Sliding Mode Observer Based Controller for Active Steering Control

A. S. M. Isira[1], N. X. Yan[1], M. M. Ibrahim[2], Shakir Saat[1], A. M. Khafe[1] and A. M. Darsono[1]
[1]Advanced Sensors and Embedded Control System (ASECS).
[2]Machine Learning and Signal Processing (MLSP).
Center for Telecommunication Research and Innovation(CeTRI).
Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer.
Universiti Teknikal Malaysia Melaka.
Durian Tunggal, 76100 Melaka
Malaysia.
sadhiqin@utem.edu.my

***Abstract*— The purpose of this paper is to enhance the performance of steering control of a vehicle. A nonlinear sliding mode observer based active steering controller that will overcome the disturbances such as road condition and crosswind is proposed. Condition of stability is given by using Lyapunov stability theory that relates to sliding mode characteristics. The controller proves that it is able to stabilize the steering wheel better when disturbances such as braking action and crosswind are included in the system. Lastly, simulations are given to prove the validity of the controller stability. In the simulations, comparisons are made between the outcome of the uncontrolled, Linear Quadratic Regulator (LQR), Sliding Mode Controller (SMC) and Sliding Mode Observer Based Controller (SMOC).**

***Index Terms*— Controller; Nonlinear System; Observer; Sliding Mode Control; Stability.**

I. INTRODUCTION

Nowadays, one of the common problems of road accidents is losing control of the car or vehicle at high speed. This is due to the driver’s failure to understand road conditions and situations that could lead to an accident. Therefore, there has been an increase in demands for active safety systems against car accidents in recent years.

In [1], an active safety system was developed based on the by-wire technologies to improve yaw moment control system that depends on the braking action on the left and right wheels. Other types of active steering systems have been reported such as Active Front Steering (AFS) [2] [3] [4], Active Rear Steering (ARS) [5] and Active Four Wheel Steering (W4S) [6]. Active steering is an effective way that can improve drivers comfort and handling. The vehicle handling and lateral stability can be controlled at the same time, if both the external yaw moment and active steering angle are adopted [7].

Some other types of new control methods for vehicle systems dynamics control have been reported such as electro actuated differentials method [8] [9]. Integrated control of active front steering and direct yaw moment generated by a distribution of braking forces was designed in [10]. In addition, in [11] the electronic stability program (ESP) was integrated with the active front wheel steering, active suspension and active anti roll bar. Four wheel steering was coordinated with wheel torque distribution by using an optimization approach as shown in [12]. A nonlinear optimization technique was utilized to determine the optimal force to be exerted by each tire controlled by active steering and brake pressures distribution reported in [13] [14]. [15] utilized the active front steering, where it developed a mechatronic steering system for car passengers that controlled electronically the superposition angle of the steering wheel prescribed by the driver.

Several types of research on the sliding mode controller have been published such as [16] that developed a vehicle model based on sliding mode controller in order to obtain desired vehicle performance via a two degree of freedom bicycle model. Another publication, [17] investigated the application of SMC by using the nonlinear sliding surface for yaw rate tracking of active front steering control where it identifies the cornering stiffness as the parameter. Chuan et al. [18] developed an integral sliding mode control (ISMC) approach for in-wheel-motor driven electric vehicles steered by differential drive assistance steering. Ghani et al. [19] proposed a sliding mode controller for a linearized single track model with the system under conditions of wet and icy μ split conditions.

This paper relates to active steering system which is an integrated steering support system for cars. The system is close to the steering systems on conventional cars but with additional functionality to withstand with disturbances such μ-split which is a split adhesion coefficient between wheels, and wind gusts or decreased road adhesion conditions. Therefore, influenced by [19], the main purpose of this paper is to propose a sliding mode observer based controller (SMOC) for a single track model. The design of the sliding mode observer is based on the sliding mode controller in the paper mentioned. There are two main features of this paper:

a) The controller design that is based on the sliding mode observer. An observer can be used in a system where not all values are measurable.
b) The controller’s performance is then compared to SMC and LQR to prove its effectiveness. It will be shown that this controller is very effective and comparable to SMC but better than LQR.

Lyapunov theory is used to prove the stability of the controller. Finally, simulations are given to prove the validity of the controller.

The rest of the paper is organized as follows. Section II presents the problem statement and the model of the vehicle. Next, Section III provides a first main contribution of this paper, the design of the sliding mode observer where the conditions of the observer stability are given. Then the second main result of this paper is presented in the same section where the design and the stability condition of the controller proposed. In order to validate the effectiveness of the controller proposed, Section V provides the simulation examples and finally Section VI concludes the paper.

II. PROBLEM STATEMENT

The uncertain linear time invariant system given by is considered as below

$$x(t) = Ax(t) + Bu(t) + Df(t) \tag{1}$$

and

$$y = Cx(t) \tag{2}$$

Where the state vector is $x(t) \in \mathbb{R}^n$, $y \in \mathbb{R}^p$, and the control input is $u(t) \in \mathbb{R}^m$, the uncertain function or disturbance vector is $f(t) \in \mathbb{R}^l$, which the n, m and l are the number of states, inputs and disturbances respectively. The system matrix is $A \in \mathbb{R}^{n\times n}$, the input matrix is $B \in \mathbb{R}^{n\times m}$ and the disturbance matrix is $D \in \mathbb{R}^{n\times l}$. It can be assumed that the input disturbance matrices B and D are in full rank without loss of generality. $\phi: \mathbb{R}^n \to \mathbb{R}^n$ is a Lipschitz nonlinear function with the Lipschitz constant γ, i.e., for any two constant vectors $a, b \in \mathbb{R}^n$, we have

$$\left\|f - \hat{f}\right\| \leq \gamma \|x - \hat{x}\| \tag{3}$$

The Luenberger’s observer can be designed as follow

$$\hat{x}(t) = A\hat{x}(t) + B\hat{u}(t) + L(y - \hat{y}) + D\hat{f}(t) \tag{4}$$

with

$$\hat{y} = C\hat{x}(t) \tag{5}$$

and we will have

$$\dot{\tilde{x}}(t) = A\tilde{x}(t) + B\tilde{u}(t) + LC\tilde{x}(t) + D[f(t) - \hat{f}(t)] \tag{6}$$

where $\tilde{x}(t) = x(t) - \hat{x}(t)$ is the error of the states.

Table 1
The active steering car system (BMW 735i) parameter values [20].

Mass of the car body, m	1864 kg
Moment of inertia for the car body, J	3654$kg \cdot m^2$
Velocity of the car, v	70 m/s
Cornering stiffness of the rear axle, c_R	213800 N/rad
Cornering stiffness of the front axle, c_F	101600 N/rad
Wheelbase of the rear axle, l_R	1.32 m
Wheelbase of the front axle, l_F	1.51 m

Based on the work of Ghani et.al. [19] with the parameter values are shown in Table I, the linearized version of the equation with disturbance is shown as

$$\begin{bmatrix}\dot{\beta}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}\beta\\ r\end{bmatrix} + \begin{bmatrix}b_{11} & b_{12}\\ b_{21} & b_{22}\end{bmatrix}\begin{bmatrix}\delta_F\\ \delta_R\end{bmatrix} + \begin{bmatrix}0\\ b_z\end{bmatrix} M_{zD} \tag{7}$$

where

$r =$ Yaw rate,
$\beta =$ Side slip angle,
$\delta_F, \delta_R =$ Front and rear steering angles,
$M_{zD} =$ Disturbance,
$a_{11} = -\mu(c_R + c_F)/mv,$
$a_{12} = -1 + \mu(c_R l_R + c_F l_F)/mv^2,$
$a_{21} = \mu(c_R l_R + c_F l_F)/J,$
$a_{22} = -\mu(c_R l_R^2 + c_F l_F^2)/Jv,$
$b_{11} = \mu c_F/mv,$
$b_{12} = \mu c_R/mv,$
$b_{21} = \mu c_F l_F/J,$
$b_{22} = \mu c_R l_R/J,$
$b_z = 1/J$

The following assumptions are taken as standard from this study:

A, B matrix pair is controllable.
The input distribution matrix B has full rank.
System with uncertainties satisfy the matching condition, such as $rank[B|f(t)] = rank[B]$

Lemma 1: [19] The hitting condition of the sliding surface

$$\sigma(t) = Cx(t) \tag{8}$$

is satisfied if

$$\rho > 0 \tag{9}$$

III. SLIDING MODE OBSERVER

This section will present the main result of this paper which is explained in the next theorem.

Theorem 1: If there exists a solution of P for observer gain $L = P^{-1}C^T$ for $C^T P^{-1} C^T C - \gamma C^T CD$ to be Hurwitz, the observer is stable.

Proof 1: Based on work of [19], the sliding surface for the observer is defined as

$$\hat{\sigma}(t) = C\hat{x}(t) \tag{10}$$

From (8), and (10), we have

$$\dot{\tilde{\sigma}}(t) = C\dot{\tilde{x}}(t) \tag{11}$$

where $\tilde{\sigma} = \sigma - \hat{\sigma}$ and is equal to

$$\dot{\tilde{\sigma}}(t) = CA\tilde{x} + CB\tilde{u} + LC^T C\tilde{x} + D[f(t) - \hat{f}(t)] \tag{12}$$

Let $\tilde{u} = \tilde{u}_{eq}$. For $\dot{\tilde{\sigma}}(t) = 0$ we have

$$-CB\tilde{u}_{eq}(t) = CA\tilde{x} + LC^T C\tilde{x} + D[f(t) - \hat{f}(t)] \tag{13}$$

Therefore, we have $u_{eq}(t)$ as

$$\tilde{u}_{eq}(t) = -(CB)^{-1}(CA\tilde{x} + LC^TC\tilde{x} + D[f(t) - \hat{f}(t)]) \quad (14)$$

and

$$\dot{\tilde{x}} = A\tilde{x} + B\left[-[CB^{-1}]CA\tilde{x} + LC^TC\tilde{x} + D[f(t) - \hat{f}(t)]\right] \quad (15)$$

From Ghani et.al [19], the input is defined as

$$\tilde{u} = \tilde{u}_{eq} + \tilde{u}_{nl} \quad (16)$$

which drives the trajectory of the observed signal in (4). The switching control $u_{nl}(t)$ used is in the form of

$$\tilde{u}_{nl}(t) = -(CB)^{-1}\rho\frac{\tilde{\sigma}(t)}{|\tilde{\sigma}(t)| + \delta}\tilde{x} \quad (17)$$

where the $\delta > 0$ and $\rho > 0$ which obeys *Lemma 1*. From (14), (16) and (17), we have

$$\tilde{u}(t) = -(CB)^{-1}\big(CA\tilde{x} + LC^TC\tilde{x} + D[f(t) - \hat{f}(t)]\big) - (CB)^{-1}\left(\rho\frac{\tilde{\sigma}(t)}{|\tilde{\sigma}(t)| + \delta}\tilde{x}\right) \quad (18)$$

The stability of the observer (4) can be determined by selecting the Lyapunov candidate as

$$V = \frac{1}{2}\sigma^T(t)\sigma(t) \quad (19)$$

Then we have

$$\begin{aligned}\dot{V} &= \frac{1}{2}\left(\tilde{\sigma}^T(t)\dot{\tilde{\sigma}}(t) + \dot{\tilde{\sigma}}^T(t)\tilde{\sigma}(t)\right)\\ &= \frac{1}{2}[(C\tilde{x})^T\Bigg[CA\tilde{x} + (CB)\Bigg(-(CB)^{-1}\Big[CA\tilde{x} + LC^TC + D\left(f(t) - \hat{f}(t)\right)\Big] - (CB)^{-1}\left(\rho\frac{\tilde{\sigma}(t)}{|\tilde{\sigma}(t)| + \delta}\tilde{x}\right)\Bigg)\Bigg]\\ &\quad + \Bigg[C\tilde{x} + (CB)\Bigg(-(CB)^{-1}\Big[CA\tilde{x} + LC^TC\tilde{x} + CD\left(f(t) - \hat{f}(t)\right)\Big] - (CB)^{-1}\left(\rho\frac{\tilde{\sigma}(t)}{|\tilde{\sigma}(t)| + \delta}\tilde{x}\right)\Bigg]^T C\tilde{x}\Bigg]\end{aligned} \quad (20)$$

For stability analysis the switching control u_{nl} is ignored because the value will definitely be negative due to *Lemma 1*. The nonlinear element $D\left(f(t) - \hat{f}(t)\right)$ can be solved using Lipschitz condition (3) where we have

$$\begin{aligned}\tilde{u}_{eq}(t) &\leq -(CB)^{-1}\big(A\tilde{x} + LC^TC + \gamma CD(x - \hat{x})\big)\\ &\leq -(CB)^{-1}(A\tilde{x} + LC^TC + \gamma CD\tilde{x})\end{aligned} \quad (21)$$

where $f(t)$ and $\widehat{f}(t)$ is assumed to be the functions of x and $\hat{x}$. From (20) and with observer gain $L = P^{-1}C^T$, we will arrive at

$$\dot{V}(t) \leq \tilde{x}^T(C^TP^{-1}C^TC - \gamma C^TCD)\tilde{x} \quad (22)$$

Therefore, if there exists a solution of P^{-1} with $\gamma > 0$ which guarantees that $\dot{V}(t) \leq 0$, the observer is said to be asymptotically stable. This completes the proof. □

IV. SLIDING MODE OBSERVER BASED CONTROLLER

To utilize the observer that has been designed in the previous section, such controller has been selected

$$u = -K\tilde{x}(t) \quad (23)$$

The overall dynamics of the system can be described as

$$\begin{bmatrix}\dot{x}\\ \dot{\tilde{x}}\end{bmatrix} = \begin{bmatrix}A - BK & BK\\ 0 & -2LC\end{bmatrix}\begin{bmatrix}x\\ \tilde{x}\end{bmatrix} + \begin{bmatrix}Df(t)\\ D(f(t) - \hat{f}(t))\end{bmatrix} \quad (24)$$

Theorem 2: For $\gamma > 0$, if there exists a solution of P for controller gain $K = B^TP$ for $A - BK + \gamma D$ to be Hurwitz, the controller (23) is stable.

Proof 2: From the overall dynamics (24), with Lyapunov candidate $V_2(t) = \frac{1}{2}x^Tx$ the following result is obtained

$$\begin{aligned}\dot{V} &\leq \frac{1}{2}\Big(x^T\big((A - BK + \gamma D)x + BK\tilde{x}\big)\ \big((A - BK + \gamma D)x + BK\tilde{x}\big)^T\Big)\\ &\leq \frac{1}{2}(2x^T(A - BK + \gamma D) + 2\tilde{x}^T(BK)x)\end{aligned}$$

and we have

$$\dot{V} \leq x^T(A - BK + \gamma D)x + \tilde{x}^T(BK)\tilde{x} \quad (25)$$

Hence, for $\gamma > 0$, if there exist a solution for matrix P for controller gain K, that guarantees that $A - BK + \gamma D < 0$ and $BK < 0$, with the observer (4), the system (1) is said to be asymptotically stable. This completes the proof. □

V. SIMULATION

In this section, an example will be given to show some details on the sliding mode observer based controller design. The performance of the controller will be compared with Sliding Mode Controller (SMC) and Linear Quadratic Regulator (LQR) from [19]. A single track car model for car steering has been acquired from [20] and [19]. From (7), the dynamics of the system (1) can be represented as

$$\begin{bmatrix}\dot{\beta}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}-1.2086 & -0.9929\\ 17.6245 & 1.18105\end{bmatrix}\begin{bmatrix}\beta\\ r\end{bmatrix} + \begin{bmatrix}0.38935 & 0.8193\\ 20.9929 & -38.6174\end{bmatrix}\begin{bmatrix}\delta_F\\ \delta_R\end{bmatrix} + \begin{bmatrix}0\\ 0.0002737\end{bmatrix}M_{zD} \quad (26)$$

The road disturbance $f(t)$ is defined by *Definition 1* and *Definition 2* from [19].

Definition 1: The μ-split braking torque of 3000Nm is represented by Disturbance Profile 2 shown in Figure 1. The step unit function mathematical model is shown as

$$f(t) = 3000; \quad t \geq 3000 \\ = 0; \quad otherwise \tag{27}$$

Definition 2: A crosswind by a single pulse with 100km/h forces is represented as Disturbance Profile 1 shown in Figure 2. The single pulse mathematical model is given as

$$f(t) = 100; \quad 4 \leq t \leq 6 \\ = 0; \quad otherwise \tag{28}$$

The performance of the controller will be evaluated under two types of road conditions, represented by μ=0.5 for wet road and μ=1 for dry road condition.

The observer gain has been chosen as

$$L = \begin{bmatrix} -240 & 1625 \\ -240 & 1625 \end{bmatrix} \tag{29}$$

The controller gain has been selected as

$$K = \begin{bmatrix} -636.7288 & -2.6722 \\ 120.6039 & 1.7099 \end{bmatrix} \tag{30}$$

The matrix C is chosen as

$$C = [0.0035 \quad 0.0050; \quad -0.0205 \quad 0.0822] \tag{31}$$

The ρ, δ and γ values are chosen as

$$\rho = 0.0045 \quad \delta = 0.0025 \quad \gamma = 1 \tag{32}$$

A. *Performance of SMOC During Braking Action*

At μ = 0.5, Figure 3 and Figure 4 show that SMOC is able to prevent a larger amount of sideslip angle compared to LQR during the braking action. However the performance of SMC is slightly better that SMOC at both μs. In Figure 5 and Figure 6, SMOC achieved lesser yaw angle displacement at μ = 0.5 and 1 which is slightly better than SMC. This shows that SMOC is affective and able to avoid large sideslip and yaw angle displacement due to braking action compared to SMC where the difference is very small as shown in all the figures.

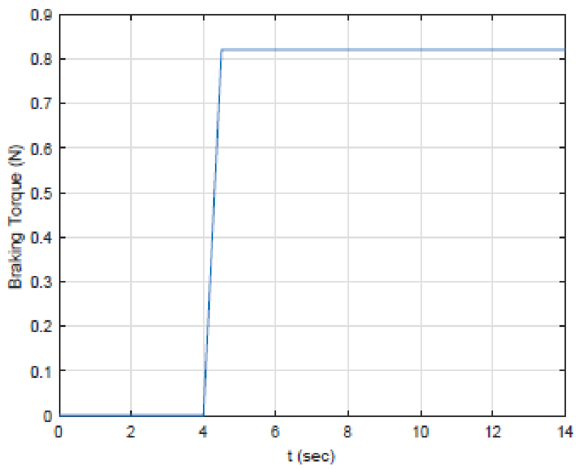

Figure 1. μ-split braking torque disturbance profile from braking action.

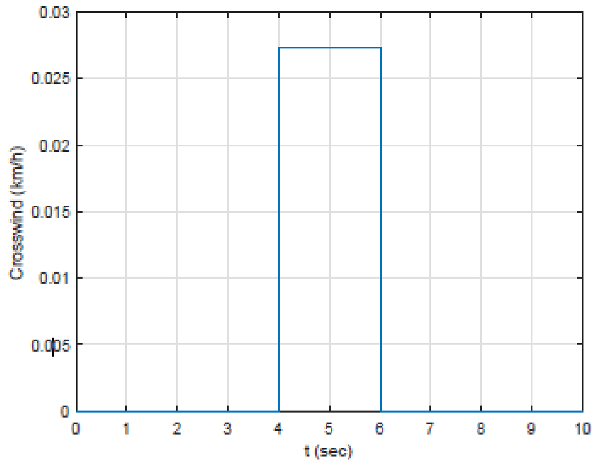

Figure 2. Crosswind disturbance profile.

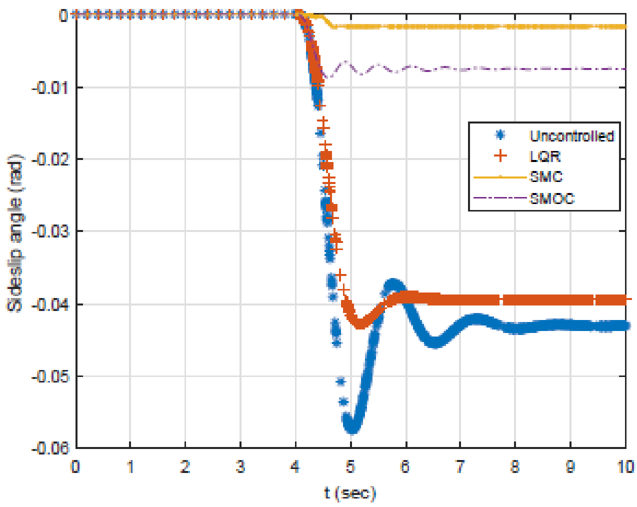

Figure 3. Sideslip angle displacement effect on the performance of SMOC with LQR and SMC under the influence of extreme braking action during wet road condition (μ = 0.5).

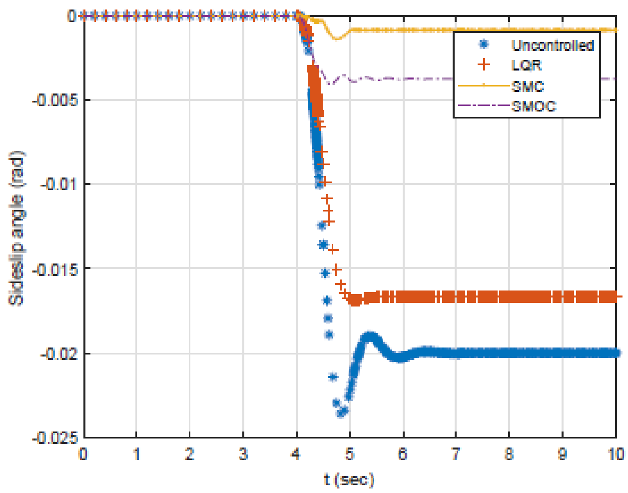

Figure 4. Sideslip angle displacement effect on the performance of SMOC with LQR and SMC under the influence of extreme braking action during wet road condition (μ = 1).

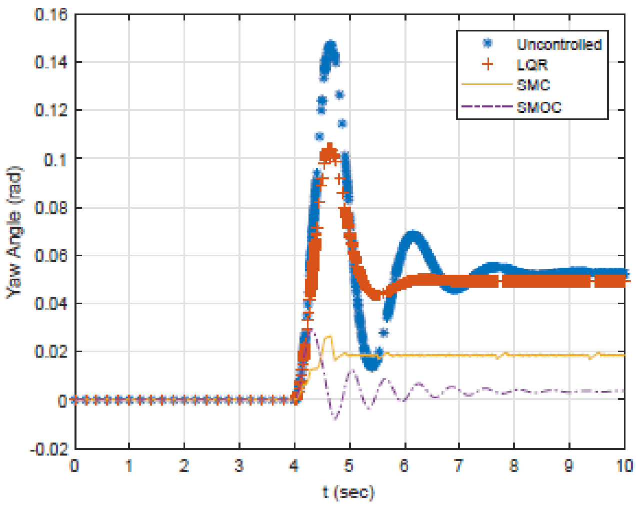

Figure 5. Yaw angle displacement effect on the performance of SMOC with LQR and SMC under the influence of extreme braking action during wet road condition (μ = 0.5).

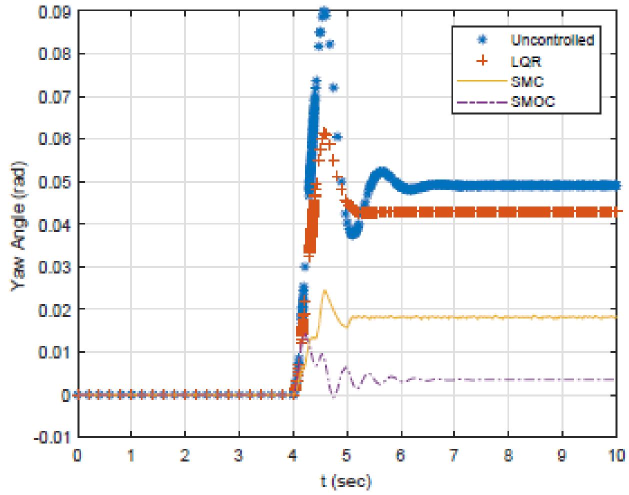

Figure 6. Yaw angle displacement effect on the performance of SMOC with LQR and SMC under the influence of extreme braking action during wet road condition (μ = 1).

B. *Performance of SMOC During Crosswind Disturbance*

At μ = 0.5 Figure 7 and Figure 8 show that SMOC performance is quite close to SMC and slightly better than LQR. This performance is similar to that shown in Figure 9 and Figure 10 where it is quite close to SMC but much better compared to LQR at μ = 0.5 and 1. This shows that SMOC is able to perform quite well when the car is under crosswind where it managed to avoid large sideslip and yaw angle displacement and comparable to SMC. The difference in performance between SMOC and SMC is quite small but still much better than LQR.

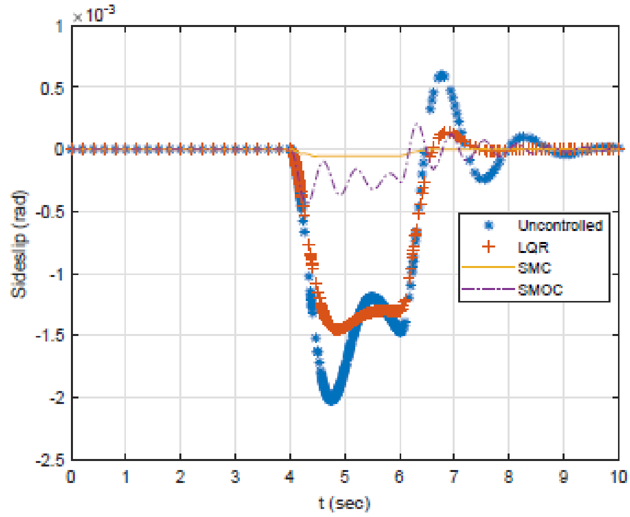

Figure 7. Sideslip angle displacement effect on the performance of SMOC with LQR and SMC under the influence of crosswind disturbance during wet road condition (μ = 0.5).

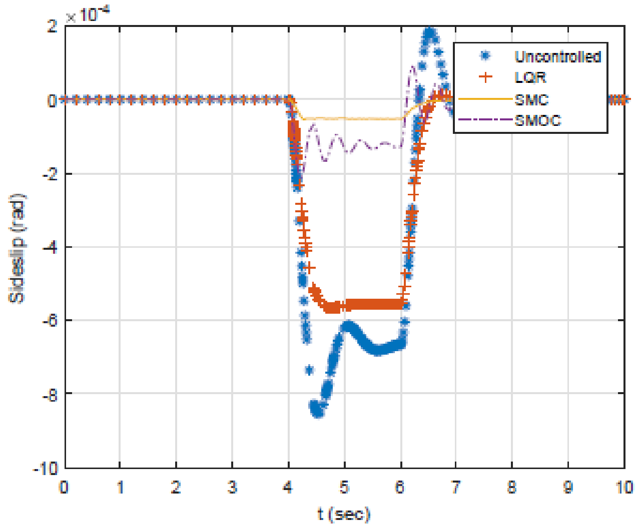

Figure 8. Sideslip angle displacement effect on the performance of SMOC with LQR and SMC under the influence of crosswind disturbance during wet road condition (μ = 1).

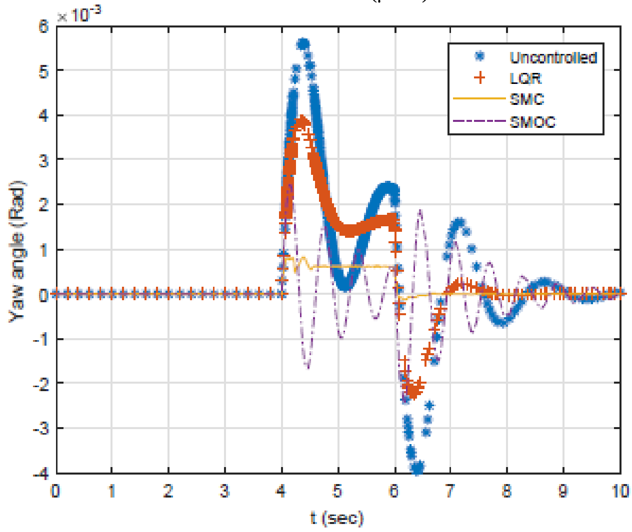

Figure 9. Yaw angle displacement effect on the performance of SMOC with LQR and SMC under the influence of crosswind disturbance during wet road condition (μ = 0.5).

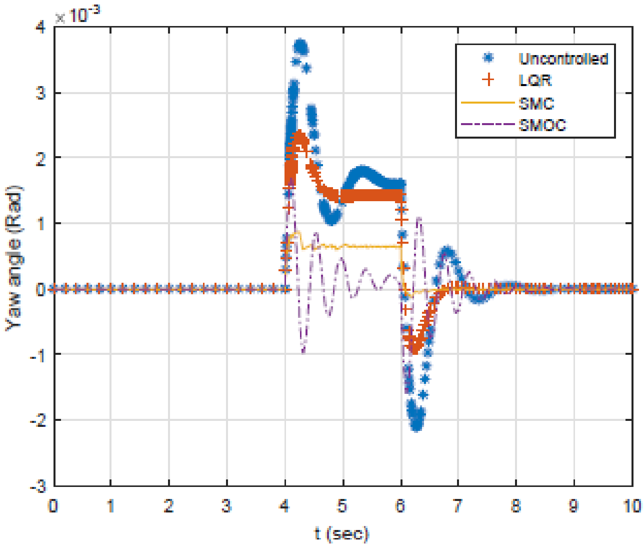

Figure 10. Yaw angle displacement effect on the performance of SMOC with LQR and SMC under the influence of crosswind disturbance during wet road condition (μ = 1).

VI. CONCLUSION

In this paper, SMOC controller has been proposed for a single track car model under the influence of external disturbances such as braking action torque and crosswind force. The stability of the controller is guaranteed by carefully analyzing the structure of the model and the nature of the disturbance. It shows that the controller is able to perform well by avoiding large sideslip and yaw angle displacement and comparable to SMC but much better than LQR controller. Due to its advantage of utilizing an observer that is normally used in a situation where not all states can be measured, the controller produced good results and promise. Hence, the objective of this paper has been met.

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