows,

$$\dot{x} = f(t,x) + g(t,x)u(t) \tag{2}$$

where x =[$\dot{y}$,$\dot{\Psi}$]' the state vector, u = δ is the control input, $\boldsymbol{f} = [-\frac{(C_f+C_r)}{mV_x}\dot{\boldsymbol{y}} - \left(\frac{L_fC_f-L_rC_r}{mV_x} + \boldsymbol{V_x}\right)\dot{\psi}, -\frac{L_fC_f-L_rC_r}{I_zV_x}\dot{\boldsymbol{y}} - \frac{L_f{}^2C_f+L_r{}^2C_r}{I_zV_x}\dot{\psi}]^T$ and g = $[\frac{C_f}{m}, \frac{L_fC_f}{I_z}]^T$ are continuous functions. We define a sliding variable s of relative degree 1, whose derivative can be expressed as follows:

$$\dot{s}(t,x) = \emptyset(t,x) + \varphi(t,x)u(t) \tag{3}$$

The aim of the controller is to ensure convergence to the sliding surface defined by s = 0. To this aim, we only require the measurement of s in real time.

The Super-twisting control law is made up of two parts. The first u_1 is a continuous and function of the sliding variable, while the second u_2 is defined by its derivative with respect to time. The control law will be given by:

$$u(t) = -u_1 - u_2 \tag{4}$$

- $u_1 = \alpha|s|^{\tau}\,\mathrm{sign}(s).\ \tau \in]0, 0.5]$
- $\dot{u}_2 = \beta sign(s)$

B. Application to lateral control of autonomous vehicles

The objective of the control law is to cancel the lateral displacement error. The control input is the steering angle and the lateral displacement is the output.
Choosing the sliding variable s as follows:

$$s = \dot{e} + \lambda e \tag{5}$$

We obtain:

$$\dot{s} = \ddot{e} + \lambda \dot{e}. \tag{6}$$

The dynamic equation of the lateral error at the center of gravity of the vehicle, compared to a reference trajectory, is given by:

$$\ddot{e} = a_y - a_{y_{ref}} \tag{7}$$

where a_y and $a_{y_{ref}}$ are the lateral acceleration of the vehicle, and the desired one on the reference trajectory respectively. The latter is given by $a_{y_{ref}} = {V_x}^2/_R$ where R is the radius of curvature of the road. Since $a_y = \ddot{y} + V_x\dot{\psi}$ [2], we have:

$$\ddot{e} = \ddot{y} + V_x\dot{\psi} - {V_x}^2/_R \tag{8}$$

Substituting (8) in (6), we obtain:

$$\dot{s} = -\frac{(C_f+C_r)}{mV_x}\dot{y} - \frac{L_fC_f-L_rC_r}{mV_x}\dot{\psi} - \frac{V_x{}^2}{R} + \frac{C_f}{m}\delta + \lambda \dot{e} \tag{9}$$

The variable s has a relative degree r =1. By identification with (3), we have:

$$\dot{s}(t,x) = \emptyset(t,x) + \varphi(t,x)u(t)$$

with:

$$\begin{cases} \emptyset(t,x) = -\frac{(C_f+C_r)}{mV_x}\dot{y} - \frac{L_fC_f-L_rC_r}{mV_x}\dot{\psi} - \frac{V_x{}^2}{R} + \lambda \dot{e} \\ \varphi(t,x) = \frac{C_f}{m} \end{cases} \tag{10}$$

by applying the super--twisting theorem, the command can become as follows:

$$\delta_{ST} = -u_1 - u_2 \tag{11}$$

- $u_1 = \alpha|s|^{1/2}\,\mathrm{sign}(s)$. From (4) we can choose $\tau = 1/2$.
- $\dot{u}_2 = \beta sign(s)$

We add an equivalent command δ_{eq} obtained by solving the equation $\dot{s} = 0$, to avoid important peaks in transient phases. This term has the role of a feedforward that approaches the system to the sliding surface, and is given by:

$$\delta_{eq} = -\frac{m}{C_f}\,\emptyset(t,x) \tag{12}$$

Therefore, the system control input (the steering angle) is defined as follows:

$$\delta = \delta_{ST} + \delta_{eq} \tag{13}$$

C. Particle Swarm optimization (PSO)

The algorithm was introduced by Kennedy and Elberhart in 1995 [21]. The method consists in using a simplified social model linked to the swarm theorem. PSO uses the velocity vector of each particle to update the position of each particle in the swarm.

PSO algorithm is based on particle intelligence. This algorithm initiates the first particle randomly which is made up of m swarm. The position updating is based on Eq. (14), since memory of particle, thinking of particle and its social action reflect in the determination of each new particle.

$$\begin{cases} v_i(j+1) = wv_i(j) + c_1r_1(p_i(j) - x_i(j)) + c_2r_2(p_g(j) - x_i(j)) \\ x_i(j+1) = x_i(j) + v_i(j+1) \end{cases} \tag{14}$$

where j and w are iteration number and inertia weight, respectively. $c_1$and c_2 are two random numbers within [0,1] uniformly. x_i represent the ith potential solution of problem and v_i is the flying velocity. p_i and p_g are personal best and global best.

We use PSO to minimize the objective function. PSO is used to find the sliding control parameters λ or β and α.

- Finding parameter λ of control SMC.
- Calculating the optimal parameters β and α of control SMC.

After the sliding surface design above, the problem of following the trajectory is transformed to become the problem of maintaining s in the equation (5) at 0 in the first case. The objective function can be defined as follows:

$$F_{obj} = \dot{e} + \lambda e. \tag{15}$$

according to (15) and (5): $F_{obj} = s$.

with $J_{min}(\lambda)$ = s: find λ so that the value of s is minimal, where λ the variable of objective function.

In the second case to optimize β and α we maintain $\dot{s}$ (derivative of sliding surface) in the equation (3) at 0. The objective function can be defined as follows:

$$F_{obj} = \emptyset(t,x) + \varphi(t,x)u(t). \tag{16}$$

according to (16) and (3): $F_{obj} = ds/dt$.

with $J_{min}(\alpha\ ,\beta\ ) = \dot{s}$: find α and β so that the value of $\dot{s}$ is minimal, where β and α the variables of objective function.

IV. SIMULATION RESULTS

To compare results obtained by controlling SMC and with the optimization of the parameters of SMC by PSO, we used the parameters of control law used in [15], such as λ , α , β, and the nominal parameters of the vehicle (see table I), and we optimize the parameters of SMC by PSO following two strategy:

- Optimize λ keeping all the other parameters of the same value as in SMC.
- Optimize α and β and keep the other parameters fixed as that of SMC.

A. The SMC control results by optimization of λ

The required parameters in PSO procedure is given in Table II.

Fig. 3 demonstrate a clear trend of decreasing the best fitness function value through each iteration.

Table II: PSO parameters

Description	Parameter	Value
Number of Iterations	iterations	50
Inertia Coefficient	inertia	1.4
Damping Ratio of Inertia Coefficient	betaInertia	0.5
Personal Acceleration Coefficient	correctionFactor1	1.8
Social Acceleration Coefficient	correctionFactor2	1.9
Population size	swarmSize	20
Maximum velocity	maxVelocity	7

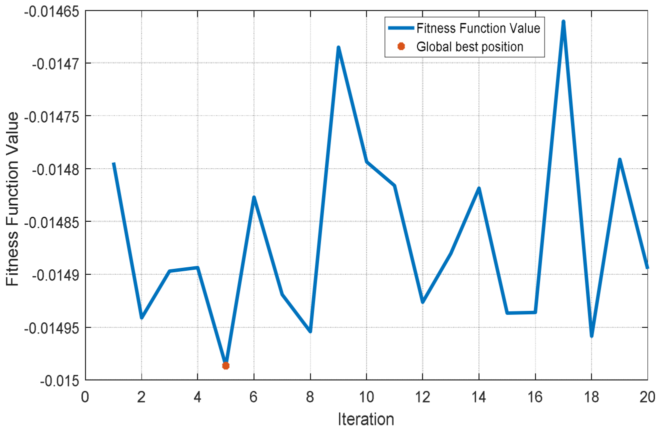

Fig. 3 Fitness Function Value of each iteration.

The results obtained from implementing PSO algorithm are given in Table III.

Table III: Value of parameter SMC by PSO algorithm

Parameter	Value	Fitness Function
λ	162.8550	-0.0154

The first test (Figures 5, 6 and 7 (a, b and c)) was carried out in order to compare the robustness of the SMC controller with the normal parameters used in [15], and with the optimization parameter λ. The lateral acceleration obtained by the optimization of the parameters of SMC with PSO is better than that obtained by the normal parameters of SMC. The longitudinal speed being almost constant (13 m/s^2).

Figure 4 shows the variations of the longitudinal speed. The lateral error, the controlled vehicle is able to follow the reference trajectory with low errors in both cases. The lateral error does not exceed 3.1 mm in first case (with normal SMC parameters) and does not exceed 0.1 mm in second case (with the optimization of the parameters SMC by PSO) in transient mode see Figure 5.

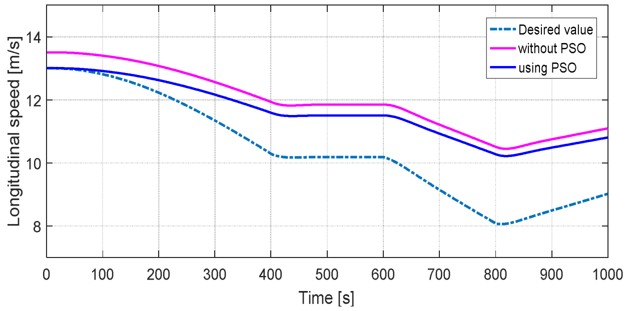

Fig. 4: Longitudinal speed

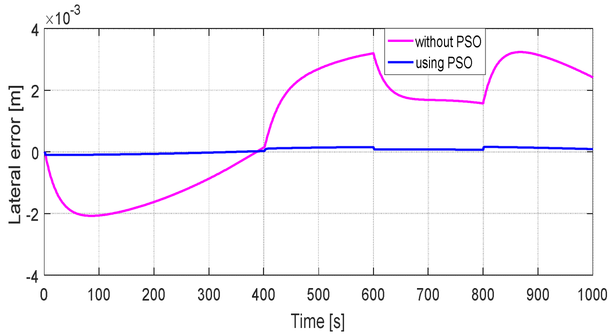

Fig. 5: Lateral error

The figure 6 shows evolution: the steering angle, the yaw rate and the lateral acceleration. From the figure we can see that the dynamic variables obtained by SMC with PSO are better than the results obtained by SMC. The variation in the steering angle obtained by SMC with PSO is less than the variation in the steering angle obtained by SMC alone. The yaw rate obtained by SMC with PSO is better than the yaw rate obtained by SMC alone.

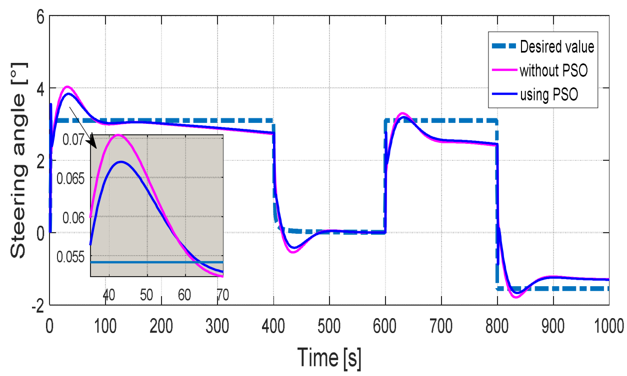

Fig. 6 a: Steering angle

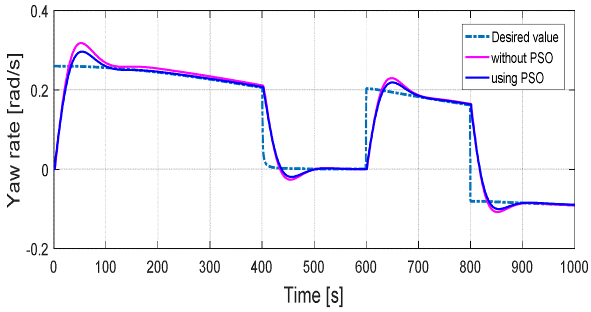

Fig. 6 b: Yaw rate

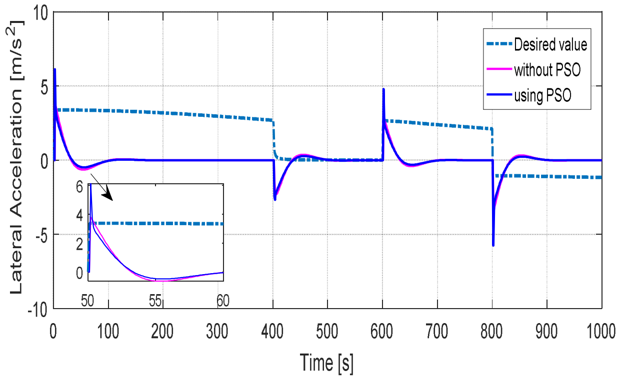

Fig. 6 c: Lateral acceleration

The SMC controller is able to follow the reference trajectory with a low error (3.1×10^{-3}) and the SMC controller with PSO is also able to follow the reference trajectory with a very low error (between -0.2×10^{-4} and 1.1×10^{-4}). This simulation shows the good performance and robustness of the controller.

B. *The SMC control results by the optimization of α and β*

The results obtained from implementing PSO algorithm are given in Table IV.

Table IV: Values of parameter's SMC by PSO algorithm

Parameters	Value	Fitness Function
α	0.6677	0.0059
β	0.9424	

The values of α and β when optimizing the parameters of SMC by PSO give good results but with oscillations.

The second test was carried out in order to compare the robustness of the SMC controller with the normal parameters used in [15], and with the parameters optimization α and β. The lateral acceleration obtained by the optimization of the parameters of SMC with PSO is better than that obtained by the normal parameters see figure 8. Figure 7 shows a longitudinal speed that is almost constant (13 m/s^2).

Figure 9 a shows the variations of the steering angle and Figure 9 b presents the lateral acceleration.

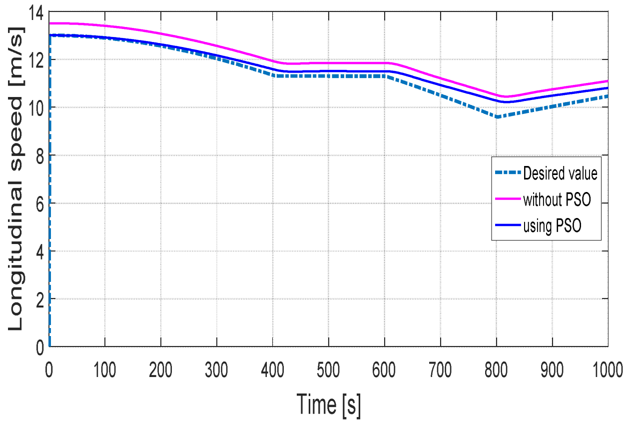

Fig. 7: Longitudinal speed

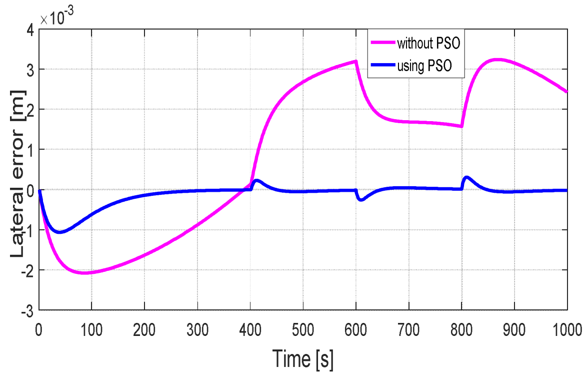

Fig. 8: Lateral error

We compare the results of the system simulation when using SMC command with normal parameters and the results when using SMC command with the optimization of their parameters by PSO. The dynamic variables obtained by SMC with PSO are better than the results obtained by SMC. The variation in the steering angle obtained by SMC with PSO is less than the variation in the steering angle obtained by SMC alone.

In the second test the chattering phenomenon appeared. To eliminate this phenomenon, I used a continuous function in the super--twisting algorithm instead of the discontinuous function used.

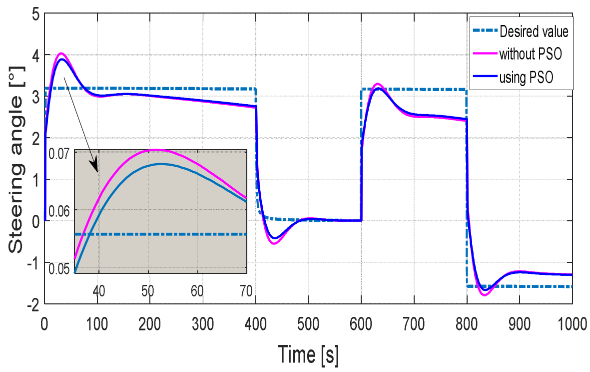

Fig. 9 a: Steering angle

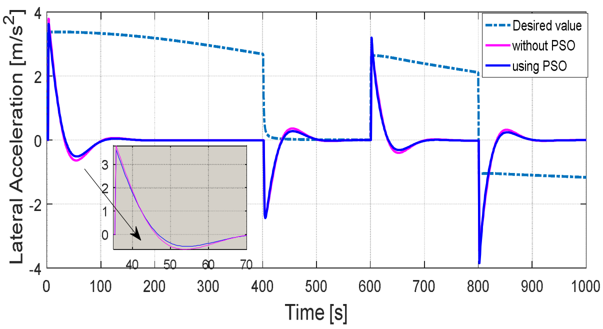

Fig. 9 b: Lateral acceleration

The SMC controller is able to follow the reference trajectory with a low error ($3.1x10^{-3}$) and the SMC controller with PSO is also able to follow the reference trajectory with a very low error (between $-0.2x10^{-4}$ and $1.1x10^{-4}$).

The first simulation is better than the second and has very low error which means good performance and robustness of the controller with new SMC parameters.

V. CONCLUSIONS

In the paper, a lateral control strategy of an autonomous vehicle has been developed. This strategy is based on the use of a higher-order sliding-mode controller the parameters are optimized according to two scenarios, in the first case, we optimize λ and in the second case we optimize α and β. The various tests carried out highlight the robustness of the control law developed since the maximum error of tracking was generally small during transient periods. Note that the comparison of the robustness of controlled SMC with PSO and controlled SMC has been done and that the robustness of controlled SMC with PSO is better than controlled SMC alone.

In future work, and in order to improve the robustness of the system, a thorough theoretical study of fuzzy logic control is carried out, a comparison of these two controllers will be studied.

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