Original Article

Psychological response to moving distance and velocity of haptic device that evokes inertia and detent sensations

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Abstract

Purpose: In this study, a "haptic device" that, when a finger (or thumb) is slid on its touchpad, replicates the sliding movement in the direction slid by the finger pulp at a set distance and velocity, with mechanical force feedback, was attached to the steering wheel of a driving simulator (DS) and used to experimentally derive the characteristics of the inertia and detent sensations perceived by the driver.

Test Subjects and Method: Ten healthy university students, ages in the range 18-22 years, and each possessing a standard motor vehicle driver's license, participated as subjects. A DS environment was configured with the haptic device mounted on a steering wheel. Haptic stimuli under 25 conditions, comprising combinations of five stages of sliding distances and five stages of sliding velocities, were presented to the subjects. As each subject simulated driving on a completely straight DS road, he/she performed operations with his/her right thumb on the pad, and standard stimuli and comparative stimuli were respectively presented. The magnitude estimation method was used to measure the psychological quantity indicating the extent of the inertia and detent sensations perceived at the thumb pulp for each pad manipulation exercise above.

Conclusions: All test subjects perceived inertia and detent sensations from the haptic device. However, velocity changes at maximum travel distances of 0.8 mm and under were not perceivable. Under all other conditions, independent increases of the maximum travel distance and velocity, respectively, caused significant increases in the psychological sensations of inertia and detent. As regards the relationships between maximum travel distance and velocity and the psychological sensations of inertia and detent, a "power exponent" was obtained that can serve as fundamental data for (future) designs.

Keywords: Haptic interface, Human-machine interaction, ITS, Car informatics, Human factors

Introduction

The rapid development in recent years of intelligent transport systems (ITS) has resulted in increased concern over driver distraction, partially owing to more interactions between the driver and information devices installed inside the vehicle. The EU-US bilateral ITS Technical Task Force provided this definition for driver distraction in 2010: "Driver distraction is the diversion of attention from activities critical to safe driving to a competing activity." As a countermeasure, multimodal user interfaces (UI) that utilize information from all five senses are considered to be more effective in remedying this situation than distraction-reduction approaches that are limited to a single sensory channel.

An example of such a countermeasure is the graphical user interface (GUI) depicted in Figure 1, in which the user rotates ("rolls") a drum-like object to select a desired menu item. This is an effective way to present one of multiple selection options within a limited display area. These kinds of GUIs have been developed in recent years and are now widely employed in in-vehicle mounted information device display forms. In the figure, a vertical (up-down) sliding motion along a touch sensor is used to perform control-related manipulations.

Tactile "sliding" inputs have become common concomitant with the proliferation of smartphones, notebook computers, etc. In designs that combine input-output UIs of this type, feedback to the pulp (ball, cushion) of the manipulating finger or fingers can enhance the sensation that one is manipulating a natural object. In the case of Figure 1, there is a sensation of inertia when one "moves" ("slides") the rotating drum and, when a selection item enters the focus (the red outlined portion of the GUI), there is feedback to the finger pulp to give sensations of inertia and detent, a kind of "clicking in" sensation such as that received when a turned rotary switch falls and locks into a (prepared) gap or indentation. This kind of force feedback enhances the sense that one has actually manipulated the GUI, and this in turn is thought to result in reduced distraction.

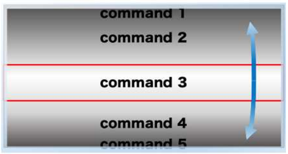

Figure 1. Example of rotating drum-type menu GUI

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In virtual reality (VR) research, the "sense of touch" is divided into "tactile" and "haptic" aspects (Makino, 2010). Tactile sensations are due to mechanical receptor cells distributed within subcutaneous tissue, and are divided into pressure, heat, and pain sensations (Takasaki, 2012). On the other hand, haptic sensations are due to receptors in muscles and joints that detect, deep within the body, force and resistance resulting from body movements.

Most of the research involving tactile manifestations in human-machine interfaces (HMI) for motor vehicle-equipped information devices involves driving (driver) support utilizing motor vibrations. One example is a "tactile belt" worn by a driver that contains eight (8) vibration motors that, when the belt is worn, are set at different parts of the driver's trunk. Right and left "turn-by-turn" information is presented to the driver using vibrations called "vibrotactile" signals (Asif, 2010). However, although turn direction is communicated via the vibrating motors, no detailed feedback similar to that presented in the GUI manipulations above is received.

The personal computer (PC) environment is another domain of research on feedback presentation via GUI manipulations. The research conducted by Tanaka (1997), in which a finger-tracing movement was realized by transmission, via a link arm, of joystick movements to a mouse, is one such example. However, this, too, involved the presentation of texture information using vibrations only, without the possibility of haptic feedback.

To resolve the issues identified above, efforts have been made to create the illusion of haptic sensations ("pseudo-haptic" sensations) via presentation of vibration stimuli using a type of multimodal effect in which vision and touch interactions are combined (Tsuchiya, 2010; Konyo, 2012). However, in this case, because the illusion of pseudo-haptic sensation is from visual information, any interference of the visual information can result in loss of the illusion. This makes application difficult in a vehicle-driving environment, in which the driver cannot always concentrate his/her vision on the equipped information device monitor. Thus, expression of the sensations of inertia and detent using tactile devices is currently technologically difficult.

The "PHANTOM" devices by 3D Systems (3D Systems, 2016) are well-known as means of presenting virtual haptic sensations. With these devices, motor torque is transmitted ("translated") to an arm having a linkage mechanism, thereby presenting a reactive force to a finger in contact with the other end of the arm. This method, however, requires a relatively large and complex apparatus, making mounting within a vehicle’s interior difficult. Glove-type devices, as exemplified by "CyberGrasp" (CyberGrove Systems, 2016), are also available. CyberGrasp employs a method whereby reactive force is presented during each finger bend in accordance with the quantity of wrapped wire connected to each finger. However, the user has to wear mechanical gloves with this method, and its highly invasive nature makes it impractical for driving.

This paper proposes a thin haptic device with operations (manipulations) on a rotating drum-type menu GUI such as that described above. When finger movements are made with a finger pulp in up-down (y-axis) directions on a touchpad installed on a vehicle's steering wheel, the pad slides, and mechanical force feedback provided to the finger pulp causes sensations of inertia and detent in the driver. First, we investigated whether this method actually causes such inertia and detent sensations. Then, using this device in simulated driving tests, we examined the extent of the inertia and detent sensations felt by drivers with changes in physical vibration parameter values. The findings can serve as fundamental data for the proposed device as regards designing the (desired) extent of inertia and detent sensations. Approval for this research was granted by the Ethical Review Board of Kanazawa Institute of Technology for research with human subjects (Approval No. 2013-013), and the research was performed with strict conformance to ethics guidelines.

Haptic Feedback Device

A slide-type touchpad (Figure 2), created for testing purposes, was used for haptic information presentation. The unit is operated by sliding the thumb forwards or backwards in the y-axis direction on an electrostatic-type touchpad set at the right spoke of the steering wheel. The touchpad reacts to the thumb movements, and responds via motor control at the y-axis by replicating the motion, forwards or backwards along the y-axis. This configuration enables a sensation of inertia at the thumb pulp and motion feedback. The strength of the haptic feedback changes with maximum movement (travel) distance and movement speed. Here, "maximum movement (travel) distance" is the movement distance, within the x-y

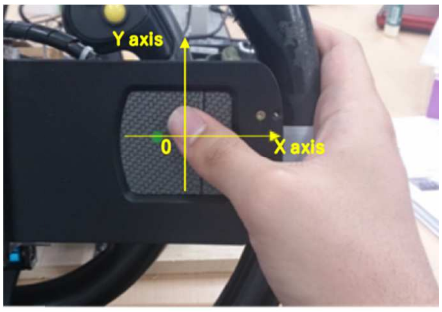


Figure 2. The haptic device (Haptic user interface, 2016)

plane coordinate system and with the midpoint of the touchpad as point of origin, from the origin (point) on the y-axis to the point where a "return" is made.

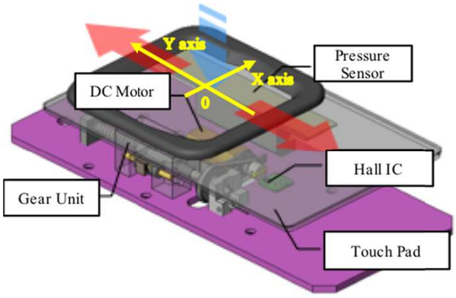


Figure 3. Configuration of the haptic device

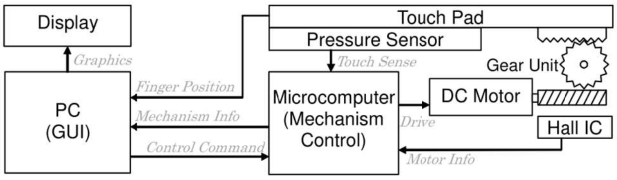


Figure 4. Block diagram showing the components and communication in the haptic device

The device comprises an ordinary DC motor connected to a feed screw shaft that reproduces by means of a belt movements produced on the touchpad placed in the axial direction on the feed screw shaft, which moves forwards and backwards. The direction of thumb movement on the device surface is detected by the electrostatic touchpad, while the pressing force is detected with a pressure sensor; motor output is controlled according to GUI software states. The numbers of motor revolutions are detected with a hall element (which uses magnets to detect motor rotation) and are reflected in output voltage changes that enable forwards and backwards movements along the touchpad to be made at voluntary velocities and distances (Figures 3 and 4). Operation states are shown with moving images (Haptic User Interface, YouTube).

When the unit is installed on a steering wheel and operated with a thumb, the touchpad moves forwards and backwards in the same direction as the sliding thumb. At such times, the touchpad slides a few millimeters in the direction of thumb movement; immediately thereafter, the touchpad slides back by the same amount. This evokes the sensations of inertia and detent.

The respective square waves of the transient movement characteristics of the prototype device, measured using motor rotation (revolution) time and the hall element, were determined via actual measurements using a digital oscilloscope (DL1540C, Yokogawa Meters and Instruments). Figures 5 and 6 show examples of the transient movement characteristics. The vertical axis shows the distance from the origin point on the y-axis ("travel distance") along which the pad moves. After the vertical axis value increases to its peak, it then declines; this expresses the reciprocating up-down movement of the pad. Figure 5 shows the characteristics with velocity (movement speed) of 62 mm/s when the maximum travel distance is changed at intervals from 0.4 mm to 7.0 mm. Figure 6 shows, as an example, characteristics when, at a maximum travel distance of 2.2 mm, velocities are changed at intervals from 49 mm/s to 100 m/s. It should be noted that because there is a large scattering in movement (travel) data due to device (mechanical) inertia and thumb pressing pressure in the vicinity of travel movement completion, such data are not plotted.

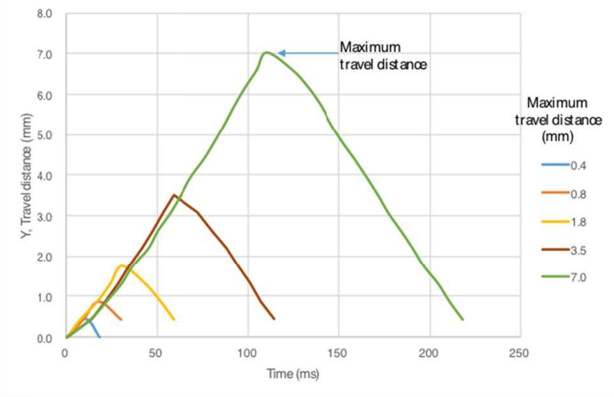


Figure 5. Travel distance and movement characteristics

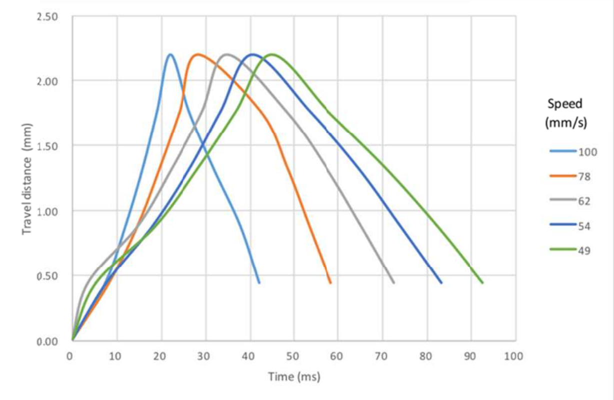


Figure 6. Velocity and movement characteristics

Experimental evaluation

1 Test subjects

The test subjects were 10 university students (8 males, 2 females), each of whom was physically and mentally healthy and possessed a standard motor vehicle driver's license. Their average age was 20 ± 2 years, and all were right-handed.

2 Test apparatus

The test apparatus used are shown in Figure 7. The driving simulator (DS) used was LCT v.1.2, Daimler-Benz.

Figure 7 Experimental setup

An actual vehicle steering wheel (diameter 260 mm), mounted on a steering wheel-type game controller (R440Force, Saitek), was used. A vibrator was installed on the handle, and was made to vibrate at 60 Hz with the idea of simulating road-induced vibration. The vibration frequency was determined via a preliminary investigation in which simple measurements were made of vibration at 60 km/hr on an actual paved road. Speed control was performed with accelerator and brake pedals (R440Force, Saitek) while viewing a speed meter displayed on the screen of a 17-inch liquid-crystal monitor (RDT1710V, Mitsubishi). (See Figure 8)

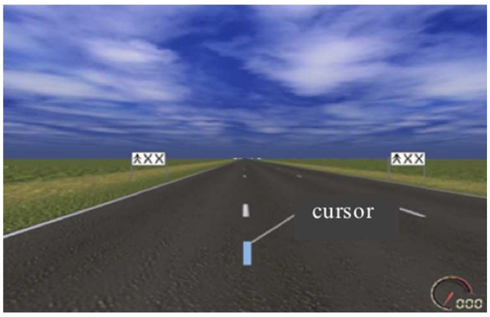


Figure 8 Monitor of driving simulator

The haptic device was placed on the right spoke of the steering wheel.

3 Test conditions

Tests were performed under supposedly dynamic ("active") conditions. Specifically, with active manipulations by the driver such as GUI menu scrolls, tactile feedback was to have been presented in tandem with the up-down sliding of menu items. However, to prevent GUI design elements from affecting haptic reception, it was determined that no screen information would be presented in these tests.

The test variables were pad maximum travel (movement) distance and velocity (movement speed), varied at the five (5) conditions listed below.

Maximum travel distance (mm): 0.4, 0.8, 1.8, 3.5, 7.0
Velocity (mm/sec): 49, 54, 62, 78, 100

Combinations of these resulted in 25 conditions.

4 Test procedures

The test performance site was the Cognitive Behavioral Science Measurements Laboratory at Kanagawa University of Technology, which has an environment controlled at 24 °C, 60% humidity, 890 lx environmental illumination, and 30 dB or less (sound pressure level, SPL) background noise level.

First, in a preliminary investigation, to confirm whether the intended sensations of inertia and detent were actually evoked, subjects were asked to perform multiple manipulations of the haptic device accompanied by simulated operation sounds on the GUI, and to report verbally on the details of their perceptions. In this case, the pad was set at 1.8 mm maximum travel distance and 62 mm/s velocity. Further, no driving task was performed, only the single task.

Next, the actual tests were performed. In the driving task, the subjects were asked to drive at 60 km/h while tracking such that a marker affixed to the DS screen overlapped the center line of a completely straight road. Practice driving was performed until the subjects had sufficiently mastered the driving task. To ensure that the subjects did not hear haptic device operation sounds, road noise of 60 dB (SPL) was presented through headphones.

After the practice driving, the dual task comprising the driving task and the tactile task was performed, and the magnitude estimation method (Noro, 1990) was used to measure sensation quantities (intensities; hereafter called "psychological quantity"). While performing the driving task, the subjects were asked to actively perform (cause) return movements along the y-axis of the slide touchpad at a signal from the experimenter. Then, combinations of the standard stimuli and comparison stimuli were automatically presented, in random order. The "standard stimuli" were set at 1.8 mm maximum travel distance, and 62 mm/s velocity. The "psychological quantity" of the sensation of inertia and detent with the standard stimuli was set at "100," with the psychological quantity for the comparison stimuli verbally reported by test subjects. Considering the need for familiarity with the tests, trial performances under each condition were conducted three (3) times.

Experimental results

The results of the preliminary investigation confirmed that all subjects perceived inertia and detent sensations. Thereafter, when the subjects experienced the tactile sensations only, without presentation of the GUI or operation sounds, it was confirmed that they perceived the same sensations of inertia and detent.

Observation of the data from the three (3) trial performances indicated that, as a result of familiarity, the third trial showed stability, with the least data scattering. Therefore, analysis for the present study was made using data from the third trial.

For each maximum travel distance, velocity vis-à-vis psychological quantity was plotted on a graph (Figure 9). From the results, it was observed that, for maximum travel distances of 0.4 mm and 0.8 mm, respectively, even with velocity increases, there were virtually no changes in psychological quantity. We surmise that this occurred either because maximum travel distances of 0.8 mm and less are under the threshold of sensation, or that they are small values in the sensation threshold vicinity, and therefore virtually imperceptible. Thus, data for the maximum travel distances of 0.4 mm and 0.8 mm were not used in the analyses that followed. Because none of the curves in Figure 9 intersect, we hypothesized that there are no crossover (interactive) effects due to maximum travel distances and/or velocities. To confirm this hypothesis, using pad maximum travel distance and velocity as factors, we performed a 3 × 5 conditions analysis of variance (ANOVA) with a two-factor within-subjects design. In this ANOVA and sub-effects tests, js-STAR 2012 release 2.0.7j (Tanaka, 2013) was used.

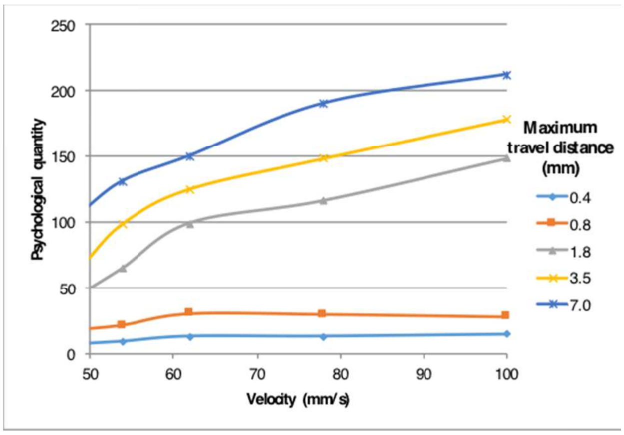
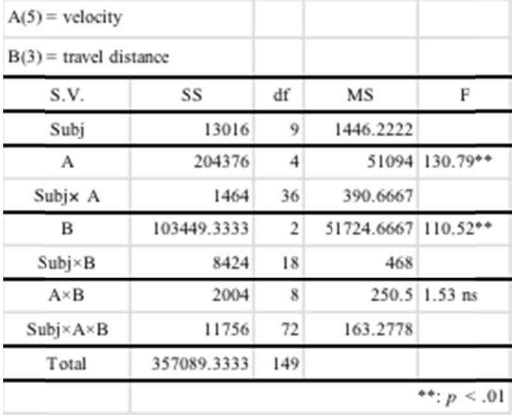


Figure 9. Relationship between velocity and psychological quantity for each maximum travel distance value

As can be seen in Table 1, the results indicated no interactive effects (i.e., interactions), and significant differences were confirmed for the main effects of velocity factor and travel distance factor.

Table 1. ANOVA results



A(5) = velocity				
B(3) = travel distance				
S.V.	SS	df	MS	F
Subj	13016	9	1446.2222	
A	204376	4	51094	130.79**
Subj× A	1464	36	390.6667	
B	103449.3333	2	51724.6667	110.52**
Subj×B	8424	18	468	
A×B	2004	8	250.5	1.53 ns
Subj×A×B	11756	72	163.2778	
Total	357089.3333	149		
	**: p < .01			

Next, a multiple comparison test using the Holm method was performed as the sub-effects test. As shown below, the results confirmed significant differences, at $p < 0.05$ significance level, between all levels of psychological quantity $R(v, d)$, the extent to which sensations of inertia and detent were experienced—where v is velocity, and d is maximum travel distance.

Maximum velocity (mm/s): (MSe = 390.67, $p < 0.05$), $R(49, d) < R(54, d) < R(62, d) < R(78, d) < R(100, d)$
$d = 1.8, 3.5, 7.0$ mm
Travel distance: (MSe = 468.00, $p < 0.05$)
$R(v, 1.8) < R(v, 3.5) < R(v, 7.0)$
$v = 49, 54, 62, 78, 100$ mm/sec

Next, for data under other conditions, a power function was found for each of maximum travel distance and velocity (Figures 10 and 11).

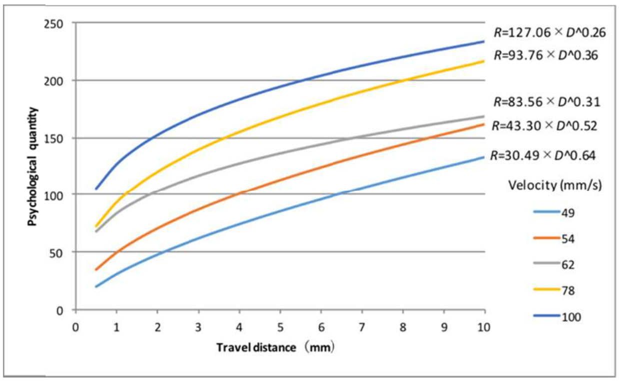


Figure 10. Extent of inertia and detent sensations perceived for travel distances

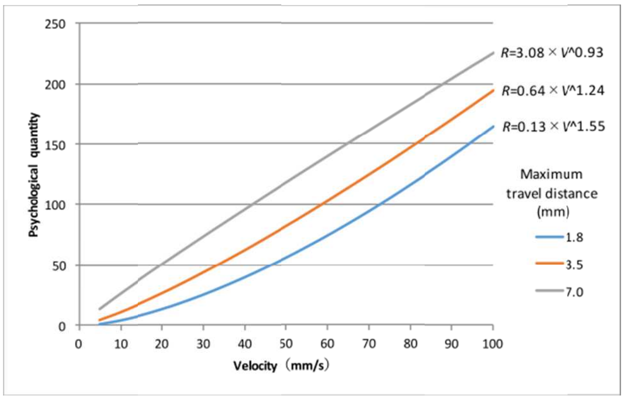


Figure 11. Extent of inertia and detent sensations perceived for velocities

Using the velocity at 49 mm/s, Formula (1) was obtained:

$$R=30.49\times d^{0.64} \tag{1}$$

The power of this d is the "power exponent." The power exponents for the other respective velocity conditions were as follows:

54 mm/s: 0.52, 62 mm/s: 0.31,
78 mm/s: 0.36, 100 mm/s: 0.26

In addition, for maximum travel distance, 2.2 mm was used to obtain Formula (2):

$$R = 0.13\times v^{1.55} \tag{2}$$

The power exponents for the other respective maximum travel distances were as follows:

3.5 mm: 1.24, 7.0 mm: 0.93

Discussions

The results of the preliminary investigation confirmed the existence within subjects of inertia and detent sensations regardless of GUI presence or absence. This confirms that a touchpad as a thin presentation device manipulated by touch sliding in the y-axis direction can, by means of communication of vector information via mechanical force feedback to the thumb (finger) pulp, engender within a driver sensations of haptic inertia and detent, which are difficult to obtain with other methods. The same is true in the case of solely tactile information that is not presented via a GUI.

Based on the test results, it appears that a threshold exists within the 0.8 mm to 1.8 mm range of maximum travel distance. Thus, under the conditions of the testing performed in this study, maximum travel distances of 1.8 mm and above were required in order to perceive velocity changes.

From the ANOVA results, it was ascertained that the maximum travel distance and velocity have independent effects on the extent of the perception of inertia and detent sensations. The larger the value of each of these variables (i.e., maximum travel distance and velocity), the larger the extent of said perception becomes.

Next, from the magnitude estimation results, as perceptual characteristics fostered by the sensation of inertia were detected as a result of changes in maximum travel distance and velocity, a power exponent was obtained. With this power exponent as reference, when using the proposed method in designs for the sensations of inertia and detent, quantitative estimation (inference) can be made as to the extent of the psychological quantity obtainable relative to the maximum travel distance and velocity used.

It must be noted however that the majority of the test subjects in this study were young men, and the effects of aging and sex differences were not clarified. In addition, in further testing of interactive effects with the GUI, the status of concrete functions of manipulations for (hypothesized) actual usage situations, and tests that take into account driving conditions such as lane changes, are necessary.

We also believe that a combination comprising the method proposed in this study and a vibration device would enable expression of even higher levels of tactile and haptic sensations, with the development of a related interface a distinct possibility. We plan to continue with investigations of this nature in the future.

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References

Asif A and Boll S, 2010. Where to turn my car? Comparison of a tactile display and a conventional car navigation system under high load condition. Proceedings of the Second International Conference on Automotive User Interfaces and Interactive Vehicular Applications, 64-71.

CyberGlove Systems Inc 2016. CyberGrasp. http://www.cyberglovesystems.com/cybergrasp/ (accessed on 18 April 2016)

“Haptic User Interface”: https://www.youtube.com/watch?v=hI48vXC4hME&feature=youtu.be (accessed on 18 June 2016)

Konyo M and Okamoto S, 2012. Pseudo haptic presentations using vibrotactile stimuli. Journal of the Robotics Society of Japan, 30(5), 475-477.

Makino Y and Maeno T, 2010. Haptic interface. The Journal of the Institute of Image Information and Television Engineers, 64(4) 502-504.

Minsky M D R, 1995. Computational haptics: *The sandpaper system for synthesizing texture for a force-feedback display*. Doctoral thesis of Massachusetts Institute of Technology.

Noro K (Ed), 1990. Illustrated ergonomics, Japan Standard Association, 566.

Takasaki M, 2012. Evolution in haptic displays. IEEJ Transactions on Electronics, Information and Systems, 133(3), 625-629.

Tanaka H and Nappa, 2013. js-STAR 2012. http://www.kisnet.or.jp/nappa/software/star/info/new.htm (accessed on 20 December 2015)

Tanaka K, Morohashi T, Maeda T, and Yanagida Y, 1997. Method of tactile presentation using impulse component in the vibration. Trans Soc Instru Contr Engin, 33(7), 680-686 (in Japanese).

3D Systems, 2016. Phantom,
http://www.geomagic.com/
(accessed on 18 April 2016.)

Tsuchiya S, Okamoto S, Konyo M, and Tadokoro S, 2010. VibTouch: Fingertip haptic interaction using virtual active touch 3rd report: Illusionary presentation of the inertia using vibrotactile stimulation. Proceedings of the 2010 JSME Conference on Robotics and Mechatronics, 1A2−D23 (in Japanese).

US‐EU Bilateral ITS Technical Task Force, 2010. Expert Focus Group on Driver Distraction: Definition and Research Needs, 5.