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TRACTION CONTROL OF VEHICLES USING SUPER TWISTING SLIDING MODE CONTROLLER AND A NOVEL TIRE FORCE ESTIMATION STRATEGY

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ABSTRACT

Traction control is an active vehicle safety feature designed to help vehicles make effective use of all the traction available on the road when accelerating on low-friction road surfaces. TCS becomes increasingly important to maintain the driver's controllability of the vehicle to enhance the driving experience under different road conditions and avoid road crashes by correcting human errors. This paper utilizes the usage of PID, sliding mode and super twisting sliding mode controllers with a nonlinear observer to obtain traction control for electric vehicles. The results of the simulation illustrate the success of the controllers to operate the vehicle at the desired wheel slip ratio. When a sudden change occurs, a super twisting controller yields the best control performance comparing to the other systems. A novel unified structure is used to estimate tire forces by using a nonlinear observer. The independence of the estimates from the vehicle tire model is the reason for the novelty of this structure.

KEYWORDS: **Super-Twisting Algorithm, High-Order Sliding-Mode Control, Traction Control, Tire Force Estimation, Extended Kalman Filter**

التحكم في الجر للمركبات باستخدام خوارزميه الالتواء الفائق للتحكم في الانزلاق واستخدام هيكل موحد حديث لتقدير قوه الإطارات

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الملخص

نظام مراقبه الجر هو من الأنظمة النشطة التي تزود بها السيارات للتحكم في انزلاق السيارة عند الضغط الزائد على دواسة الوقود على الطريق معامل احتكاكه منخفض، حيث أصبح الان من الأنظمة الغاية في الأهمية لزيادة التحكم في السيارة وتعزيز تجربه القيادة تحت الظروف المختلفة للطريق وأيضا للحد من حوادث الطرق عن طريق تجنب الخطأ البشرى والعمل على تصحيحه. يلخص هذا البحث ثلاثة أنواع مختلفة من طرق التحكم في الانزلاق للسيارات التي تعمل بالكهرباء مع استخدام مراقب غير خطى. توضح النتائج نجاح الثلاث أنواع المختلفة من طرق التحكم في الجر في الحفاظ على معدل الانزلاق المسموح به، كما توضح أيضا ان أفضل طريقه تحكم في حاله حدوث تغير مفاجئ هي طريقه الالتواء الفائق لنظام الانزلاق. يتم أيضا استخدام هيكل موحد حديث لتقدير قوه الإطارات عن طريق استخدام مراقب غير خطى والجديد في هذا النظام هو عدم اعتماد النتائج المستنتجة على نموذج الإطار الخاص بالسيارة.

الكلمات المفتاحية: خوارزميه الالتواء الفائق؛ التحكم عن طريق نظام الانزلاق عالي الترتيب؛ التحكم في الجر؛ تقدير قوة الإطارات؛ مرشح كالمان الممتد.

1. INTRODUCTION

Traction control plays an important role in safety during acceleration on dry or slippery roads by preventing wheel slippage because it can directly enhance drive efficiency, safety, and stability. Traction is the Vehicular propulsive force produced by friction between tire and road (Gerstenmeier, 1986). The amount of traction changes depending on a variety of factors such as the surface of the road, the conditions of the tire and the weight of the vehicle as well as the driver's behavior. Hard braking, oversteering and severe acceleration each affect the traction of the wheel. One-third of the fatal crashes worldwide are due to loss of driver control over the vehicle (Gerstenmeier, 1986).

The super-twisting algorithm (STA) is a well-known second-order sliding-mode control (2-SMC) algorithm introduced by Levant (1993). The chattering phenomenon found in the conventional sliding-mode control (SMC) algorithm prevents it from being extensively used in practice. Second-order sliding mode control is a better solution to reduce the chattering effect without affecting the robustness of the system because it uses the second time derivative of the sliding variable instead of the first derivative. Moreover, unlike Second-order sliding mode control, which needs the first time derivative of the sliding variable, STA does not require the information of time derivatives of the sliding variable, which makes its implementation easier.

Tire forces and road friction coefficients estimation are usually used in traction control to enhance the control performances. Various approaches have been introduced to estimate tire forces. In Ray (1995), Vehicle motion and tire force histories are estimated using an extended Kalman filter. In this model, tire force characteristics or external factors that affect vehicle motion is not required for the nonlinear estimation procedure. The simulation shows the effectiveness of the extended kalman filter to provide adequate state estimates for advanced ground vehicle control. In some studies, estimating tire forces are independent of tire models. The vertical tire forces are estimated Based on the longitudinal and lateral load transfers as well as the static loads on each wheel,

Antonov et al. (2011) used the unscented Kalman filter for estimation purposes such as vehicle states. Experimental tests show that the unscented kalman filter has good accuracy and robustness than the standard Kalman filter. In Cho et al (2010) and Rajamani et la. (2006) Wheel dynamics, rotational wheel dynamics and vehicle longitudinal dynamics have been used to estimate the longitudinal tire force acting on each tire. For example, In Cho et la. (2010) a Lyapunov function was used and the longitudinal tire force was estimated to satisfy the Lyapunov stability conditions. In Canudas-de-Wit et al (2003), the observer used Lyapunov stability theory as well; the nonlinear observer is used to estimate tire-road forces depending only on the wheel angular velocity.

Peoples nowadays give more attention to the protection of the environment so that the number of electric vehicles is increasing. In addition, the electric motors can produce very quick and precise torque compared to conventional internal combustion engines. Electric vehicles with in-wheel motors have drawn the attention as the vehicles can use the individualized control of wheel torques to achieve stable and efficient driving conditions.

In Yin, Oh, and Hori (2009), the traction control based on a maximum transmission torque estimation (MTTE) approach was proposed. The estimation is carried out by an open-loop disturbance observer, which requires only the input torque and the wheel speed. The estimated maximum transmission torque is used in

the controller. Yamakawa and Watanabe (2006) proposed a TC method using an optimal distribution of traction forces between the front and rear wheels by criteria of minimal tire friction work. The simulation applied in an electric car.
In Yamakawa et al. (2007) more complex driving situations were studied, such as driving on a rough road with a slope to validate that the proposed approaches improve vehicle mobility. Also Savitski et al. (2017) proposed traction control for the off-road electric vehicles in different maneuvers on an icy surface. Integration between SMC & PID control and combining between the functionalities of wheel slip and vehicle speed controller is used to increase the adaptability and performance in different situations. These studies were applied to a vehicle with four individual electric motors.

Amodeo, Ferrara, Terzaghi, and Vecchio (2010) present a second-order Sliding-Mode traction controller. The sliding-mode observer is used with the controller to estimate the tire-road adhesion coefficient. The traction control is achieved by maintaining the wheel slip at the desired value. In Suwat et la. (2015), a super-twisting algorithm is used to obtain traction control for road vehicles. The controller is used to operate the vehicle such that the desired wheel slip ration is achieved. A nonlinear observer is coupled with the controller to estimate the tractive forces.

In this paper, a nonlinear controller with observer is used for the traction control of the vehicle. The purpose of the controller is to control the vehicle to achieve a desired wheel slip ratio at different surfaces. The proposed control scheme in this paper is considered as an alternative SMC-based scheme to the ones in Amodeo et al. (2010) and de Castro et al. (2013).

In Amodeo et al. (2010) the sub-optimal 2-SMC is used which demands more information than STA. Thus, the implementation of STA is simpler as it depends only on the current value of the sliding variable. De Castro, Araújo, and Freitas (2013) proposed wheel slip control of electric vehicles based on a SMC- CI (Conditional integrator). The CI is used to overcome the chattering and to enable a smooth transition to a PI control law when the slip is Close to the set point. However, STA performs better in the proximities of the sliding surface because the SMC and CI framework proposed in de Castro et al. (2013) preserves the performance and robustness of the ideal SMC only outside a boundary layer of a sliding surface.

The structure of this paper is as follows: Section 2 presents some preliminaries. Followed by the longitudinal dynamic model of vehicles during accelerating maneuvers in section 3. In Section 4, control design is presented. Finally Simulation and results are resented in section 5.

2. PRELIMINARIES

2.1 Super-twisting sliding-mode control:

The super-twisting algorithm (STA) is one of the most promising second-order sliding-mode control (SMC) algorithms for the systems having relative degree one with respect to the sliding variable, Levant (1993). STA is considered as a solution for the chattering problem that appears in the conventional sliding mode controller while maintaining the same robustness and performance as that of SMC. The chattering problem is harmful, because it leads to low control accuracy, high wear of moving mechanical parts and high heat losses in power circuits. (Rivera et al. 2011). Consider the below dynamics system in (1), The STA can be expressed as in equations (2&3) (Levant, 1993; Shtessel, Edwards, Fridman, & Levant, 2014).

$$s^{\bullet} = u + a(t) \tag{1}$$

$$U = h|s|^{0.5}\,\mathrm{sgn}(s) + w \tag{2}$$

$$\dot{w} = -\beta\ \mathrm{sgn}(s) \tag{3}$$

Where S is the scalar state variable and $S \in$ R, U is the control input and $U \in$ R

$\dot{w} = -\beta\ \mathrm{sgn}(s)$,

η >0 & β >0 are the control Parameters and a (t) is the unknown function For more details, the reader refers to Levant (1993) & Shtessel et al. (2014).

2.2 Longitudinal tractive force estimation:

In Rezaeian et al. (2015) a novel tire-force estimation strategy is proposed. In this strategy, a nonlinear observer is used to calculate the tire forces. The proposed structure uses dedicated modules to estimate the longitudinal and vertical tire forces. The advantages of this strategy is the independence of tire parameters on the road surface conditions and vertical mass variation. In this paper, the tire forces estimation strategy in Rezaeian et al. (2015) is presented in this subsection. The estimation of longitudinal tire forces only is discussed in this paper. The reader is referred to Rezaeian et al. (2015) for more details about the other modules.

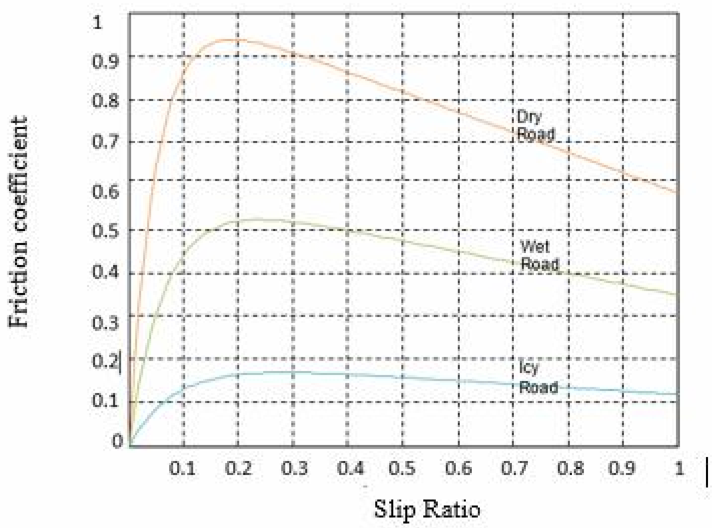


Figure 2. Typical trends of longitudinal friction coefficient.

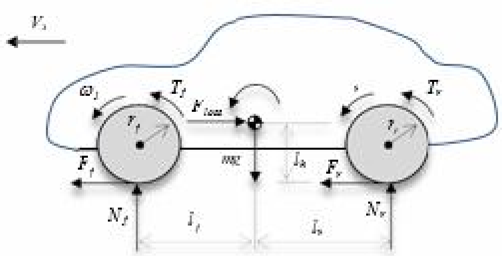


Figure3. Longitudinal model of the vehicle.

3. LONGITUDINAL DYNAMIC MODEL

In this model, only longitudinal forces are considered. The model is a bicycle model. The dynamic equations of the Vehicle in the longitudinal direction are obtained As:

$$F_f + F_r - F_{loss} + mg = m\dot{v}_x \tag{4}$$

$$F_{loss} = F_a + \frac{M_{yf}}{r_f} + \frac{M_{yr}}{r_r} \tag{5}$$

$$F_a = \frac{1}{2} A C_d r v_x^2 \tag{6}$$

$$T_i - r_i F_i - M_{yi} = I_i \dot{w}_i \text{ , i= \{f, r\}} \tag{7}$$

Where v_x is the longitudinal velocity of the vehicle center of gravity, F_f and F_r are the front and rear tractive force respectively. F_{loss} Combines the aerodynamic drag force F_a and the rolling resistance. A is the frontal area of Vehicle, ρ is the air density, C_d is the aerodynamic drag coefficient, m is the vehicle mass, M , M_{yf} Are the front and rear rolling resistance moments,, are the moments of inertia of the axles, ω_f, ω_r are the front and rear tire rotational speeds, r_f, r_r are the tire effective rolling radius. T_f , T_r are the input torques and N_f, N_r are the normal loads .The normal loads are given as:

$$N_f = \frac{l_r mg - l_h m\dot{v}_x - h_a F_a}{l_r + l_f} \tag{8}$$

$$N_r = \frac{l_r mg + l_h m\dot{v}_x + h_a F_a}{l_r + l_f} \tag{9}$$

$$l_i = \frac{r_i w_i - v_x}{Abs(v_x)} \tag{10}$$

Where λ_i is the slip ratio. There are many factors affect the friction coefficient, which makes the behavior of the tractive forces complicated, such as road conditions, wheel slip, road surface, tire type, etc. The typical friction coefficient in dependency of the slip ratio is shown in Figure (3). It shows that some amount of slip is required to produce tractive force however; an excessive slip leads to a loss of the force.

4. CONTROL DESIGN

4.1 Controller Design:

In this paper, a super twisting algorithm-based sliding mode controller, SMC, PID controllers are designed for the system Described by (4) – (10). The control objective is to operate the Vehicle such that the desired slip ratio λ^* is achieved.

For the STA-based sliding mode controller and conventional SMC design, the reader refers to Suwat et al. (2015). After applying the conventional SMC design, the corresponding control law would become:

$$U_i = (\frac{I_i}{1-l^*})(-\frac{1}{r_i m}F_{loss} + \frac{1}{r_i m}F_f + \frac{1}{r_i m}F_r + (1-l^*)\frac{r_i}{I_i}F_i + h_i \operatorname{sgn}(s_i)) \tag{11}$$

In addition, the control law for STA would become:

$$U_i = (\frac{I_i}{1-l^*})(-\frac{1}{r_i m}F_{loss} + \frac{1}{r_i m}F_f + \frac{1}{r_i m}F_r + (1-l^*)\frac{r_i}{I_i}F_i + h_i |s_i|^{0.5} \operatorname{sgn}(s_i) w_i) \tag{12}$$

$$w_i = -b \operatorname{sgn}(s) \tag{13}$$

Where η& β > 0. In this research, an observer is used to estimate F_r, F_f.

4.2 Observer design:

In this paper, the controller is coupled with a novel observer to estimate F_r, F_f. The wheel dynamic model proposed is used to develop the observer, where the inputs of the observer are the torques acting on each wheel and the angular velocity of each wheel. The effects of rolling resistance is neglected since the dominant force here is the longitudinal tire force. The wheel dynamics can be expressed as:

$$T_i - r_i F_i = I_i \dot{w}_i \quad , \text{i= \{f, r\}} \tag{14}$$

In electric vehicles, the driving torque is available via the electric motor drive. The angular velocity can be estimated by using an observer that its structure is similar to that of a Proportional-Integral-Derivative (PID) controller, i.e.:

$$I_i \ \hat{}_i = {}_i - {}_i \ \tilde{}_i + (\ \tilde{}_i + \int \tilde{}_i + (\tilde{}_i / \ )) \tag{15}$$

Where and are the PID gains, $\tilde{}_i$ is the estimated longitudinal tractive force, and the error in angular velocity estimate is $\tilde{} = - \hat{}$, and $\hat{}$ is the angular velocity estimate. For the estimation of longitudinal tire force and observer stability proof, the following Lyapunov function is defined:

$$v_x = 0.5 \ \tilde{}^2 , \ \dot{v}_x = \tilde{}_i \ \tilde{}_i \tag{16}$$

$$\text{And: } \dot{v}_x = \frac{1}{I_i} (- \ \tilde{} - \ \tilde{}_i - \int \tilde{}_i - (\tilde{}_i / \ t) \ \tilde{}_i \tag{17}$$

Where: $\tilde{} = {}_i - \tilde{}_i$, and ((0) = $\tilde{}$ (0) = 0). With selecting:

$$\tilde{} = (-1/r) (\ ' \ \tilde{}_i + \ ' \int \tilde{}_i + \ ' (\ \tilde{}_i / \ t) \tag{18}$$

By applying PID gains as (0 < ′ < ,) ′ = $_i$, ′ = , $\dot{v}_x \leq 0$ is guaranteed. Then, both $\tilde{}$ and $\tilde{}$ will converge to zero. Finally, the estimated longitudinal tractive force becomes:

$$\tilde{}_i = (\ ' \tilde{} + \ ' \int \tilde{} + \ ' (\tilde{}_i / \ ) - I_i \dot{}_i + {}_i) / \tag{19}$$

The observer requires an initial value for the estimated longitudinal tractive force, that can be simply chosen as the initial torques divided by the effective tire radius.

5. SIMULATION STUDIES AND RESULTS

The vehicle parameters are adopted from Amodeo et al. (2010) and are tabulated in

Table (1). Only longitudinal forces are considered. The controlled plant in this model is the vehicle and represented in equations (4) - (10). The percentage of the target slip (λ) is 10%. All simulations were carried- out by means of MATLAB-Simulink.

Table 1.Parameters of the vehicle and the friction model.

Parameter	*Value*
m	***1202 kg***
I_f, I_r	***1.07 Kg m^2***
l_f	***1.15 m***
l_h	***0.53 m***
F_{roll}	***0.013***
r_f ,	***0.32 m***

Figures (4 - 18) show the simulation results. The friction coefficient at the first second is set to (μ=1) and after two seconds it is changed to be (μ=0.1) to simulate a sudden change in the road condition. Figures (4-8) show the results using super twisting sliding mode control. Then the controller can drive the system successfully to achieve the desired slip ratio, as shown in figure (8).The controller successfully reduced the input torques to keep the slip ratio constant, although the friction coefficient was decreased 10- times. When the friction coefficient value was changed, there were some pitching oscillations and estimation errors. Also, there were small jumps in the slip value, but they converged back to the desired value because of the robustness of the STA controller. Finally, the STA controller was efficiently able to handle the pitching oscillations and estimation errors.

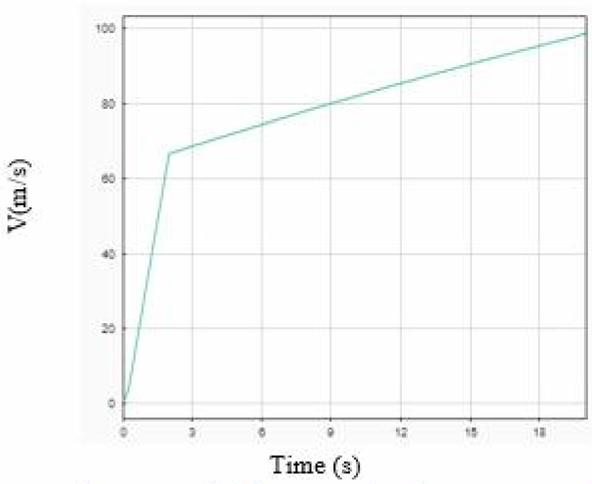


Figure 4. Velocity rate using the STA- controller

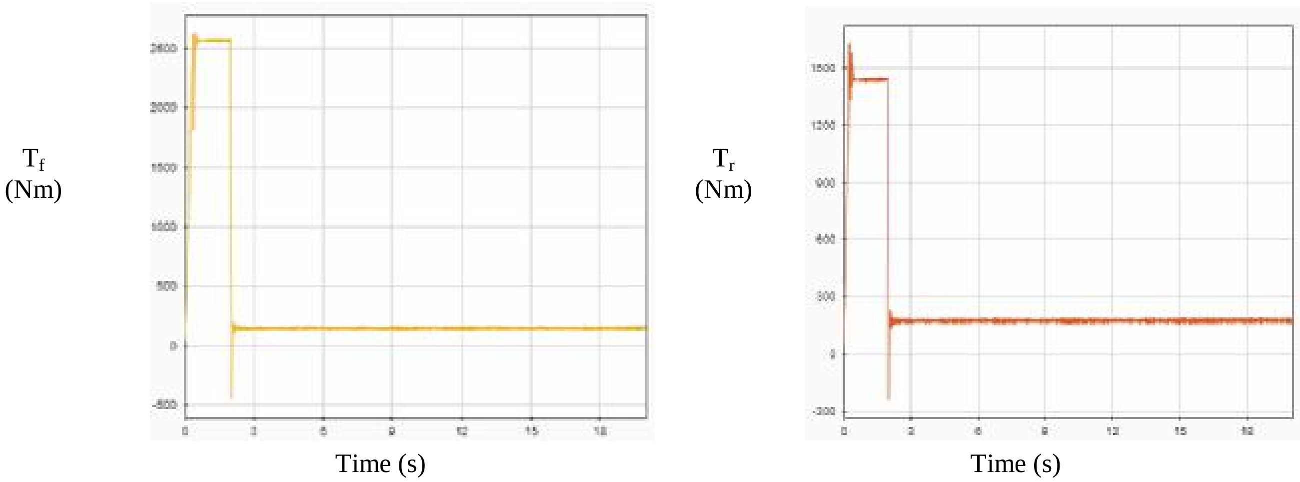


Figure 5. Input torque commands using the STA-controller and the observer

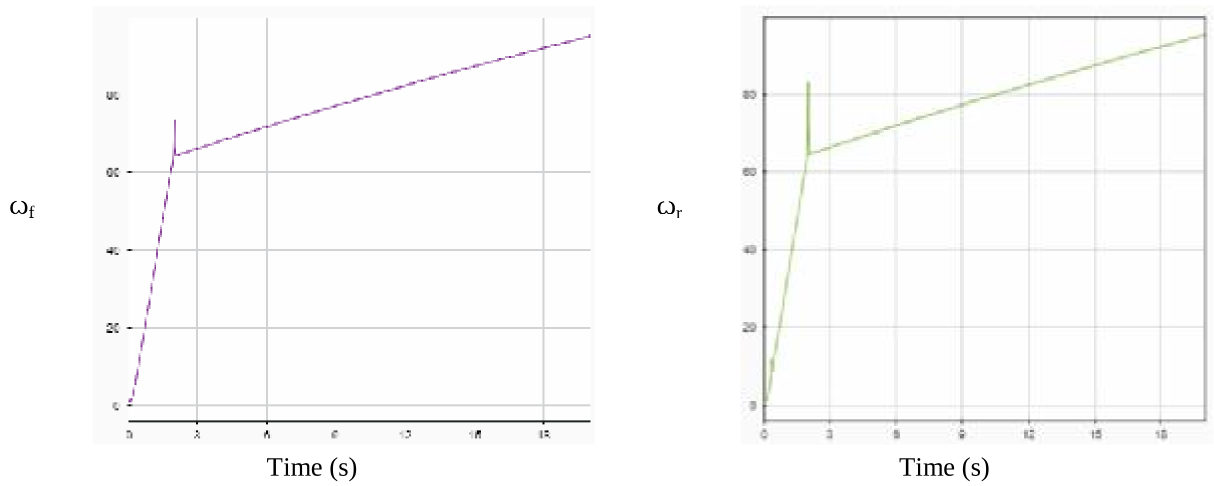


Figure 6. Rotational speeds using the STA-controller and the observer

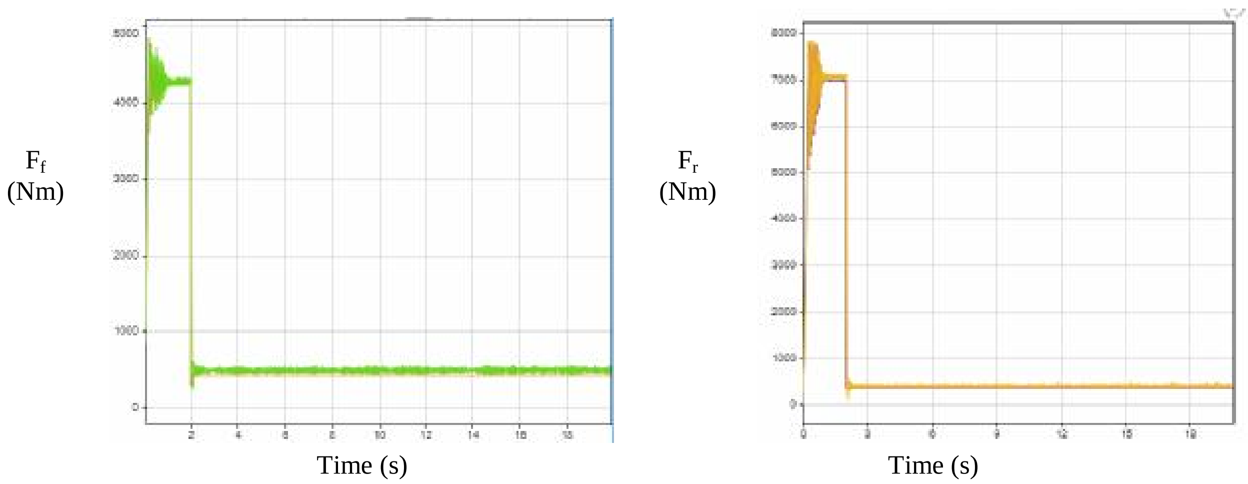


Figure 7. Tractive forces using the STA-controller and the observer

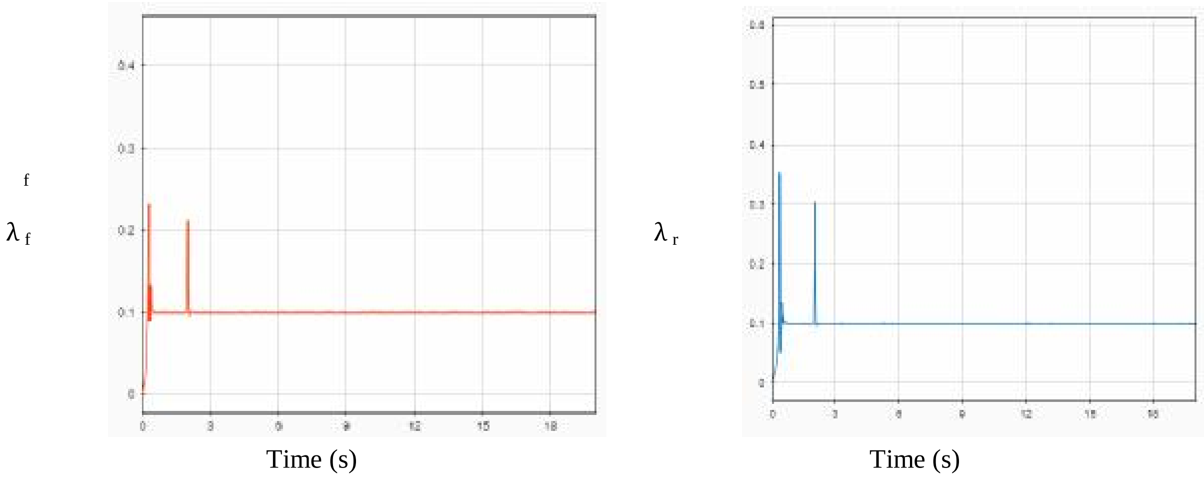


Figure 8. Slip ratios using the STA-controller and the observer

The conventional SMC successfully drove the system to operate at the desired wheel slip ratio, figures (9-13). When the friction coefficient was decreased, the controller effectively reduced the input torques to keep the wheel slip ratios constant. In this model η_i = 120 and $\beta = 80$. When the friction coefficient suddenly changes, large jumps of the slip ratio occurred because of the slow convergence rate of the control system. The large jumps can be decreased by increasing the value of $\eta_{i.}$ However, this will result in increasing the chattering phenomena. The major advantage of the STA controller over conventional SMC is reducing the chattering that occurred in the torque command, Also the small difference between STA control law and SMC control law make replacing SMC with STA easily to overcome the chattering.

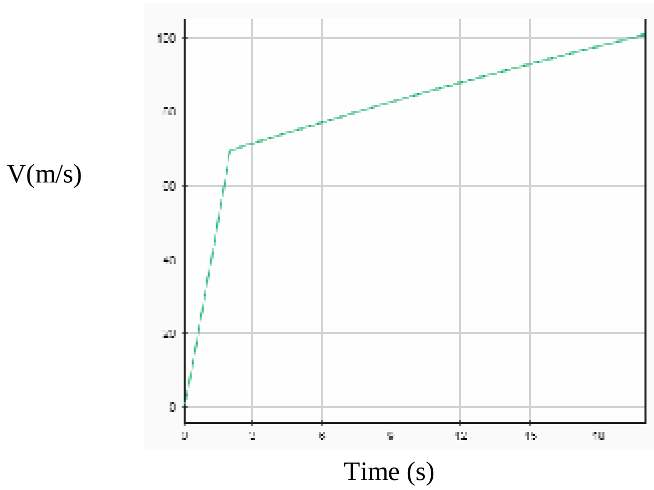


Figure 9. Velocity rate using the conventional SMC and the observer

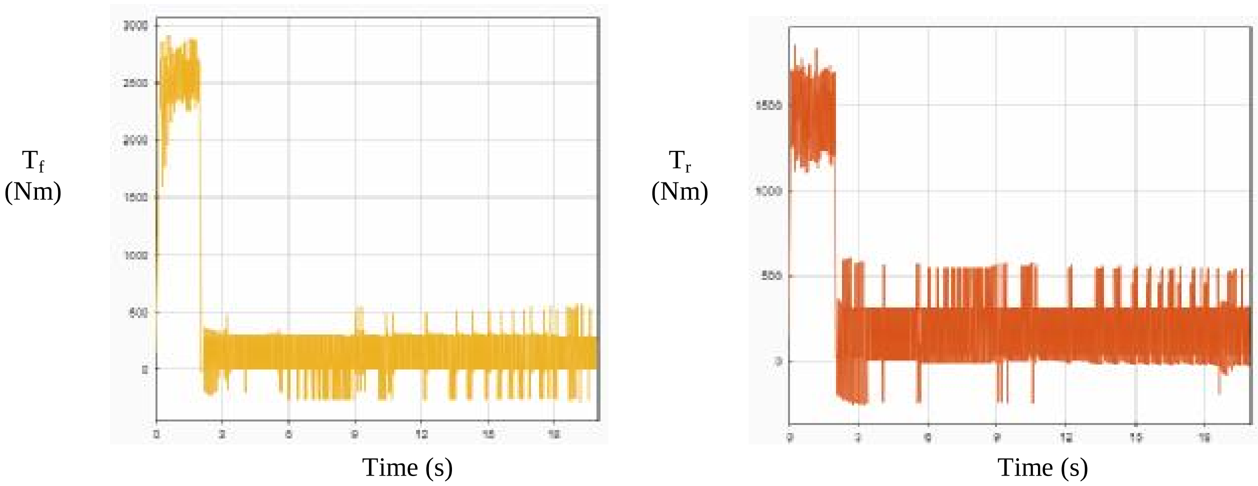


Figure 10. Input torque commands using the conventional SMC and the observer

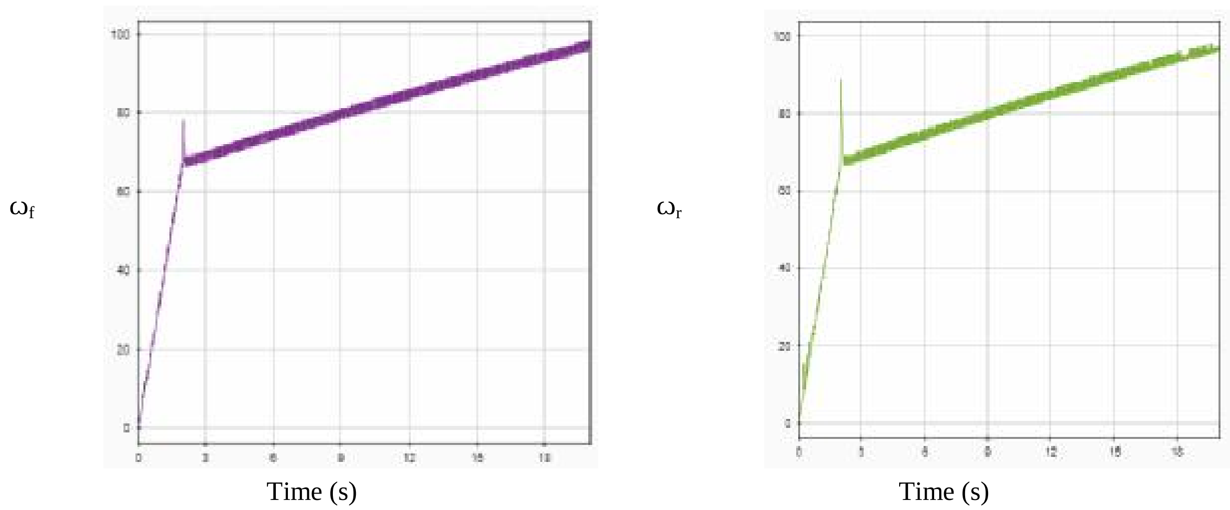


Figure 11. Rotational speeds using the conventional SMC and the observer

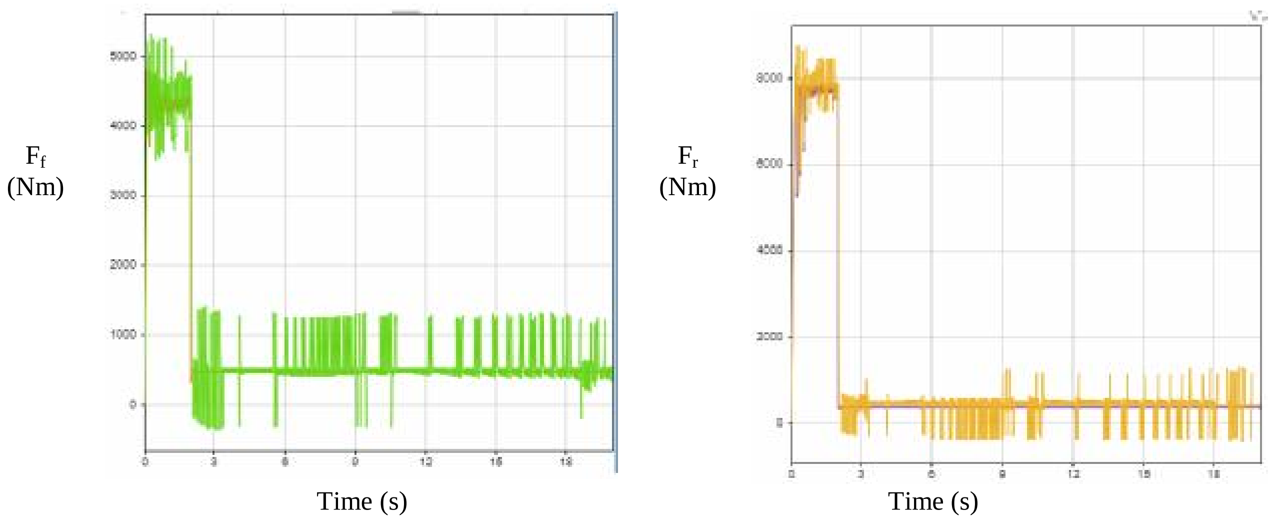
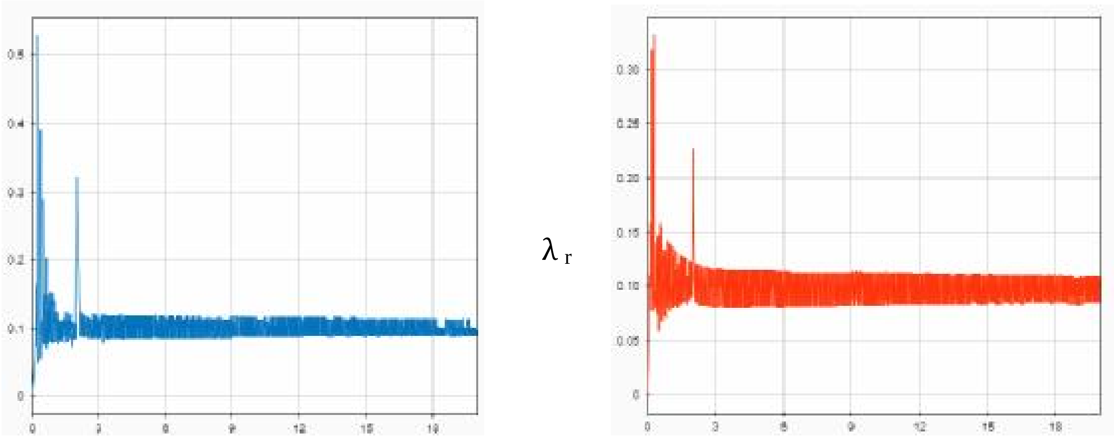


Figure 12. Tractive forces using the Conventional SMC and the observer

λ_f λ_r

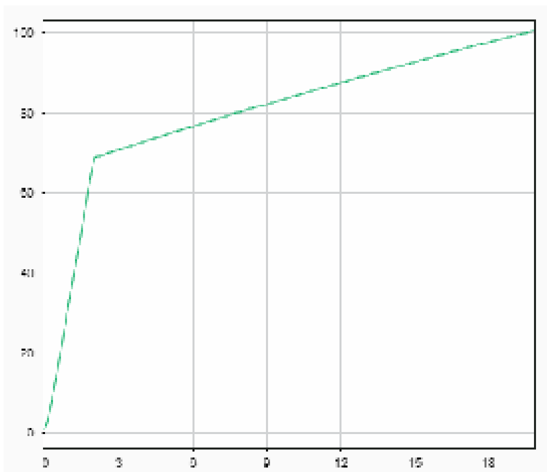


Time (s) Time (s)

Figure 13. Slip ratios using the Conventional SMC and the observer

Figure (14- 18) show that the controller can successfully drive the vehicle at the desired wheel slip ratio using a PID controller. When the friction coefficient suddenly changes, large jumps of the slip ratio occurred as shown in figure (18) and the controller takes more time to handle this change comparing to SMC and STA.

V (m/s)



Time (s)

Figure 14. Velocity rate using the PID controller and the observer

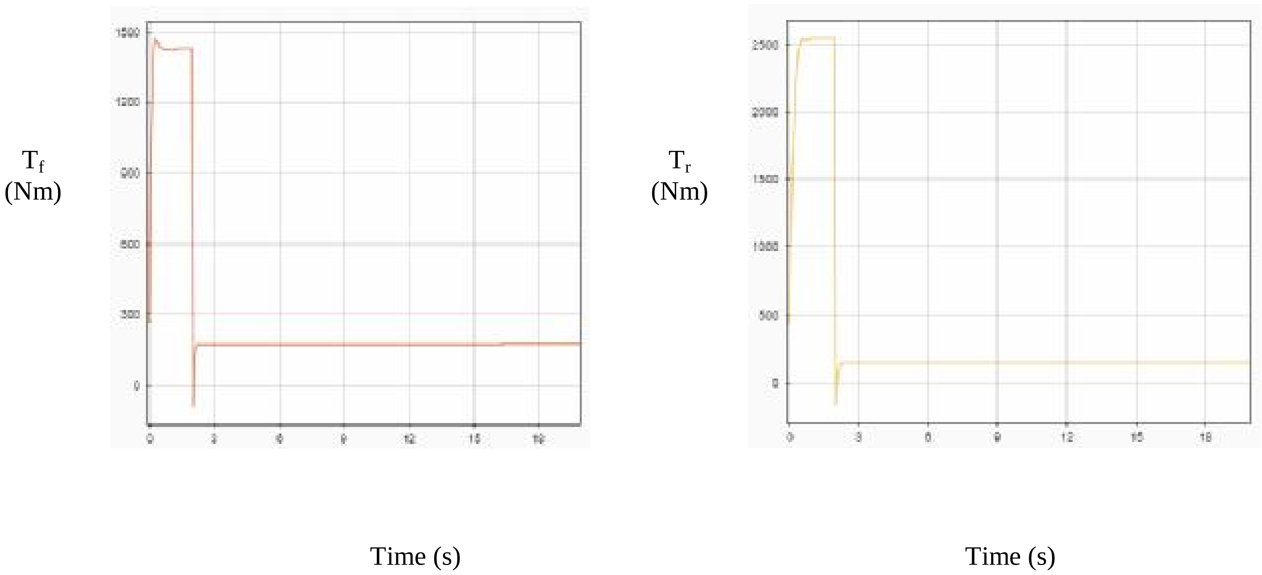


Figure 15. Input torque commands using the PID controller and the observer

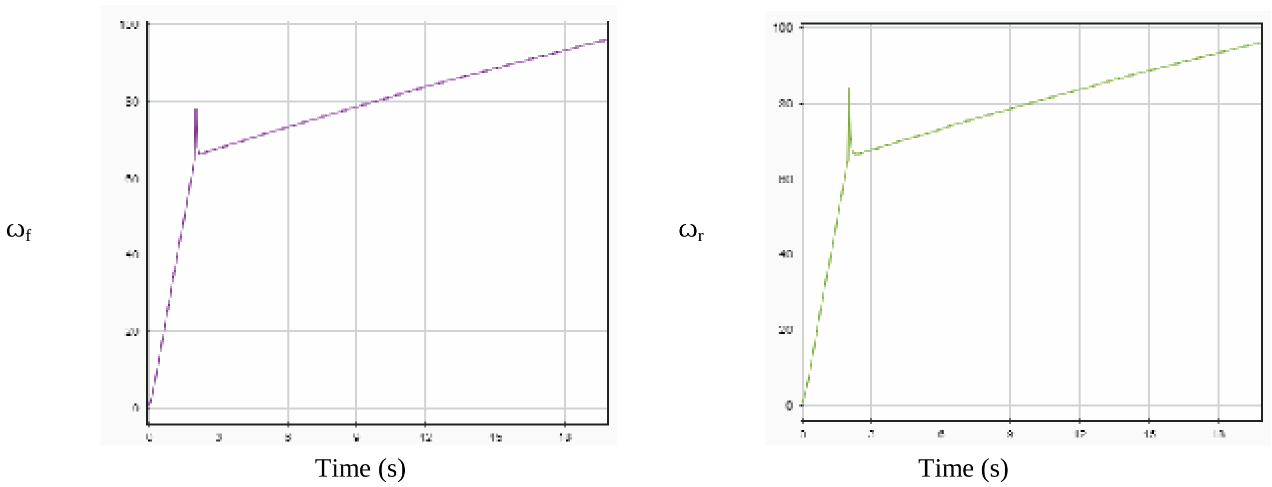


Figure 16. Rotational speeds using the PID controller and the observer

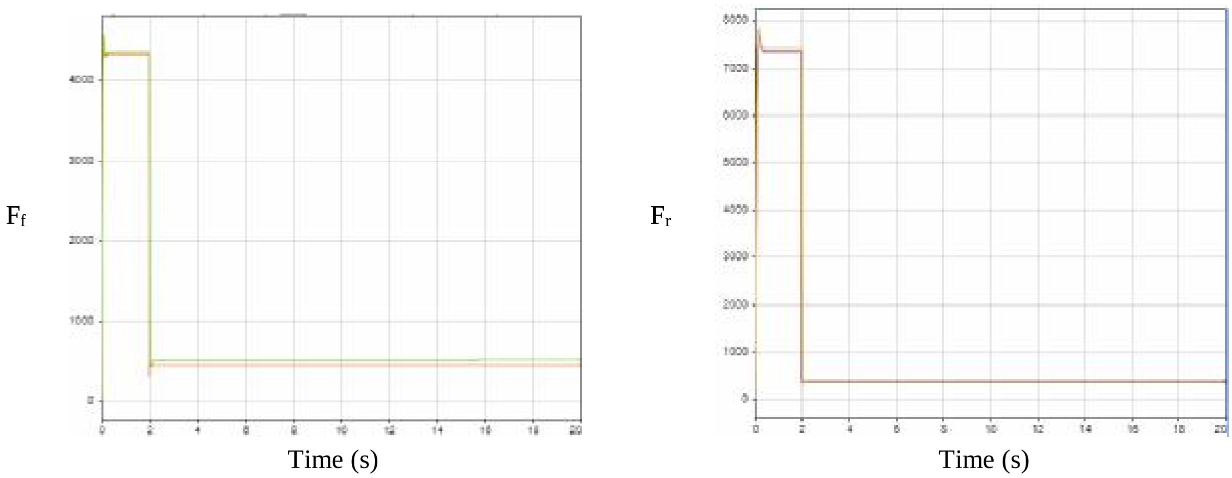


Figure 17. Tractive forces using the PID-controller and the observer

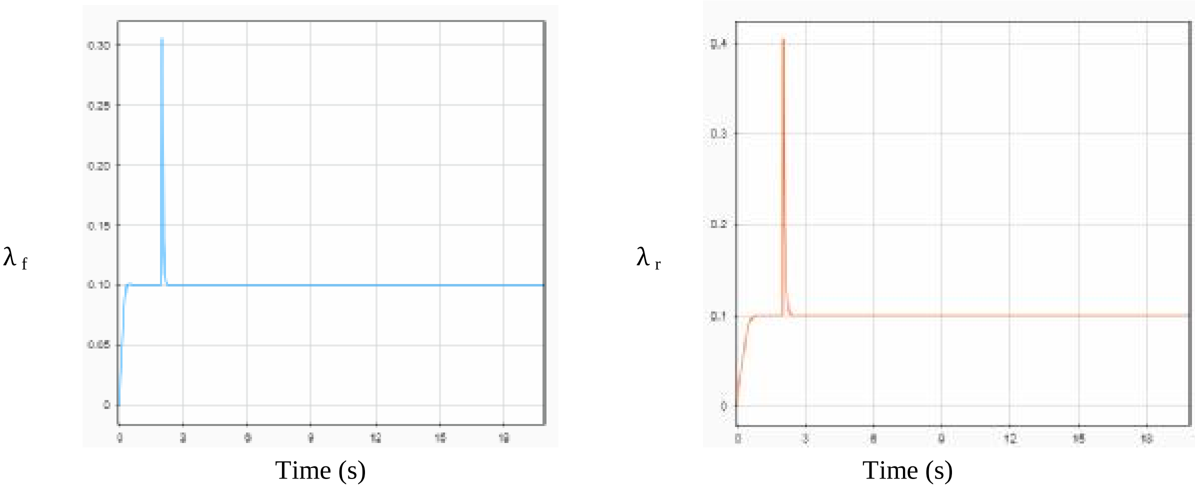


Figure 18. Slip ratios using the PID-controller and the observer

7. CONCLUSIONS

This paper has presented a STA-based control system for vehicle traction control. The controller is a combination of STA control law and a novel nonlinear observer. The Conventional SMC method is also presented. the design of a super twisting sliding mode controller is obtained by replacing the control part of the sliding mode controller with the STA. The simulation illustrates the effectiveness of the proposed control scheme. Longitudinal dynamic modeling of a two-axle vehicle during acceleration maneuvers has been presented. Traction control based on three types of controllers; PID, sliding mode controller and super twisting sliding mode controller were discussed. The results show that the controllers successfully drove the System to operate at the desired slip ratio. The STA-controller provided superior control performance when a sudden change occurs comparing to the conventional SMC and PID controllers. In addition, the small difference between STA control law and SMC control law make replacing SMC with STA easily to overcome the chattering Phenomena.

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