Two-time Scale Control for Lane Keeping of 4WS Autonomous Ground Vehicles

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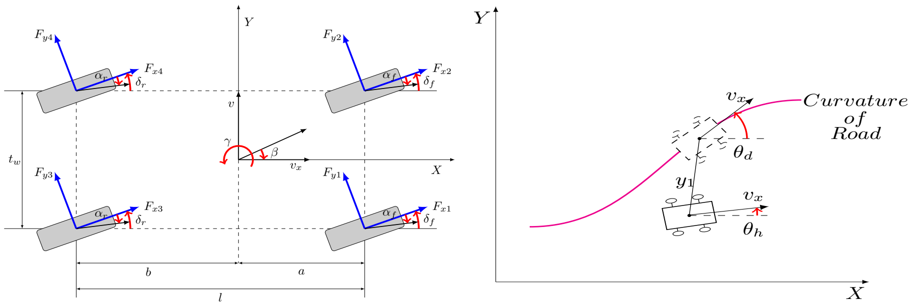
Abstract

Due to rapid developments in the radar technology and electronic control units (ECUs), the autonomous car has become a reality. The autonomous car improves the safety of the passengers by assisting the drivers in emergency situations. One of the important feature of autonomous cars is the active steering control (ASC). ASC alters the driver's steer input angle intelligently to improve the directional stability at higher speeds. In ASC control design, the major problems are the uncertain vehicle parameters and external disturbances. The parameters contributing to the uncertainties include sprung and unsprung mass of the vehicle, tire properties, spin inertia, normal reactions etc. whereas, the external disturbance constitutes air drag. In literature, different robust control techniques are proposed to solve these problems. To name a few, fuzzy logic control, model predictive control, switching control and integrated control are reported. A more popular approach of sliding mode control (SMC) is also used. The problem with conventional SMC is chattering due to it's discontinuous nature. Different estimation techniques such as inertial delay control and disturbance observer are used in combination with SMC to reduce the chatter. Another line of research known as two-time scale (TTS) observer is also found in literature to estimate the uncertainties. Although popular, it's application for ASC is not yet reported in the literature.

In this paper, a new approach of SMC based TTS control is proposed for ASC. A four wheel steered (4WS) model as shown in Fig. 1 is considered for control design. The lateral v and yaw dynamics γ of the vehicle are obtained using Newton's laws of motion. The 4WS model is advantageous in a way that it provides both lateral and yaw control of the vehicle as compared to a front wheel steered model. To design the control law, the application of ASC for lane keeping is considered as shown in Fig. 1b. In Fig. 1a, F_{xi} and F_{yi} represent the longitudinal and lateral forces at all the four wheels, where i stands for $1-4$. α_f/α_r and δ_f/δ_r denote the side-slip and steering angles at front and rear wheels respectively. a, b are the distances from front and rear axle to the center of gravity (C.G.) respectively and β and t_w represent body-slip angle and track width respectively. In Fig. 1b, v_x is the longitudinal velocity, y_1 is the lateral offset and θ_d, θ_h represent the desired and actual heading angles respectively.



(a) (b)

Figure 1: (a) Dynamic model of a 4WS (b) Trajectory tracking.

The objective of the controller is to maintain the desired trajectory of the vehicle despite of uncertainties in the vehicle parameters and the external disturbances. The state space model of lane keeping dynamics is given as

$$\dot{y}_1 = y_2; \qquad \dot{y}_2 = u_1 + d_1 \tag{1}$$

$$\dot{\theta}_1 = \theta_2; \qquad \dot{\theta}_2 = u_2 + d_2 \tag{2}$$

where, u_1 and u_2 are the control inputs, $\theta_1 = \theta_h - \theta_d$ and d_1 and d_2 are the lumped disturbances comprising uncertain parameters and external disturbances. Controller is designed to ensure that $y_1 \to 0$ and $\theta_1 \to 0$ so that the vehicle tracks the desired trajectory. For control design, two sliding surfaces are considered as $\sigma_1 = c_1 y_1 + y_2$ and $\sigma_2 = c_2\theta_1 + \theta_2$ where, c_1 and c_2 are positive constants. To ensure reaching phase elimination, these sliding surfaces are modified to $\sigma_1^\star = \sigma_1 - \sigma_1(0)e^{-\alpha_1 t}$ and $\sigma_2^\star = \sigma_2 - \sigma_2(0)e^{-\alpha_2 t}$ where, α_1 and α_2 are the positive constants and $\sigma_1(0)$, $\sigma_2(0)$ are the initial values of σ_1 and σ_2 respectively. The controller is designed to ensure that $\sigma_1^\star$ and $\sigma_2^\star$ go to zero given by

$$u_1 = -c_1 y_2 - \alpha_1\sigma_1(0)e^{-\alpha_1 t} - k_1\sigma_1^\star - \hat{d}_1; \qquad u_2 = -c_2\theta_2 - \alpha_2\sigma_2(0)e^{-\alpha_2 t} - k_2\sigma_2^\star - \hat{d}_2 \tag{3}$$

where, k_1 and k_2 are the positive constants and $\hat{d}_1$ and $\hat{d}_2$ are the estimates of d_1 and d_2 respectively. These estimates are obtained using TTS observer and the filter proposed as

$$\hat{d}_j = \frac{1}{\varepsilon_j}(\sigma_j^\star - \hat{\sigma}_j^\star); \qquad \dot{\hat{\sigma}}_j^\star = -k_j\sigma_j^\star - u_{jn} + \frac{1}{\varepsilon_j}(\sigma_j^\star - \hat{\sigma}_j^\star) \tag{4}$$

where, $j = 1, 2$, $\varepsilon_j > 0$ and $u_{jn} = -\hat{d}_j$. The stability of the designed controller is proved using Lyapunov stability. From the stability analysis, it is verified that the estimation error, $\tilde{d}_j = d_j - \hat{d}_j$ and $\sigma_j^\star$ converge and are ultimately bounded. By selecting appropriate values of ε_j and k_j, the bounds are maintained in the neighborhood of zero. $\sigma_j^\star$ converging to zero, ensures that y_1 and θ_1 go to zero which fulfills the proposed control objective.

To verify the performance of the proposed controller, simulation is performed for two types of maneuverings, double lane change and J-turn using MATLAB/Simulink. It is assumed that the vehicle is moving with a constant speed of 20 m/s. The road is considered to be made up of dry asphalt with coefficient of friction, $\mu = 0.8$. Fig. 2 shows the simulation results for double lane change maneuvering. Figs 2a and 2b show the magnitude of crosswind (CW) disturbance and road curvature respectively. As can be seen from Figs 2g and 2h, the estimation errors $\tilde{d}_1$ and $\tilde{d}_2$ converge to zero which proves the effectiveness of proposed TTS observer to estimate the uncertainties. As seen from Figs 2c and 2d the lateral offset and heading angle error converge to zero, as desired. Figs 2e and 2f show the generated front and rear steering angles respectively. Similar results are obtained for J-turn maneuvering as well.

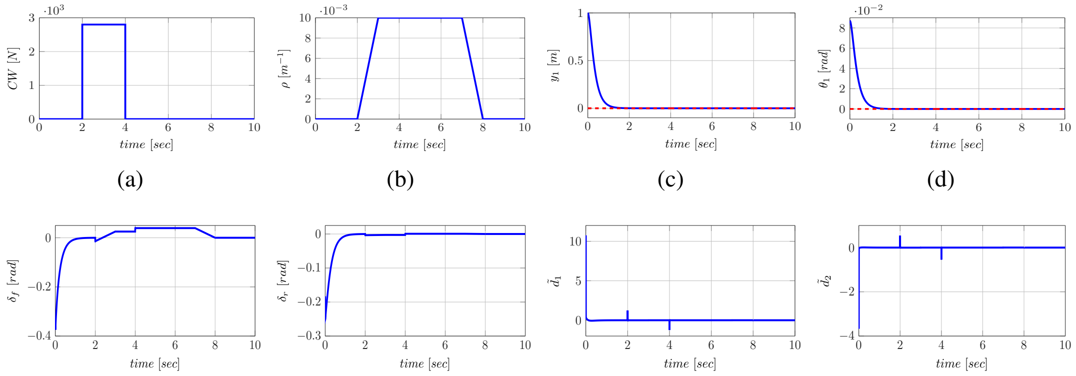


Figure 2: Simulation results for double lane change maneuvering.

To conclude, in this paper an active 4WS controller is designed for the lane keeping of autonomous vehicles. The proposed sliding mode based TTS controller successfully estimates the external disturbances and uncertainties in the system parameters. The control signal is free from chatter, improving the actuator performance. The ability of the controller to maintain the vehicle on the desired trajectory is proved mathematically and verified using MATLAB/Simulink simulation. The simulation results validate the robustness of the proposed controller to different maneuverings such as the J-turn and double lane change.