Concave-Convex Surface Perception by Visuo-vestibular Stimuli for Five-Senses Theater

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Abstract. The paper describes a pilot study of perceptual interactions among visual, vestibular, and tactile stimulations for enhancing the sense of presence and naturalness for ultra-realistic sensations. In this study, we focused on understanding the temporally and spatially optimized combination of visuo-tactile-vestibular stimuli that would create concave-convex surface sensations. We developed an experimental system to present synchronized visuo-vestibular stimulation and evaluated the influence of various combinations of visual and vestibular stimuli on the shape perception by body motion. The experimental results urge us to add a tactile sensation to facilitate ultra-realistic communication by changing the contact area between the human body and motion chair.

Keywords: vestibular stimulation, ultra realistic, multimodal, tactile.

1 Introduction

With the progress in video technology and the recent spread of video presentation equipment, we can watch stereoscopic movies and large-screen high-definition videos not only in large amusement facilities but also in our private living rooms,. The next step for enhancing the presence of audiovisual contents will be to add other sensory information, such as tactile, haptic, olfactory, or vestibular information. After SENSORAMA, a pioneering system in multisensory theater, a number of similar attractions have been developed for the large amusement facilities. In order for a new technology to make its way to our living rooms, it is important to establish a methodology with the aim of not only faithfully reproducing the physical information, but also of optimizing it for human perception. If the sensory stimuli can be fully optimized, it is expected that a highly effective system can be developed with inexpensive, simple, and small equipment.

R. Shumaker (Ed.): Virtual and Mixed Reality, Part I, HCII 2011, LNCS 6773, pp. 225–233, 2011.

The authors have proposed *Five-Senses Theater* [1-3] to generate "ultra-realistic" sensations [4]. The "theater" we envision here would be widely available in living rooms as "home theater" and offer an interactive framework rather than just a way to experience contents. In this paper, we focus on motion sensation, which is one aspect of Five-Senses Theater. We developed an experimental system to integrate visual and vestibular sensory information and conducted a pilot study to investigate how to effectively generate vestibular sensation with visual stimuli. We also present a tactile-integrated prototype, which we plan to use in psychophysical experiments on multisensory integration.

2 System Design

Sensory inputs involved in self-motion sensation are mainly visual, vestibular, and somatosensory signals. In chair-like vehicles, such as driving simulators or theater seats, we generally detect velocity information using visual cues and detect acceleration and angular acceleration information using mechanical cues (vestibular and tactile sensations), respectively.

A stationary observer often feels subjective movement of the body when viewing a visual motion simulating a retinal optical flow generated by body movement. This phenomenon is called vection [5-8].

Acceleration and angular acceleration are sensed by the otolith organs and semicircular canals. These organs can be stimulated by mechanical (e.g., motion chair [9,10]), electrical (e.g., galvanic vestibular stimulation [11]), and thermal means (e.g., caloric tests). Electrical stimulation can be achieved with a more inexpensive configuration than the others can. However, it affects anteroposterior and lateral directions differently, and there have been no reports that it affects the vertical direction. In addition, its effect is changed by the electrical impedance of the skin. In thermal stimulation, cold water is poured directly into the ear, which is not a suitable experimental stimulus with computer systems.

In this study, we choose a motorized motion chair (Kawada Industries, Inc.; Joy Chair-R1), to stimulate the vestibular system with haptic modality. The motion chair has two degrees of freedom (DOF) in roll and pitch rotations. To reproduce exact physical information, a motion chair needs six degrees of freedom [12]. However, such motion chairs tend to be expensive and large-scale. We constructed an experimental system using a simple 2-DOF motion chair as an approximate representation since size and cost are constrained in home use.

Figure 1 shows the configuration of the experimental system for generating visual stimuli and controlling the motion chair. The motion chair and the visual stimulus are controlled by different computers on a network with distributed processing, coded by Matlab (The MathWorks, Inc.), Cogent Graphics Toolbox, and Psychophysics Toolbox. Synchronization of the stimuli was performed over the network. Position control was adopted to drive the motion chair. A voltage proportional to the desired angle is applied by a microprocessor (Microchip Inc.; PIC18F252) and a 10-bit D/A converter (MAXIM; MAX5141). A visual stimulus is presented to a 100-inch screen by a projector on the floor (NEC; WT600J).

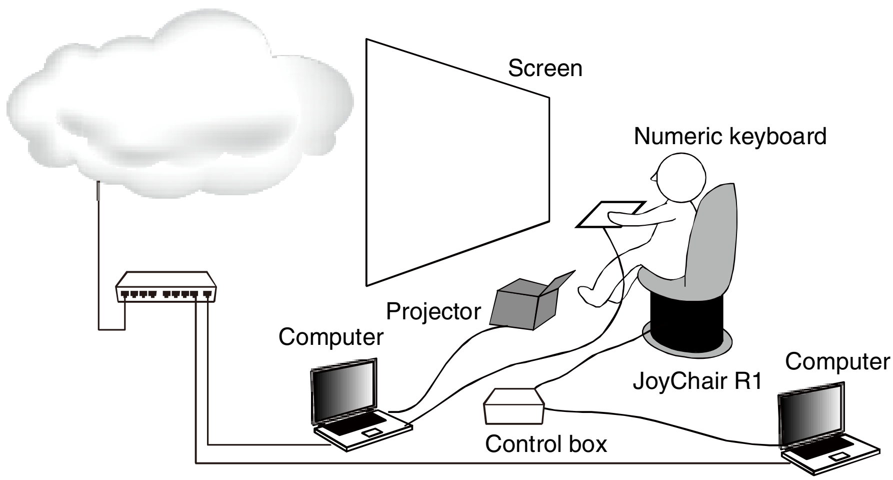

Fig. 1. System configuration

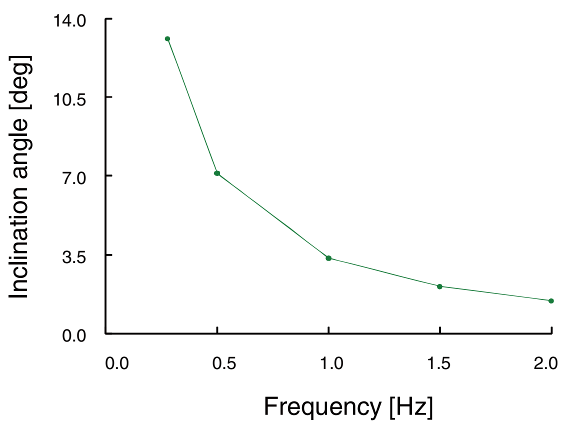

Fig. 2. Perceptual threshold where the participant could not notice vibration noise of the motion-chair versus amplitude (inclination angle) and frequency

We need to not only drive the chair within the maximum rotation velocity but also to know the perceptual threshold of vibration noise. Figure 2 shows the perceptual threshold of a smooth motion. The threshold was determined by asking a naïve participant (24-year-old male) to control the level of the amplitude and frequency and to alter them until they were not detectable (i.e., with the adjusting method). In addition, ten male naïve participants (details later) reported that they did not feel vibration noise under the criteria. The results show that the vibration noise could be perceptually ignored under the combinations of amplitude and frequency, which were below the line in Fig. 2. In the following experiment, we choose the experimental parameters to drive the motion chair to meet the criteria for perceptual unawareness of vibration noise.

We measured delay time between the onset of visual stimuli and motion-chair stimuli in advance. The delay time can be reduced up to one video frame (33 ms) by adjusting the onset of the visual stimuli. Each computer over the network synchronizes the time between visual and motion-chair stimuli.

3 User Study

Ten male participants, aged 19–33 years, participated in the experiments. We decided to use males only because it has been reported that women experience motion sickness more often than men [13,14]. None of participants had any recollection of ever experiencing motion sickness, and all had normal or corrected-to-normal vision. They had no known abnormalities of their vestibular and tactile sensory systems. Informed consent was obtained from the naïve participants before the experiment started. Recruitment of the participants and the experimental procedures were approved by the NTT Communication Science Laboratories Research Ethics Committee, and the procedures were conducted in accordance with the Declaration of Helsinki.

Visual stimuli generated by Matlab with Cogent Graphics Toolbox were radial expansions of 700 random dots. The distance between the participant and the screen was 1.72 m. The size of each dot was 81.28 mm. Resolution was 1024×768 (XGA). Participants wore an earmuff (Peltor Optime II Ear Defenders; 3M, Minnesota, USA) to mask the sound of the motion chair.

In each trial, a stimulus was randomly selected from experimental conditions. Subjects were seated in the motion chair with their body secured with a belt. They were instructed to keep their heads on the headrest of the chair. Figure 3 shows the experimental procedure. Subjects were instructed to watch the fixation point on the screen during the trial. After five seconds, the stimuli were presented for 20 seconds.

The experimental task was to respond whether the shape they overran was a bump (convex upward), a hole (concave) or a flat surface (plane) by pressing a key of a numeric keyboard. Buttons were labelled ‘bump’, ‘hole’ and ‘flat’. No feedback was given during the experiment. Data from a seven-point scale of motion sickness (1. not at all; 4. neither agree nor disagree; 7. very much) were also collected. Three visual conditions (Bump/Hole/Flat) × 3 motion-chair conditions (Bump/Hole/Flat) × 3 velocity conditions (20, 30, 40 m/s) × 10 trials (a total of 270 trials) were conducted. Subjects had 15-minute breaks after every 28 trials, but could rest at any time. A typical experiment lasted about three hours and thirty minutes. The translational velocity of the motion chair was expressed as velocity of optical flow. The shape was expressed by titling the chair forwards and backwards, i.e., by modifying the pitch rotation, which corresponded to the tangential angle on surface.

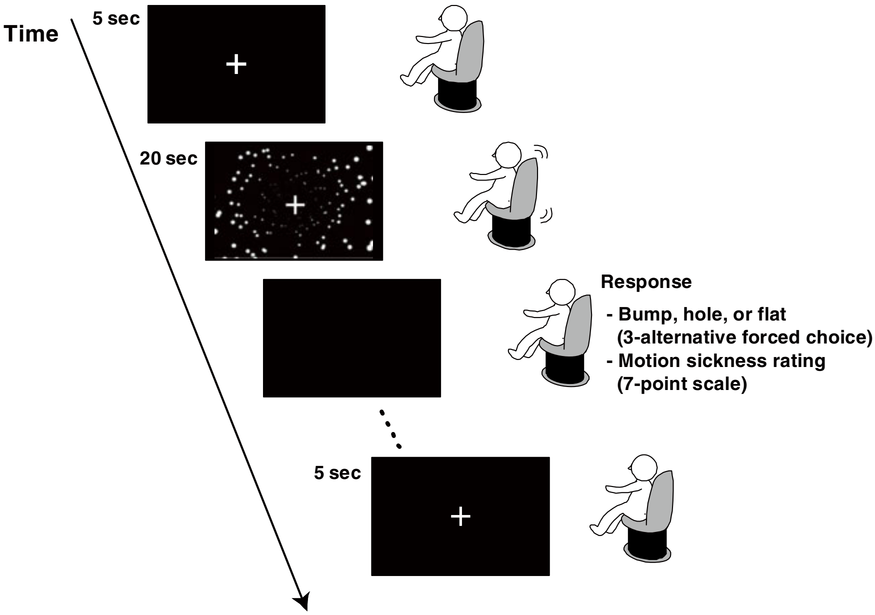

Fig. 3. Experimental procedure

The vertical velocity of optical flow was determined by a combination of the translational motion and pitch rotation from the profile of the shape. The profile of the shape ($y=f(x)$) was Gaussian as follows:

$$f(x)=\frac{1}{\sqrt{2\pi\sigma}}\exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\} \tag{1}$$

where $\sigma=1.1$ since the maximum of the tilt of the motion chair

$$\theta=\arctan\left\{\frac{d}{dx}f(x)\Big|_{x=\mu\pm\sigma}\right\} \tag{2}$$

was set to 13.5 degrees from the limit of the motion chair's angle. After ten seconds from start, the height was at the maximum (i.e., $x=\mu$). The translational velocity was calculated by $v=dx/dt$.

The results of shape perception by visuo-vestibular stimulation are shown in Fig. 4. Experimental results show that shape perception was greatly affected by vestibular stimulation. The results suggest that the tilt of the chair, 13.5 degrees, was large enough to judge the shape independent of visual stimuli. Reducing the angular amplitude of the chair motion or weakening the effect of the vestibular sensory stimuli (e.g., adopting around 2.2 degrees of tilt perception threshold [15] or slower angular acceleration) can be expected to increase the effect of visual stimuli.

In contrast, it seems the visual stimuli should be redesigned to augment the effect. When the motion chair stimulus was a flat surface and the visual stimulus was not a flat surface, the responses were almost evenly split among the three surfaces. This indicates that it is difficult to perceive the sensation of non-flat surfaces only from visual stimuli.

The velocities of optical flow we used in the experiment did not greatly affect the shape perception. Subjective motion-sickness scales of from all subjects were not larger than 2, which means that the experimental stimulus did not cause motion sickness.

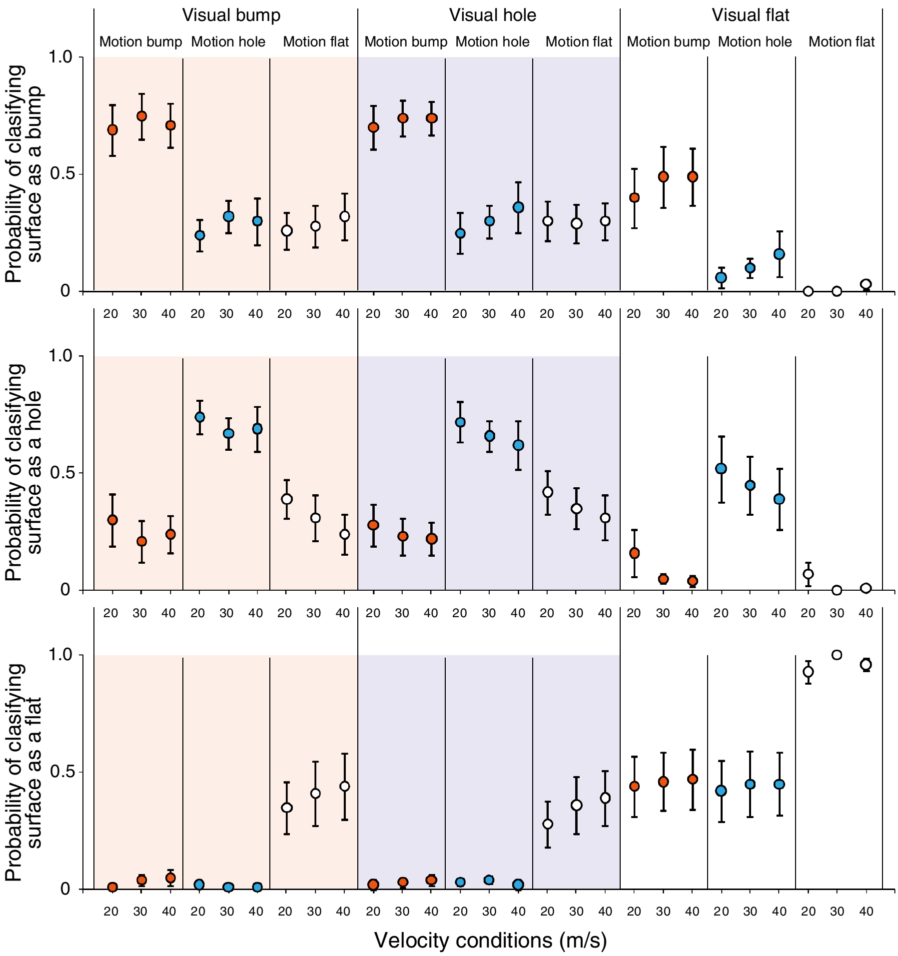

Fig. 4. Surface classification probabilities. Subjects mainly used information of the tilt of the motion chair to identify the shape.

4 Enhancing Tactile Stimulation

Integration of visuo-vestibular stimuli with tactile stimuli is expected to enhance the perception of self-motion. When we drive a car and accelerate it, the body is pressed to the seat. If our body is pressed to the seat more strongly, we will perceive a stronger subjective motion against the direction of pressure. In our motion chair system so far, we have not yet implemented the pressure stimulation, which would simulate acceleration or deceleration of body motion.

Figure 5 shows the design of the tactile stimulator for changing the pressure between a seat and human body. The tactile stimulator is composed of voice-coil motors with a pin-array and plates with holes. Figure 6 shows a layout drawing of the tactile stimulator on the seat of a motion chair.

We expected that when the voice-coil motor with the pin-array vibrates at lower frequencies, such as sub-hertz, a pressure sensation will be induced rather than vibration sensation, because Merkel disks, which convey pressure information, are the most sensitive of the four main types of mechanoreceptors to vibrations at low frequencies.

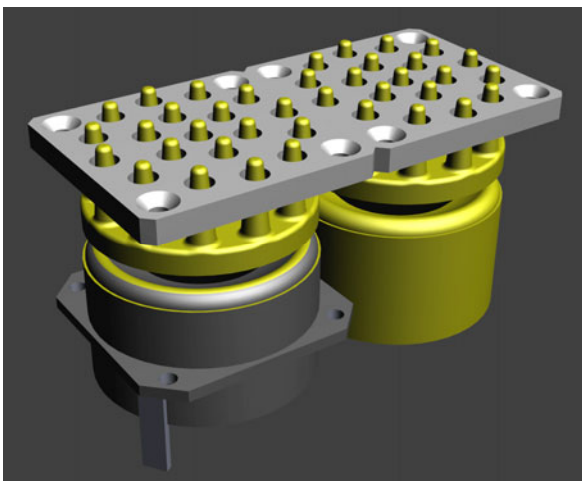

Fig. 5. Schematic design of tactile stimulator with voice-coil motor and pin-array

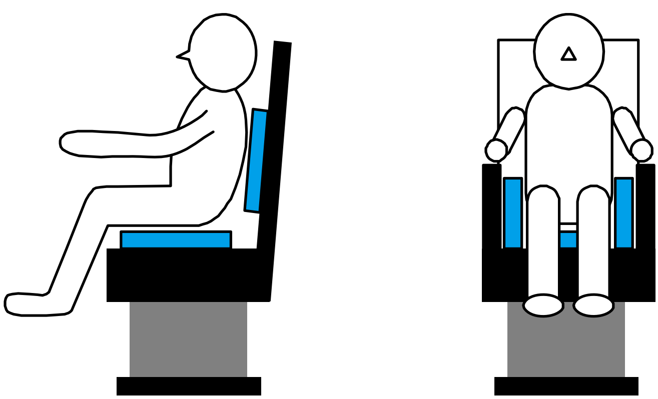

Fig. 6. Layout drawing of the tactile stimulator on the seat of a motion chair

Figure 7 is a photograph of a prototype of the tactile stimulator. The pin-arrays of the tactile stimulator are made of ABS resin. Four sets of voice-coil motors were connected as a unit. To measure the pressure between the seat and human body, each unit was connected on pairs of strain gauges in a Wii Balance Board (Nintendo, Inc.). The tactile stimulators were driven with a computer with a D/A board (DA12-8(PCI), CONTEC Co., Ltd.) and a custom-made circuit (including an amplifier).

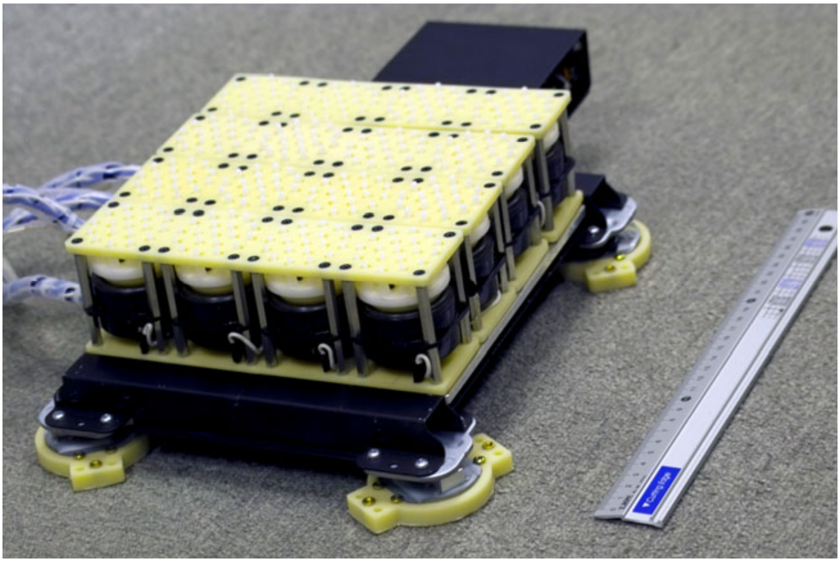

Fig. 7. Prototype of tactile stimulator to generate the sensation of being pressed to a seat

5 Conclusion

In this paper, we reported a pilot study of presenting visuo-vestibular stimulation to generate convex or concave surface perception. The results of the pilot study indicate that we should redesign the effective stimulus combination of the visuo-vestibular stimuli. After that, we will conduct a further experiment with different parameters in an attempt to augment the effect of visual stimuli. We are also planning to conduct an experiment with the tactile stimulator integrated with the visuo-vestibular system to better understand the effectiveness of these stimuli.

Acknowledgement. This research was supported by the National Institute of Information and Communication Technology (NICT). We thank Dr. Takeharu Seno for his valuable comments on visually induced self-motion perception, and Mr. Shohei Komukai for his contribution to building the experiment setup.

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