Drone rider: Enhanced feelings of flying using a vibratory and passively inclining foot plate

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***Abstract*— This study investigated the effects of two techniques to improve the sense of immersion and flying for flight simulators in immersive virtual reality environments. To test their effects, we used a drone simulator, with an operator standing on a drone and controlling it over a natural landscape by inclining his/her body toward the travelling direction. The first technique involved vibratory feedback through a foot plate that delivered the simulated vibration and sounds of the left and right propellers of the drone. The second technique involved the passive roll and pitch rotation of the foot plate when the operator actively shifted the center of his/her body mass. In a user experiment involving 12 participants, the passive inclination of the stage was found to enhance immersive feelings, while the vibratory feedback to the soles were found to enhance both feelings of flying and immersion. This study helps develop a drone and other flying simulators using immersive virtual reality settings.**

I. Introduction

Body levitation in immersive virtual reality (VR) environments allows us to enjoy extraordinary experiences. Further, e-sports requiring moderate exercises could help maintain fitness. We have been developing Drone Rider, which is a VR experience where a human rides on a drone and flies over spectacular landscapes or races with other riders through city buildings. A key technique for such VR applications is determining how to effectively induce a sense of levitation by using haptic or non-visual stimuli.

Earlier studies demonstrated that the combination of vection and haptic stimuli effectively induced the sense of self-motion [1], [2], [3]. For example, in a study by Nilsson et al. [2], vibratory stimuli to soles were found to influence the feelings of horizontal travel in a VR setting. Sound stimuli can be also effective in enhancing the sense of self-motion [4]. Based on these studies, we hypothesize that audible vibrations to soles along with flight images improve the sense of levitation and immersion in the drone simulator. As far as we know, thus far, the effects of vibrotactile stimulation to the soles on the sense of flying have not been investigated for flight simulators in VR environments. Further, the introduction of passive rotation of the foot plate would be efficient because it matches the postures of the virtual fuselage and operator. This study experimentally tested the effects of sole vibration and passive stage inclination on the sense of levitation and immersion.

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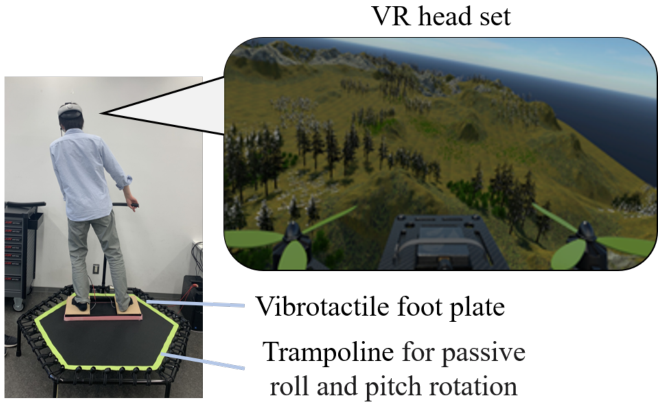

Fig. 1. Experimental setting of VR drone rider. The user wears a virtual-reality head set on a vibrotactile foot plate that passively rotates around roll and pitch axes.

II. Methods

A. Apparatus

The apparatus mainly comprised a VR head set (Meta Quest 2, Meta Platforms, Inc., CA), trampoline (Honei, China), and vibrotactile foot plate, as shown in Fig. 1. The footplate was laid on the trampoline and had two voice-coil motors (Vp7, Acouve Laboratory Inc., Japan) installed on its surface for left and right feet. Each motor was placed at the forepart of each foot. They were connected to an audio amplifier (FX-AUDIO-FX-2020A+, North Flat Japan, Japan). An operator, that is, the rider, stands on the foot plate with each foot on the respective voice-coil motor while holding a safety handle. According to the voluntary shift of the center of body mass, the foot plate passively inclines toward the roll and pitch directions. This design allowed us to match the body posture and that of a drone in the virtual environment, with the aim of improving the feelings of flying and immersion.

B. Software system and VR field

Unity (2021.3.21f1) was used to develop the drone simulator. The tilt of the VR head set was converted linearly to the drone's velocity. The forward/backward speed of the drone was determined by the pitch angle of the head set. In addition, the tilt around the roll determined the drone's yawing velocity. In the VR environment, the operator flew over a natural field on a drone. The drone did not move vertically to change its altitude; it moved only over a horizontal plane without obstacles.

C. Vibratory stimuli to soles

The sound was reproduced by a voice coil motor in contact with the operator's soles so that the drone's propeller sound could be picked up via the sole as vibrations. When the drone turned to the left, the rotation speed of the right side propeller increased, and when it turned to the right, the rotation speed of the left side propeller increased. The vibration amplitude of the voice coil motor on the opposite side of the turning direction was increased to represent the increase in volume of propeller sound with increasing rotation speed. The voltage inputs to the voice coil motors were linearly changed with the angular velocity of the drone.

D. Participants

Twelve university students (four females) in their 20s participated in the experiment after providing written informed consent. They could freely abandon the experiment if they suffered from severe motion sickness. The protocol of the study was approved by Institutional Review Board, Hino Campus, Tokyo Metropolitan University (H23-9).

E. Procedures

Before the main experiment, the participant acclimated to the manipulation of the drone simulator. This session typically lasted 1–2 min. After the 3-min break, the main experiment began.

In the main experiment, the participant operated the drone freely for each of the four conditions (with/without vibration $\times$ with/without passive stage rotation) that were presented in randomized order. The participant was encouraged to steer the drone around yaw axis unless motion sickness was felt. The flight experience lasted 40 s for each condition. In the condition without passive stage inclination, participants stood on a wooden board placed on a trampoline frame. In the no-vibration condition, the experiment was conducted by having participants stand on a foot plate without a voice coil motor. The vibratory foot plate was used merely to produce the propeller sounds.

After the experience, participants immediately answered each of the following questions using a 9-point scale (1: little and 9: very much). Questionnaire items were Q1 (Did you feel like you were flying?) and Q2 (Was the experience immersive?). After completing the questionnaire, participants rested on a chair for 3 min before the next trial.

F. Data analysis

For each question item, the reported scores were standardized (z-score) for each participant. The standardized scores of Q1 (sense of flying) and Q2 (sense of immersion) were then analyzed using the two-way analysis of variance with the trampoline and vibratory stimuli conditions being two factors.

III. Results

Tables I and II summarize the results of the analysis of variance for Q1 and Q2, respectively. As depicted in Table I, the vibration to soles was effective for the sense of flying; however, the passive rotation of the stage was not. Further, as depicted in Table II, both the vibration and passive stage were effective for the sense of immersion.

TABLE I
Summary table of analysis of variance for Q1 (Sense of flying)

Factor	Sum of squares	d.f.	F-value	p-value
Passive inclination	0.31	1	0.61	0.44
Sole vibration	4.35	1	8.62	0.0053
Interaction	0.16	1	0.32	0.57
Error	22.19	44		
Total	27.0	47		

TABLE II
Summary table of analysis of variance for Q2 (Sense of immersion)

Factor	Sum of squares	d.f.	F-value	p-value
Passive inclination	2.95	1	4.42	0.041
Sole vibration	3.56	1	5.33	0.026
Interaction	0.11	1	0.16	0.69
Error	29.38	44		
Total	36	47		

IV. Discussion and Conclusion

We evaluated the effects of passive inclination of the foot plate and vibratory stimuli to soles, representing propellers, on the sense of flying and immersion in a VR setting where a human rides on a drone and enjoys flying over a natural park. A user study revealed that sole vibrations increased subjective scores for feelings of flying and immersion. Further, the passive foot plate motion led to an increase in the immersion score. A few participants reported moderate levels of motion sickness, which should be alleviated in the future.

Contrary to our expectations, passive rotation of the stage on the trampoline did not improve operators' feeling of levitation. This may be because the inclination of the drone's CG imperfectly matched that of the operator's body in our setup. The posture of the drone was determined by that of the head set and, thus, did not directly refer to the inclination of the foot stage. This issue will be resolved in the future and we will further explore the effect of passive stage rotation.

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