Investigation of the Conflict between the Driver and a Vehicle Steering Assist Controller

LIANG-KUANG CHEN and BO-JUN SHIEH
Department of Mechanical Engineering
National Taiwan University of Science and Technology
No.43, Sec. 4, Keelung Rd., Taipei 106
TAIWAN

Abstract: - A serial vehicle steering assist controller is designed using variable structure model reference adaptive control. Due to the variation in human driver behavior, the stability of the compensated system is not guaranteed and conflict between the driver and the steering assist controller may exist. A model predictive control based driver model is employed to represent the variation in driver intention, and the conflict is observed in computer simulations. A simple decision making algorithm is implemented as a preliminary attempt, and the conflict situations are successfully avoided when the driver model is a performant steering controller. Future work of this research includes the revision of the decision making algorithm to incorporate the driver state and the transitions of controller states using fuzzy logics.

Key-Words: - vehicle steering assist, driver interaction

1 Introduction

Human error is believed to be the main factor that leads to vehicle accidents. Several vehicle active safety systems have been developed and implemented to help the driver to avoid vehicle crashes. However, regardless of the different objectives, eventually the designed active safety systems will function together with the human driver to influence the vehicle motions. The driver behavior needs to be appropriately considered in the design of the safety systems. As an example, for vehicle lateral control, the human factor research indicates that three components are commonly observed in the guidance and control levels of human driving, namely, the precognitive, the pursuit, and the compensatory behavior [1]. In the control engineering community, several driver steering control models have been developed to represent the pursuit and compensatory behavior and the well-known cross-over principle driver model is developed (see, e.g., [2-4]). A survey of the early driver steering control models has been presented by Reid in [5]. Hess and Modjahedzadeh [6] augmented the cross-over principle model with the high frequency modes to represent the neuromuscular dynamics of the human driver. To describe the pursuit component in the driver behavior, the neural network and optimal control have been modified to include preview and used as the driver steering control model in [7-9]. However, these models are more complex and application to control design is difficult.

The driver models reported in the literature are mostly developed to describe the average driver behavior. They are useful in the analyses and simulations, however, for the control design purposes a simplified model with the potential to be updated on-line is more desirable. For this purpose, several time series based driver steering control model have been reported [10-12]. These driver steering control models are expected to benefit the design of vehicle active safety systems. Specifically, in this study the variations in driver behavior is modeled as uncertainty driver model parameters, and a serial steering assist controller is to be designed using the adaptive control technique.

The adaptive control has been applied to vehicle active safety systems design, as reported in [13-15]. However, these papers describe the adaptive control with respect to vehicle parametric variations or the changes in the vehicle-road interaction, the driver variations are not considered. In [16,17], Chen et al. reported the development of a serial steering assist controller with respect to the driver parametric uncertainty using the model reference adaptive control (MRAC). The driver is modeled as an un-known constant, or slowly varying, linear system with delay. While these assumptions may be appropriate for the compensatory behavior during normal driving scenarios, the pursuit behavior and other human considerations may be more suitably modeled by more complex driver models, e.g. the
optimal preview model and the neural network model (see [7-9] for example). The consequence of this difference is that the MRAC designed based on the simplified driver models may not function properly when the driver pursues his goal (including trajectory tracking and driving comfort), and this may lead to a conflict situation between the driver and the controller. The research reported in this article aims to resolve this problem by implementing a decision making algorithm.

2 Problem Formulation

The objective of this research is the problem arises from the inadequacy of the driver model used in the MRAC design. The problem is first illustrated using computer simulations since human behavior is not repeatable. The simulations include a vehicle model, a pursuit-oriented driver model, and a MRAC design. The models and the MRAC design will be presented in this section and the difference between the driver objective and the control objective will be evident in simulations. A simple decision making algorithm (switcher) will be presented in section 3 to resolve this situation. Driving simulator experiments with human drivers will be conducted afterwards to verify the benefit of the decision making algorithm.

![Fig.1 Block diagram of the proposed control structure](image)

2.1 Vehicle model

To investigate vehicle lateral motions, a dynamics model for the vehicle is needed. In this study, a 3DOF model for the lateral, yaw, and roll motions is adopted [18]. The basic structure of this model is briefly summarized below:

\[
\begin{bmatrix}
Y_\delta \\
N_\delta \\
\delta_f
\end{bmatrix} =
\begin{bmatrix}
m & 0 & m_k h & 0 & 0 & 0 \\
0 & I_z & I_x & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\dot{\beta} \\
\dot{\phi} \\
\dot{\phi}_r \\
\end{bmatrix}
\]

(1)

and

\[
m = m_k + m_{NR}
\]

\[
Y_\beta = -(C_{af} + C_{aw})
\]

\[
Y_r = \frac{bC_{aw} - aC_{af}}{u}
\]

\[
Y_\phi = C_{aw} \frac{\partial \delta_r}{\partial \phi} + C_{rf} \frac{\partial r_f}{\partial \phi}
\]

\[
Y_\delta = C_{af}
\]

\[
N_\beta = bC_{aw} - aC_{af}
\]

\[
N_r = -\frac{a^2C_{af} + b^2C_{aw}}{u}
\]

\[
N_\phi = aC_{rf} \frac{\partial r_f}{\partial \phi} - bC_{aw} \frac{\partial \delta_r}{\partial \phi}
\]

\[
N_\delta = aC_{af}
\]

\[
L_\rho = -c_R
\]

\[
L_\phi = m_k g - k_R
\]

where \(\delta_f\) is the vehicle front steering angle, \(\beta\) is the side slip angle, \(r\) is the vehicle yaw rate, \(\phi\) and \(p\) are the vehicle roll angle and roll rate respectively. \(m\) is the total vehicle mass, including the sprung mass \((m_k)\) and the unsprung mass \((m_{NR})\). \(h\) is the distance form the roll axis to CG, \(a\) is distance from front to CG, \(b\) is distance from rear to CG, \(I_z\) is moment of inertia about z-axis, \(I_x\) is moment of inertia about x-axis, \(I_{xz}\) is product of inertia about x-z axes, \(K_R\) is effective suspension roll stiffness, \(c_R\) is effective suspension roll damping coefficient. The coordinate system is defined according to the SAE convention.

Equation (1) can be denoted as \(E \dot{x} + Fx = G \delta_f\), assuming constant vehicle speed, the state space model of the form \(x = Ax + B \delta_f\) is yielded, where \(A = -E^{-1}F\) and \(B = E^{-1}G\).
2.2 MRAC steering assist controller
A Variable Structure Model Reference Adaptive Control (VSMRAC) reported in [17] is employed in this study. The VSMRAC is designed to address the delay and parametric uncertainty in the driver model, and the Lyapunov Stability Theorem is applied to ensure the stability of the compensated system. The control structure of the VSMRAC is shown in Fig. 2.

\[ x(t) = Ax(t) + Bu(t - h) \]
\[ x(t_0) = x_0 \]
where \( x(t) \in \mathbb{R}^n \) is the state variable, \( u(t) \in \mathbb{R} \) is the input variable of the driver, in this study the input to the driver is assumed to be the vehicle lateral position error. \( h > 0 \) is a known input delay.

The control objective is to select \( u(t) \) such that \( e(t) \) converges to zero
\[ \lim_{t \to \infty} e(t) = \lim_{t \to \infty} (x(t) - x_m(t)) = 0 \]

let the control \( u(t) \) be of the form
\[ u(t) = c(t) \hat{x}_m(t + h | t) + \alpha(t)u_m(t) \]

where \( c(t) \in \mathbb{R}^{1 \times n} \) and \( \alpha(t) \in \mathbb{R} \) are the adaptation gains, \( \hat{x}_m(t + h | t) \) is the predicted state variables based on the reference model, defined in the following equations:
\[ \hat{z}(t) = A_m z(t) + B_m u_m(t) \]
\[ z(t_0) = x_m(t_0) \]
\[ x_m(t + h | t) = z(t) + e^{Ah} [x_m(t) - z(t - h)] \]
and \( z(t) \in \mathbb{R}^n \) is the predictor state variable. With the introductions of an auxiliary model and an appropriate sliding function, the update laws of the adaptation gains can be determined by examining the derivative of the Lyapunov function. Thus the stability of the designed VSMRAC can be assured. The details of the control derivations can be found in [17].

2.3 Driver model
Although in the design of the VSMRAC the driver is modeled as a simple linear system with delay, in the simulations the driver model is replaced by a pursuit oriented driver model. In [19] Ungoren and Peng reported a Model Predictive Control (MPC) based driver model and intended to use the model update to represent the driver adaptation. In this study this MPC based driver model is employed and with the adaptation part removed. As indicated in [19], the resulting model is in effect very similar to the optimal preview driver model presented by MacAdam in [8]. The structure of the MPC driver model is shown in Fig. 3. Effectively, the MPC driver model is minimizing a cost function based on a sliding function to account for the future trajectory tracking error and error rate. The future trajectory is predicted based on a linear vehicle model. Different weighting functions and coefficients can be tuned to represent different driver behavior. For the detailed control implementation and computations the interested readers are referred to [19] and [20] for references.
assumptions used to develop the VSMRAC are not valid and the closed-loop system may not be stable. For carefully tuned MPC driver model, the simulations results show that the VSMRAC still performs reasonably well during a continuous lane change type scenarios; this set of results are not included for space considerations. This implies that with this set of MPC driver model parameters, the difference between the MPC driver model and the assumed structure in VSMRAC is not significant. The robustness of the VSMRAC is capable to handle the discrepancy. However, Fig. 4 to Fig. 6 show the same simulations with another set of MPC driver model parameters. In this case, the MPC driver model corresponds to a driver trying to track his future goal which is significantly different than what is assumed in the VSMRAC. Therefore, it is evident that in the second cycle of the lane changes (near 700sec) the driver steering angle ($\delta$) starts to increase and the VSMRAC output ($\delta_c$) exhibits radical modifications. Consequently the closed-loop system becomes unstable.

3 The Decision Making Algorithm and Simulations

From the simulations it is also observed that the MPC driver model is very sensitive to the modifications from the steering assist controller. Once the VSMRAC changes the steering input to the vehicle, and thus the vehicle states, the MPC driver model senses the difference and generates the corresponding modification accordingly. It is also observed that the output from the VSMRAC ($\delta$) exhibits high frequency switching patterns which are common in variable structure control. The resulting driver output from the MPC driver model also exhibits slight high frequency modes. Naturally a human cannot operate at a high frequency switching mode due to physical limitations. In the future a low pass filter can be appended to the MPC driver model to yield a more realistic simulation.

In this article a simple decision making algorithm (switcher) is employed. The decision is based on the difference between the difference between the driver’s steering command and the controller’s modification. A threshold is tuned by trial-and-error to determine whether to deactivate the VSMRAC. That is, let $N = |\delta_c - \delta_d|$ be the difference, if

\[
\begin{align*}
|\delta_c - \delta_d| &= N \leq M \text{, then } \delta_S = \delta_c \\
|\delta_c - \delta_d| &= N > M \text{, then } \delta_S = \delta_d
\end{align*}
\]

where $M$ is the threshold, $\delta_d$ is the MPC driver model steering command, $\delta_c$ is the VSMRAC output, and $\delta_S$ is the steering input to the vehicle. Although extremely simple, this switcher successfully avoids...
the conflict situation observed in Fig. 4 - Fig. 6. The simulation results with the same MPC driver model and VSMRAC together with the switcher are presented in Fig. 7- Fig. 9. In this case the continuous lane changes are successfully achieved. However, it is evident that this switching function will let the MPC driver model overrides the VSMRAC whenever the amount of the “steering assist” exceeds the threshold. This approach is reasonable only when the MPC driver model is a performant steering controller. However, to model the driver performance degradation in the realistic driving, it is not reasonable to always assume that the driver is a high performance steering controller. Furthermore, the sudden switching between the on/off states may introduce undesirable disturbance to the human driver. Therefore, an on-line driver state assessment mechanism is being incorporated into the decision making algorithm, and a smoother transition between the activation/deactivation of the VSMRAC steering assist control using fuzzy logic is in progress.

4 Conclusion

In this research the conflict between a steering assist controller and the human driver is investigated using computer simulations. The steering assist controller is designed based on a simplified driver steering control model, and a variable-structure model reference adaptive control is proposed to address the delay and parametric uncertainty in the driver model. However, in the simulation the model predictive control based driver steering control model is employed to represent a different control strategy which is common in realistic human driving. Due to the violation of the assumptions made in the control derivations, the stability of the compensated system is not guaranteed and the simulations illustrate the conflict between the driver command and the control modifications. A simple decision making algorithm is programmed to switch off the controller whenever the difference between the driver command and the controller output is too large. Simulation results indicate that this switching successfully avoid the conflicting situation when the driver model is a reasonably well steering controller. An on-line driver state assessment algorithm is being incorporated to the decision making process, and a fuzzy logic based decision making algorithm will be developed to generate a smoother transition for the activation of the steering assist controller. Future work also includes the driving simulator experiments with the human driver to validate the designed steering assist system.

Acknowledgment:
This research is sponsored in part by the National Science Counsel in Taiwan under the contract number: NSC 96-2221-E-011 -131 -MY2. The financial support is greatly appreciated.
References: