A Haptic Lane-Keeping Assist System Based on Cooperative Status between Driver and Assist System

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Abstract: The present study proposes a method to estimate the cooperative relationship between human and machine in the haptic guidance control of a steering-assist system. In addition, a gain-tuning control method based on detection of cooperative status is proposed. The proposed method is applied to a lane-keeping assist control that enables the driver to change lanes smoothly. Finally, its effectiveness is demonstrated by experiments using a driving simulator.

Keywords: Haptic Guidance, Haptic shared control, Lane-keeping assist, Lane-changing, Steering

1. INTRODUCTION

In many advanced driver-assistance systems, haptic guidance or haptic shared control has drawn much attention as a human-machine interface because it enables the human operator to interact and communicate continuously with the assist system [1].

The smooth transition of control authority is a key issue for an effective human automated system [2]. The continuous physical interaction of haptic shared control should result in a smooth transfer of automation authority between the human and the automated system. In the automotive safety field, haptic pedals [3] and haptic steering controls [4] [5] have been developed. Existing studies utilized environmental variables for authority transfer. Thus, the driver could not intentionally transfer authority in a given situation.

The present study proposes a method of estimating the cooperative relationship between the driver and automated system in the context of haptic shared control of steering. The pseudo-power and pseudo-work exerted on the vehicle motion by the driver's steering or control actuator's input are utilized for analyzing the cooperative relationship between these two agents. In addition, a gain-tuning control method is proposed based on the detected cooperation status.

2. COOPERATIVE STATES BETWEEN HUMAN AND CONTROL SYSTEM

Figure 1 presents a block diagram of the overall haptic steering system. Two agents, the human driver and the assist system, cooperatively operate a single plant, the steering mechanism, in order to achieve appropriate vehicle motion. In the figure, τ_{sys} is the torque generated by the assist system motor, τ_{dr} is the torque exerted on the steering wheel by the driver's hand, and θ_{str} is the steering wheel angle.

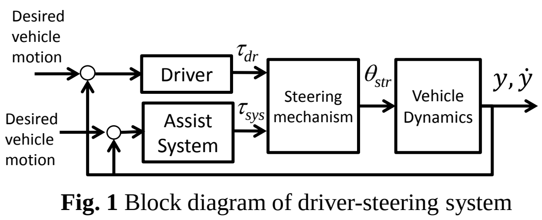

Fig. 1 Block diagram of driver-steering system

The effect of the two agents' steering input on vehicle motion is investigated. This study focuses specifically on lateral control of the vehicle. Pseudo-power pairs p_{dr} and p_{sys} are defined in Eqs. (1) and (2) as indices of the influence of each agent's steering input on vehicle lateral motion.

$$p_{dr} \triangleq \tau_{dr}\dot{y} \tag{1}$$
$$p_{sys} \triangleq \tau_{sys}\dot{y} \tag{2}$$

where $\dot{y}$ denotes the lateral velocity of the vehicle.

The pseudo-work W_{dr} and W_{sys} exerted on the steering system by the driver and that exerted by the assist system are given below.

$$W_{dr} \triangleq \frac{1}{\Delta T}\int_{t-\Delta T}^{t} p_{dr}(\tau)d\tau = \frac{1}{\Delta T}\int_{t-\Delta T}^{t} \tau_{dr}(\tau)\dot{y}(\tau)d\tau \tag{3}$$
$$W_{sys} \triangleq \frac{1}{\Delta T}\int_{t-\Delta T}^{t} p_{sys}(\tau)d\tau = \frac{1}{\Delta T}\int_{t-\Delta T}^{t} \tau_{sys}(\tau)\dot{y}(\tau)d\tau \tag{4}$$

Here, ΔT denotes a time window for the work calculation.

These two work values are used to define the cooperative states between the human driver and the control system as follows (Table 1).

State I: Driver-led cooperative state
The driver holds the initiative for vehicle operation with the assist control in a cooperative manner.

State II: Driver-led uncooperative state
The driver holds the initiative for steering control while the assist control attempts to operate the steering against the driver. The driver may attempt to override the system.

State III: System-led
This state includes the following two sub-states.
III-a System-guided cooperative state
The human driver is guided by the assist control.
III-b System-led uncooperative state
The human driver resists the assist control.
It should be noted that it is difficult to distinguish these two sub-states because it is difficult to measure the equivalent torque generated by muscle force.

State IV: Passive
This state occurs for a short time because of inertia or because SAT is dominant. Disturbance torque from the road environment etc. also may lead this status.

Table 1 Cooperative status between human and control system

		w_{dr}	
		$\leq -\gamma^2$	$\geq \gamma^2$
w_{sys}	$\geq \beta^2$	[State III] System-led	[State I] Driver-led cooperative
	$\leq -\beta^2$	[State IV] Passive	[State II] Driver-led uncooperative

β and γ are offset values to waive judgment in a very small work region.

3. DESIGN OF A LANE-KEEPING ASSIST SYSTEM BASED ON COOPERATIVE STATE ESTIMATION

The torque of the haptic guidance control for lane-keeping assist is defined in Eq. (5) based on a preview driver model.

$$\tau_{sys}(s) = \frac{K(W_{sys})}{Ts+1}\left(L\varphi(s) + e(s)\right) \tag{5}$$

Here, L is the preview distance, ϕ is the heading (yaw) angle in the driving lane, and e is the lateral error in the lane. Scalar $K(w_{sys})$ is the gain function, and T is the time constant.

When the human driver decides to change lanes, the cooperative status becomes state II (driver-led uncooperative) (Table 1). In the controller, gain $K(w_{sys})$ in Eq. (5) is defined as

$$K(W_{sys}) \triangleq \begin{cases} \frac{K_0}{1+exp(-aW_{sys}+b)} & \text{(StateII)} \\ K_0 & \text{(else)} \end{cases} \tag{6}$$

where $a = 10$ and $b = 0.4$. This control method decreases the gain according to the effort of the system w_{sys} to oppose the driver's action in state II. The sigmoid function in Eq. (6) realizes smooth shifting of the gain change.

The present paper proposes a method to detect the driver's intent to change lanes using the estimated cooperative state. In state II (driver-led uncooperative), gain is decreased with our proposed method as in Eq. (6). The present paper defines lane-change intent using the gain K:

$$K(W_{sys}) \leq \delta^2 \tag{7}$$

where the constant $\delta^2 = 0.3$ is determined by trial and error.

When the driver's intent to change lanes is detected by Eq. (8), the target lane center y_d is changed:

$$y_d = \begin{cases} y_{current} - \Delta y & (\dot{y} \geq \epsilon^2) \\ y_{current} + \Delta y & (\dot{y} \leq -\epsilon^2) \\ y_{current} & (else) \end{cases} \tag{8}$$

where Δy is the lane width. Scalar ϵ^2 is introduced to set a dead zone.

Note that a smooth lane change can be expected even though this method suddenly changes the target lane because gain K gradually decreases during the lane change and then gradually increases in the final part of the lane change, according to Eq. (6).

4. EXPERIMENTS

4.1 Method

A fixed-base driving simulator was used for the experiments. The three levels in the condition of the assist system were no-system, gain-tuned, and time-to-line crossing (TLC) [6].

No-system: No assist system was installed in the vehicle.

Gain-tuned: The gain-tuned control method (i.e., the proposed system) was activated.

TLC: For comparison with the gain-tuned condition. When TLC < 1.5s, the system switches from the target lane to the next one.

There were two scenarios in the experiments. If the host vehicle (HV) approaches the lead vehicle (LV), the participant has to change lanes from right to left quickly after lane-changing from left to right for overtaking. There is one LV in scenario A. There are multiple LVs in scenario B, which requires spending a long time in the right lane while overtaking.

Performance and activity are evaluated for each condition based on the lateral error and steering wheel reversal rate (SRR).

4.2 Results

Figure 2 presents an example of the gain-tuning system performance and plots the responses of the HV and other variables in the gain-tuned condition in scenarios A and B. Changes in cooperative status were detected before and after lane changing; then the gain decreased appropriately during lane changing. The target lane center was switched after the gain decreased in both scenarios.

Figure 3 presents the lateral error. In scenario A, the mean of the lateral errors was 0.346m (SD 0.084) for no-system, 0.216m (SD 0.129) for the gain-tuned system, and 0.114m (SD 0.092) for TLC. A repeated-measure ANOVA with a system factor indicated that the main effect of the system condition was significant ($F(2,18) = 11.5$, $p = 0.001$). A post-hoc test using the Bonferroni method indicated a marginally significant difference between no-system and the gain-tuned system ($p = 0.096$), a significant difference between no-system and TLC ($p = 0.001$), and no significant between gain-tuned and TLC ($p = 0.280$). In scenario B, the mean of the lateral errors was 0.334m (SD 0.206) for no-system, 0.188m (SD 0.150) for the gain-tuned system, and 0.194m (SD 0.086) for TLC. A repeated-measure ANOVA with a system factor indicated that main effect of the system condition was significant ($F(2,58) = 14.8$, $p = 0.000$). A post-hoc test using the Bonferroni method indicated a significant difference between no-system and the gain-tuned system ($p = 0.000$), a significant difference between no-system and TLC ($p = 0.002$), and no significant gain-tuned and TLC ($p = 1.000$). This result demonstrates that both assist systems significantly decreased the lateral error in the lane-keeping phase.

Figure 4 presents the mean of the SRR values during overtaking in scenario A and lane-changing in scenario B. In scenario A, the values were 1.077/s (SD 0.427) for no-system, 0.866/s (SD 0.325) for the gain-tuned system, and 0.950/s (SD 0.287) for TLC. A repeated-measure ANOVA with a system factor revealed that the main effect of the system condition was marginally significant ($F(2,28) = 3.215$, $p = 0.055$). A post-hoc test using the Bonferroni method revealed no significant differences between no-system and the gain-tuned system ($p = 0.121$), between no-system and TLC ($p = 0.630$), and between the gain-tuned system and TLC ($p = 0.443$). However, the results indicated that the mean SRR was the smallest with the gain-tuned system. In scenario B, the values were 0.601/s (SD 0.270) for no-system, 0.529 (SD 0.261) for the gain-tuned system, and 0.502/s (SD 0.261) for TLC. A repeated-measure ANOVA with a system factor revealed that the main effect of the system condition was significant ($F(2,118) = 3.309$, $p = 0.040$). A post-hoc test using the Bonferroni method revealed no significant differences between no-system and gain-tuned system ($p = 0.180$), and between gain-tuned and TLC ($P = 1.000$). Marginally significant was found between no-system and TLC ($p = 0.071$). These results implied that the proposed system might achieve smoother lane changing in the situation that requires quicker steering operation, such as scenario A.

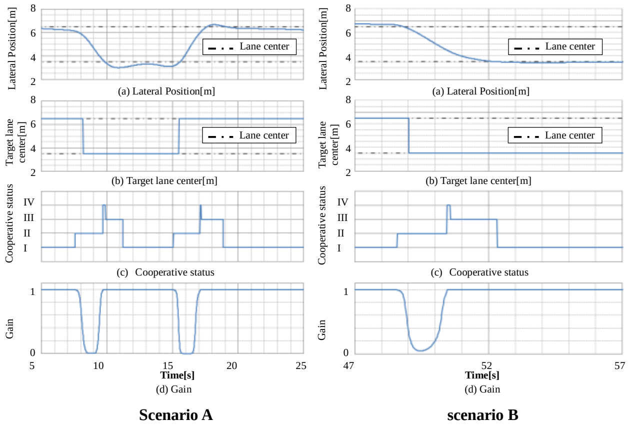

Fig. 2 Plots of the gain-tuning control system responses

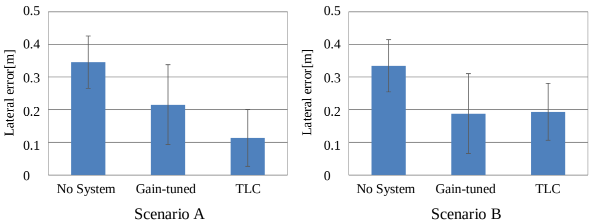

Fig. 3 Lateral error

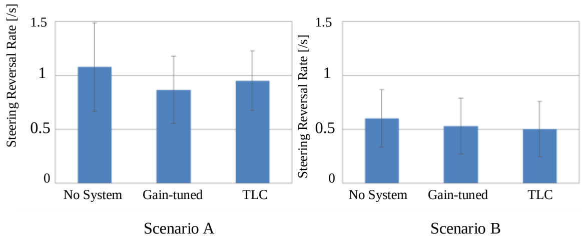

Fig. 4 Steering reversal rate

5. CONCLUSION

A new method of estimating the cooperative relationship between a driver and an assist system in the haptic-guidance control of a steering-assist system was proposed. The method is based on the pseudo-work exerted on vehicle motion by the steering inputs of a driver or a control actuator. A gain-tuning control method was proposed for lane-keeping assist control in order to enable the driver to change lanes smoothly. Driving simulator experiments indicated that the proposed system realized smooth lane changing even with lane keeping assist system. In addition, the results implies that the proposed system might achieve the smaller SRR or smoother steering operation in lane changing scenarios that require relatively quicker steering operation. In addition, the proposed system and the TLC system significantly improved lane-keeping performance in straight driving with haptic guidance.

In a future study, the proposed method will be applied to other situations and adapted to other assist systems. In addition, disturbances will be considered in the driving simulator experiments.

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