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Control Transferring between Automated and Manual Driving using Shared Control

Takahiro Saito
Ritsumeikan University
Kusatsu, Shiga, 525-8577, Japan
is0215vv@ed.ritsumei.ac.jp

Takahiro Wada
Ritsumeikan University
Kusatsu, Shiga, 525-8577, Japan
twada@fc.ritsumeikan.ac.jp

Kodei Sonoda
Ritsumeikan University
Kusatsu, Shiga, 525-8577, Japan
koheisonoda@gmail.com

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Abstract

In this research, we propose a method to connect automated and manual driving by haptic shared control (HSC) to achieve shared authority mode and authority transfer method in this mode. Driving simulator experiments showed that the smoother steering behaviors were observed with the proposed method even when rapid steering was required just after taking the control by human drivers.

Author Keywords

Authority sharing; Authority transfer; Automated driving; Driving automation; Haptic shared control.

CCS Concepts

Human-centered computing: [Interaction design]: Interaction design process and methods, User interface design & Interface design prototyping

Introduction

In level 2 and 3 of automated driving (SAE [1]), drivers may be required to take charge as backup for the driving tasks, and there are cases when it is necessary to transfer authority from automated to manual driving. Therefore, much research has been conducted on human factors in automated driving.

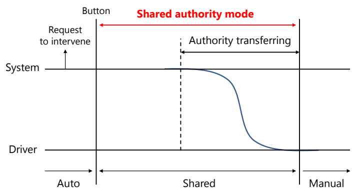

Figure 1: Conceptual diagram of authority transfer method via shared authority mode

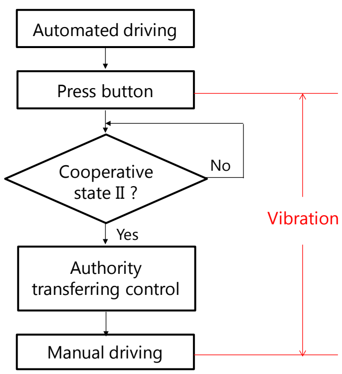

Figure 2: Flow of proposed control method

For example, many studies have been conducted on a driver's reaction during automated driving when an automated driving system (ADS) issues a request to intervene (RTI) [2], [3]. There are also many studies on situation awareness during automated driving for improving the control performance of human driver during and after taking over the control [4], [5].

On the other hand, in most of the studies, the control authority was immediately transferred by button pressing, steering, and pedal operation. However, these works pointed out that steering behavior may become unstable during and just after the transfer, when the driver needs to steer quickly [6], [7].

Therefore, we propose a method to connect automated and manual driving by haptic shared control (HSC) to achieve an authority sharing method and an authority transfer method. Driving simulator experiments were conducted assuming driver-initiated authority transfer to confirm the effectiveness of the proposed method.

Control authority sharing / transferring method

A. Transition to shared authority mode - Overview

We propose a method for authority transfer via a shared authority mode. Fig.1 shows the conceptual diagram of the proposed method. Suppose that the vehicle is being driven in the automated driving mode. There are cases where the authority transfer is initiated by both, an ADS and a human driver. In both cases, when the driver pushes a button, the driving mode is transferred to the shared authority mode, in which the vehicle is supposed to be operated by the ADS and the human driver cooperatively using HSC [8]. In this mode, when the driver's steering intention is detected, control authority is transferred gradually to the driver according to the driver's steering activity. By using this method, we aim for smooth authority transferring.

B. Implementation method

Fig.2 shows a flow of the proposed control method. Assume that the driver drives in the automated driving mode, which is capable of steering control by Lane Keeping Assistance System (LKAS) and accelerator control. The driver presses the button attached to the steering wheel. At this time, the mode transfers to the shared authority mode, and the vibration motor on the wrist of the driver induces vibration. At the same time, the system starts to estimate the driver's steering intention. That estimation uses judgment of cooperative state that is based on the relationship between torques exerted by the driver and the ADS, which was proposed in [9]. When detecting the driver's steering intention, steering authority is transferred gradually to the driver according to gain-tuning method.

C. Control method of LKAS

A simple PD feedback control of the steering angle was used for the LKAS, as shown in Eq. (1). τ_{das} denotes the system torque. $\theta(t)$ and $\theta_d(t)$ are the current and desired steering wheel angles, respectively. K_p is the proportional gain $(= 6.0)$, K_d is the differential gain $(= 0.003)$. $\theta_d(t)$ is determined by a second-order preview driver model to reduce the lateral error of the vehicle from its desired position.

$$\tau_{das} = K_p\big(\theta_d(t) - \theta(t)\big) - K_d\dot{\theta}(t) \qquad (1)$$

In the proposed method, the driver's steering intention which conflicts with the ADS's intentions is detected as

Figure 3: Driving simulator

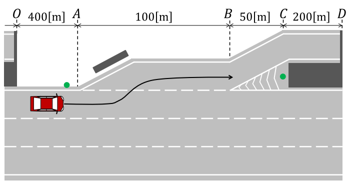

Figure 4: Experimental scenario

Group	$G = 0.006$	$G = 0.014$
Sex	male: 11 female: 1	male: 12 female: 0
Age	mean: 21.5 SD: 0.90	mean: 22.3 SD: 0.98
Driving experience [year]	mean: 2.10 SD: 0.84	mean: 2.67 SD: 0.97
Driving frequency [times/year]	mean: 33.4 SD: 51.2	mean: 32.1 SD: 58.0

Table 1: Attributes of participants

state II: driver-led uncooperative state. If such a state is detected through the driver’s steering intention, the accelerator control is released and steering authority is transferred according to the gain–tuning method.

D. Gain-tuning method

Gain-tuning method is shown by Eq. (2). When state II is detected through the driver’s steering, K_p gain decreases while pseudo-work W_{drv} is positive. Using this method, smooth authority transfer from automated driving by LKAS to manual driving by driver is achieved Further, amplitude of the vibration exerted to the wrists is changed along with K_p gain. On account of the amplitude of the vibration, it is expected that the driver can understand the progress of the authority transfer.

$$K_p(t_i) = K_p(t_0) - G \sum_{j=1}^{i} \mathrm{sgn}\left(K_p(t_j)\right) \left|K_p(t_j)\right|^p f(W_{drv}(t_j)) \quad (2)$$

$$f(x) := \begin{cases} x & (x \geq 0) \\ 0 & (x < 0) \end{cases} \quad (3)$$

Experiment

A stationary driving simulator was used for this experiment (Fig.3).

A. Method

1) Scenario

We assume a situation where a driver exits a highway due to a change in the intention change during automated driving, as shown in Fig.4. The driver steers to the left to over-ride the ADS, and exits the highway.

2) Condition

Experimental factors are G gain condition of gain-tuning method (a between-subject factor), and method condition (a within-subject factor).

The gain condition G has two levels ($G = 0.006, 0.014$). The method condition has four levels (manual driving, no gain-tuning, gain-tuning, gain-tuning+vibration). In the manual driving condition, the participant drives manually. In the no gain-tuning condition, K_p gain is suddenly dropped to zero without using Eq. (2). In the gain-tuning condition, K_p gain is tuned using the proposed gain-tuning method in Eq. (2). In the gain-tuning+vibration condition, the K_p gain is tuned using the proposed gain-tuning method in Eq. (2) same as the gain-tuning condition, and a vibration is given to the wrist bands of the driver simultaneously.

3) Procedure

First, the participant underwent five manual driving trials to get used to the driving simulator. Then, we moved on to the main experiment.

All participants undertook the manual driving condition first, then, followed by the automated driving conditions (no gain-tuning, gain-tuning, gain-tuning+ vibration). The order of the automated driving conditions was randomized. The session of manual driving condition consisted of one practice and two measurement trials. The session of the automated driving condition constituted of two practice and measurement trials.

In the automated driving condition, the participant places his/her hands on the knees and gazes at the road during driving. An interchange appears in front of the driver, and a beep sound is issued for a second when the vehicle reaches a point 380m before point A. After listening to this beep, the participant presses the button. Then, the participant exits the highway using the steering wheel and pedals.

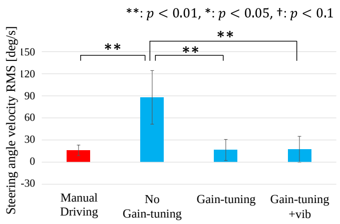

Figure 5: Mean RMS values of the steering angular velocity. The error bars show the standard deviation.

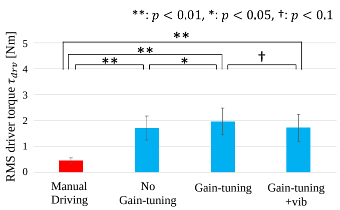

Figure 6: Mean RMS values of the driver torque at $G = 0.014$. The error bars show the standard deviation

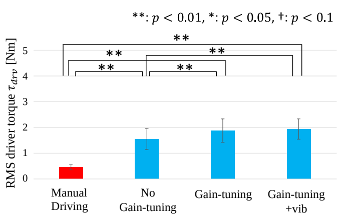

Figure 7: Mean RMS values of the driver torque at $G = 0.006$. The error bars show the standard deviation.

4) Participants

Subjects participating in this experiment were 24 drivers (23 males, 1 female) aged 20-24 year, who possessed a driver’s license. All participants gave written informed consent. Twelve participants were assigned for each gain condition (Table 1).

B. Result

1) Steering angular velocity

As an index of steering stability, the root mean square (RMS) value of the steering angular velocity was used (Fig.5). Two-way ANOVA showed significance of main effects of methods ($F(3{,}138) = 163.6,\ p = .000$) and gain factors ($F(1{,}46) = 5.772,\ p = .020$), but not in case of their interactions ($F(3{,}138) = 1.76,\ p = .184$).

Post-hoc test by the Bonferroni method for the method factor showed that the steering angular velocity without gain-tuning method was significantly larger than that with manual driving($p = .000$), gain-tuning($p = .000$), and gain-tuning+vibration ($p = .000$). Further, there were no differences between the manual driving method and the gain-tuning ($p = 1.000$) or gain-tuning+ vibration ($p = 1.000$).

2) Driver torque

Fig.6 shows the average RMS values of the driver torque at $G = 0.014$ as an index of driver workload. The error bars show the standard deviation. Two-way ANOVA showed significance of main effects of the method factor($F(3{,}138) = 241.9, p = .000$) and interactions ($F(3{,}138) = 3.491,\ p = .017$), but not of the gain factor ($F(1{,}46) = .013,\ p = .911$).

One-way ANOVA at $G = .006$ showed the significance of the simple main effect of the method factor ($F(3{,}69) = 141.557,\ p = .000$). One-way ANOVA at $G = 0.014$ also showed the significance of the simple main effect of the method factor ($F(3{,}69) = 107.939,\ p = .000$). Post-hoc test by Bonferroni correction for the method factor at $G = 0.014$ condition showed that the torque in the manual driving was significantly smaller than that with no gain-tuning ($p = .000$), gain-tuning ($p = .000$), and gain-tuning+vibration ($p = .000$). In addition, torque with gain-tuning condition was significantly larger than that with no gain-tuning condition ($p = .033$). However, the difference of the gain-tuning and gain-tuning+ vibration conditions was marginally significant ($p = .091$). Results at $G = 0.006$ show similar tendency (Fig.7).

C. Conclusion

Transfer from automated driving to manual driving showed that the steering stability (Fig.5) reduced and driver workload (Fig.6) increased as compared to manual driving. The instability of the steering behavior was improved by introducing gain-tuning method either with or without vibration. The results from the high gain condition ($G = 0.014$) suggests that the driver workload decreased by adding vibration, which was comparable with the no gain-tuning method.

These results suggest that our proposed authority transfer method from automated to manual driving via the shared authority mode has improved the stability of the steering behavior in driver-initiated transfer.

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