Haptic Device for Vehicular Instrument Controls Using Electrorheological Fluids

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Abstract. This paper presents control performances of an electrorheological (ER) fluid-based multifunctional haptic device which is applicable to realization of in-vehicle comfort functions. By combining the functions into a single device, the proposed haptic device can transmit various reflection forces for each comfort function to a driver without requiring the driver’s visual attention. As a multifunctional haptic device, a single ER knob, which is capable of both rotary and push motions, is designed and manufactured. In-vehicle comfort functions are constructed in virtual environment which makes the functions to communicate with the haptic device. Subsequently, a feed-forward controller using torque/force maps is formulated for the force tracking control. Control performances such as reflection force of the haptic device are experimentally evaluated via the torque/force map-based feed-forward controller.

1. Introduction
In recent years, vehicles provide various comfort functions to a driver such as audio, window, road and traffic information, air conditioner, etc. The growing number of comfort functions requires for several different control devices to be installed in dashboard as secondary controls of vehicles. These various secondary control devices can decrease the attention of a vehicle driver, and which is one of the most common causes of traffic accidents [1]. However, by combining the in-vehicle functions, information can be transmitted without requiring a driver’s visual attention. Therefore, several research works have been performed on driver-vehicle interaction. Among them, haptic devices with the sense of touch have been actively researched to consolidate the in-vehicle functions into a single device [1-4]. The traditional consolidating control device using motors has difficulty in realizing precise tactile feeling and stopping force [1]. Therefore, some researches have been recently made by adopting smart materials such as electrorheological (ER) fluids whose advantages are fast response, simple mechanism, continuous force control and high stability [2-4]. However, these research works are still limited to rotary motion although the in-vehicle comfort functions need not only rotary motion but also push motion. Furthermore, advanced haptic device should be evaluated in feasible situation such as integrated haptic architecture of driver and vehicle. Consequently, the main contribution of the
present work is to propose the ER fluid-based haptic knob and to evaluate its control performances within integrated haptic architecture of driver and in-vehicle functions.

2. ER fluid-based haptic knob
In this work, in order to achieve both rotary motion and push motion within a single device, a cylindrical type mechanism is devised. Figure 1 shows a schematic configuration of the proposed multifunctional haptic knob. The knob is composed of upper disk electrode, lower disk electrode and reaction spring. The between upper and lower disk is a specific gap fully filled with ER fluid. The ER fluid has been employed as a controllable fluid. When a electric field of $E$ is applied to the ER fluid, the shear stress ($\tau$) can be expressed by

$$
\tau = \tau_s(E) + \eta \dot{\gamma}, \quad \tau_s(E) = \alpha E^\beta 
$$

where $\eta$ is the dynamic viscosity, $\gamma$ is the shear rate, and $\tau_s(E)$ is the dynamic yield stress of the ER fluid. $\alpha$ and $\beta$ are the intrinsic values of the ER fluid. $E$ is the input voltage which is the control input for the ER haptic knob.

Among several operation modes of an ER fluid-based device, in this work, the shear and flow modes are significantly developed for the rotary and push motions, respectively. Therefore, the torque($T$/force($F$) model is mathematically described for each motion as follows:

$$
T = \sum_{i=1}^{3} \left[ 2\pi R_i^2 h + \pi \left( R_i^2 - (R_i - r)^2 \right) \frac{R_i + (R_i - r)}{2} \right] \alpha(E)^\beta \text{sgn}(-\dot{\theta}) 
+ \sum_{i=1}^{3} \left[ 2\pi R_i^3 \eta \dot{\theta} + \eta \frac{R_i}{h} \dot{\theta} \pi \left( R_i^2 - (R_i - r)^2 \right) \frac{R_i + (R_i - r)}{2} \right] + C_{cf} \text{sgn}(-\dot{\theta}) + C_{cf} \dot{\theta} 
$$

$$
F = 3 \frac{c(h + t)}{g} (A_p - A_r) \alpha(E)^\beta \text{sgn}(-\dot{x}) + \sum_{i=1}^{3} \frac{12 \eta (h + t)}{w_i g^3} (A_p - A_r)^2 \dot{x} + k x + D_{cf} \text{sgn}(-\dot{x}) + D_{cf} \dot{x}
$$

where $\dot{\theta}$ is the rotational velocity of the knob in rotary motion. $g$ is the gap size. $c$ is a coefficient which depends on flow velocity profile. $w$ is the electrode width. $x$ and $\dot{x}$ are the displacement and velocity of the knob in push motion. $k$ is a spring constant. $C_{cf}$ and $D_{cf}$ are the coefficient of Coulomb friction for rotary mode and push mode, respectively. $C_{cf}$ and $D_{cf}$ are the coefficient of viscous friction for rotary mode and push mode, respectively. $A_d$ and $A_r$ are the disk area and the rod area, respectively. $\text{sgn}(\cdot)$ is a signum function. The other geometric parameters are shown in Figure 2 and the proposed ER haptic device is then manufactured and shown in Figure 3.
3. Haptic architecture with virtual environment

In this work, a virtual environment is established by considering control operations of various in-vehicle functions within a real passenger vehicle such as menu shifting, window opening, etc. Figure 4 shows the established virtual environment which has the data display windows for input and output measurements, and four in-vehicle function menus: heater/air conditioner, entertainment, window and seat. The proposed haptic architecture is composed of the manufactured ER haptic knob, virtual in-vehicle functions, torque/force reflection algorithm and driver as shown in Figure 5. The haptic knob then interacts with the virtual environment of in-vehicle functions. When the driver operates the ER knob, the position information is transferred to the virtual environment. Then the torque/force map to generate the desired torque and force for the ER knob is selected according to the corresponding event such as menu shift event, window opening event, etc.

In order to achieve the desired torque and force at the ER knob, a feed-forward controller based on inverse model of the torque/force model in Equation (2) is adopted in this work.

\[ V_T = g \left( \sum_{i=1}^{n} \frac{2\pi R_i^2 h + \pi (R_i^2 - (R_i - t)^2)}{2} \alpha \text{sgn}(\theta) \right)^{\frac{1}{\beta}}, V_F = g \left( \frac{\tilde{F}}{3 \frac{c(h+t)}{g} (A_p - A_e) \alpha \text{sgn}(\xi)} \right)^{\frac{1}{\beta}} \]  

(3)

where \( V_T \) and \( V_F \) are the input voltages for rotary motion and push motion, respectively, as control inputs. \( \tilde{T} \) and \( \tilde{F} \) are calculated by eliminating fluid viscous term and friction term from the desired torque and force trajectories which are obtained by the torque/force map upon the measured position information.

4. Results and discussions

Figure 6 shows the experimental configuration to evaluate control performance of the proposed multifunctional haptic device in the virtual environment realized by LabVIEW. The knob connected to the disk is operated by a person who is a vehicle driver. When he or she operates the ER knob, the
position information is obtained from the encoder and LVDT. A specific in-vehicle function in the virtual environment is then visually operated and generates the desired torque or force by the map upon the position information. The feed-forward controller given by Equation (3) is then activated for the ER knob to reflect the desired torque or force to a driver. In this work, the torque or force is measured by a 6 axes force/torque transducer (ATI, Nano25). Figure 7 shows torque tracking control results for the event of menu shifting in rotary motion. A person rotates the knob from 0 deg to 180 deg, and then rotates back to original position. In this work, the event of menu shifting occurs at 45 deg, 90 deg and 135 deg, which are the shifting positions from heater/air conditioner to entertainment, from entertainment to window, and from window to seat, respectively. And the stopping torque is applied at 0 deg and 180 deg. As clearly observed from the results, the desired torque from virtual environment is favourably followed by the feed-forward controller. Figure 8 shows force tracking control results for the event of window opening in push motion. According to the displacement of knob, the window opening position was adjusted from 0mm to 20mm and the corresponding force from 0N to 80N was reflected to a driver. From the results, it is observed that the desired force is well generated by the virtual in-vehicle function and achieved from the ER knob by activating the controller.

5. Conclusion
In this work, a new type of electrorheological (ER) fluid-based haptic knob was proposed as a multifunctional haptic device and its control performances were evaluated in virtual environment of in-vehicle comfort functions. The ER haptic knob has been innovated with actuation mechanism capable of both rotary and push motions with a single knob. The manufactured knob was interacted with the virtual environment, in which various events of in-vehicle functions including menu shifting and window opening were constructed by LabVIEW. Subsequently, it has been demonstrated that the desired torque and force trajectories were well achieved for both rotary and push motions via the feed-forward controller based on inverse model. The results presented in this work are quite satisfactory justifying that the proposed haptic device is one of potential candidates which can be effectively utilized in vehicular comfort functions.

References
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