InertiaVibe: Low-fidelity Simulation of Inertia using Head-mounted Vibrotactile Feedback to Reduce Cybersickness and Enhance VR Experience

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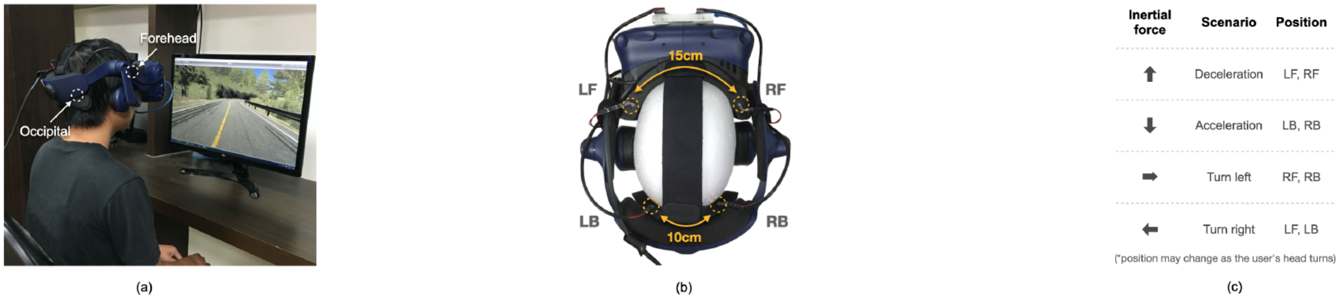

Inertial force	Scenario	Position
⬆	Deceleration	LF, RF
⬇	Acceleration	LB, RB
➡	Turn left	RF, RB
⬅	Turn right	LF, LB

(*position may change as the user's head turns)

Figure 1: (a) Image of the user taking a right turn in the VR application. (b) Overview of the device design. (c) Design of feedback pattern.

ABSTRACT

Visually induced motion sickness in VR, or cybersickness, is a major barrier to VR adoption. We present InertiaVibe, a low-fidelity approach to simulate the experience of lateral inertial forces using headset-integrated vibration motors. Specifically, we use 4 vibration motors positioned at both sides of the forehead and the occipital bone, and vibrate the pair of motors in the direction of the inertia force during lateral acceleration, deceleration, and turning. To first evaluate how users think about the vibrotactile feedback in different scenarios, we conducted a pilot study with 12 participants. Results show that their opinions on the vibration were positive. Most users reported improvement of both realism and immersion, and they generally felt less discomfort.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality; Haptic devices**.

KEYWORDS

Virtual reality, vibrotactile feedback, cybersickness, VIMS, simulator sickness, realism, immersion

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1 INTRODUCTION

Virtual reality (VR) technology has been widely used in multiple applications such as entertainment, education, and skill training. However, several discomforts accompanied by VR technology block users from engaging in the VR world. Symptoms such as nausea, headache, and fatigue have been reported when exposed in the virtual environment for a certain extent of time and get worse if

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continuous locomotion is involved. As the technologies of sensing and display evolve rapidly, sickness related to software and hardware issues (e.g., Motion-to-Photon latency, low frame rate, etc.) will be overcome eventually. Nonetheless, the motion sickness caught in VR locomotion, also known as cybersickness [28], visually induced motion sickness (VIMS) [4] or simulator sickness [25], is caused by the VR content itself, so it cannot be easily solved by upgrading the hardware. The symptoms of cybersickness or VIMS are very similar to traditional motion sickness, with the difference being that physical movement is usually limited or absent during VIMS [27]. The most widely accepted theory of the cause is sensory conflict theory [34], which states that motion sickness is induced by the conflict between visual and vestibular perceptions. When navigating in a virtual environment without actual body movements, users receive only visual perception but lack vestibular one. It is very common when experiencing VR locomotion such as driving, flying, riding, and sliding because users have to use controllers or joysticks to initiate an artificial movement due to restricted physical space. The conflict comes from their vision, telling their brain that they are moving,while their proprioception being static. This mismatch activates the defensive mechanics of the human body and thus caused poisoning-like reactions [46].

To reduce motion sickness in VR locomotion, several approaches have been put out with different aspects of tradeoffs. Reducing field-of-view(FOV) [14], viewpoint snapping [38], and teleportation [22] aim to reduce visual stimuli, but both decrease the immersion and the sense of presence. Adding rest frames [8] like car framework help users building their internal mental model of staying still in a vehicle, but some scenarios don't have a framework to implement such as active sliding or passive camera motions. Artificial rest-frame works, but it highly affects immersion as well. Some studies employed vestibular stimulation methods to reduce sensory mismatch. Galvanic vestibular stimulation(GVS) [9] and bone-conducted vibration(BCV) [43] try to interfere with the user's vestibular system by distracting the balance portion of the user's brain. So the user's brain has less weighting on the vestibular signals [26] and thus perceives less sensory mismatch. Notably, GVS poses a risk to certain populations and potential risk to the body after long exposure is unknown. Active body movement [35], Motion platforms [1] bring back a certain level of motion sensations to lower the sensory mismatch. However, body movement causes fatigue easily, and only suitable for active locomotion while motion platforms take larger space and higher cost. Phantomlegs [30] and Walkingvibe [20] provide different types of feedback to compensate for the lost vestibular stimuli. They use subtle haptic cues to enhance realism in walking scenarios while reducing sickness. Though, the explanation of its effectiveness needs to be investigated.

Although the cybersickness is an essential obstacle to be tackled, we think the overall VR experience considering the higher immersion, realism, and less discomfort will be the optimal goal to pursue. After carefully reviewed the aforementioned techniques, we decided to continue the concept of WalkingVibe and develop applications other than walking or running for more general use. In this work, we design the haptic feedback with vibrators on the HMD. The vibration pattern corresponds to the inertial force of four directions while moving in continuous planar locomotion (e.g., driving, biking, sliding, etc.). This pattern is easy to be connected to the user's internal mental model as effective as the rest-frame theory. Furthermore, it does not require any visual modification and is possible to be used in the scenarios (e.g., skiing or skateboarding) that rest-frames cannot do. We conducted an 12-subject pilot study to investigate how users think about vibrotactile feedback. We then discussed the future work of our design and the possible improvement of the device.

In summary, this paper makes the following contributions: 1) A prototype design of haptic feedback that is easy to integrate into the existing HMD 2) A pilot study showed that vibrotactile feedback can improving the realism, immersion, and comfort.

2 RELATED WORK

2.1 Techniques for mitigating cybersickness

Teleportation [22] [6] [19] and reduced FOV [7] [14] approaches are commonly used in VR applications for mitigating cybersickness. The teleportation techniques remove or shorten the progress of motion. Without the dynamic optical flow, the sensory conflict is eliminated but the immersion is lowered as well [6]. Reduced FOV techniques aim to cut down the visual stimuli around the peripheral vision, but the VR experience is decreased either. For example, FPS games need to take care of enemies around, the reduced FOV might hinder the gamer's performance of enemy hunting. Rest frame [8] [36] techniques alter the user's mental model, let the user's brain interprets some parts of the scene moving as vehicle motion but not body motion. This technique can effectively weaken sensory mismatch but it doesn't generalize well. For instance, when taking a train or airplane we can have a window as the frame, but skating or skiing doesn't have natural frames. Active body movement approaches [41] [21] [40] such as walking-in-place [35] mitigate cybersickness by introducing some body motions. However, they cause fatigue quickly. Sensory re-coupling approaches [9] [43] [44] [11] [31] [1] [15] [32] emphasize using multi-sensory signals to compensate with visual signals. Galvanic vestibular stimulation(GVS) applies current through electrodes placed on the mastoids behind the user's ears. The electrical signals are directly passed into the user's vestibular system and induce body sway. Either noisy GVS [44] or synchronized GVS with the yaw direction of virtual motion [15] are able to reduce cybersickness. However, GVS poses health risks to certain populations and has an unknown risk to the body after long time exposure. Sarah D'Amour et al. [11] used two fans to produce airflow in front of the user while playing the bicycle riding video. They discussed the effectiveness might come from skin tactile that is consistent with the user's mental model or the fresh air decreases body temperature that eases the sickness [33]. Séamas Weech et al [43] [44] used random and angular corresponding bone conductive vibrations(BCV) placed on the mastoids to simulate the similar effect of GVS. They found that BCV might disrupt the vestibular system like the GVS method. In their studies, the subjective experience such as presence and immersion has not been assessed. But BCV's frequency range of 200-400Hz [43] may induce discomfort and users may feel annoying when they hear the sound of the vibration frequency. Motion platform [31] [1] gives more vivid movement and has been used for reducing simulator sickness. But this approach might arise traditional motion sickness [5] [4] despite its expensive setting and price. Some researches tried to simplify the motion platform and install vibrators on the seat [11] [31]. Some of them have effects with lower SSQ scores but another not. Sarah D'Amour et al. [44] argue that head vibration might work because of the higher sensitivity of the head. PhantomLegs [30] and WalkingVibe [20] applied tapping and vibration on the head that synchronized to the footstep to reduce cybersickness with an enhancement of realism in the walking scenario.

2.2 Vibrotactile feedback around the head

Most of the prior works apply vibrotactile feedback to increase immersion. FaceHaptics [45] used a robot arm attached to the HMD which can rotate and moving toward to provide wind, warmth, or water spray haptic cues to the face. Masque [42] designed four customed shear tactors on HMD to provide facial skin stretch which could be used for motor racing, object collision, or viewing guidance. VaiR [37] generated an accurate and realistic airflow simulation by two sets of rotary air nozzles. Headblastor [29] used six head-mounted air propulsion jets to eject compressed air to force the head move. The perception of lateral acceleration improves user experience, presence, and emotional response in VR. Several studies that applied vibrations on the head [16] [2] [24] [13] [12] as the navigation cues. Kaul and Rohs [23] utilized multiple vibrators distributed in three concentric ellipses around the head for directional guidance. They further studied the funneling illusion on the head using the same vibrotactile actuators [24]. Jelte Bos [3] studied the traditional motion sickness in the off-vertical axis rotation study and found that motion sickness could be reduced by applying high-frequency vibration to the head and by mental distraction. WalkingVibe [20] used subtle head vibrations to reduce motion sickness in the walking scenario. Unlike Weech et al. [43] applied BCV at the timing of angular acceleration, WalkingVibe applied head vibrations at the timing of the footstep. Their easy-to-integrate design not only mitigates cybersickness but also enhances walking realism. In this work, we extend the idea of BCV and WalkingVibe by using head vibrations to reduce cybersickness on continuous movement circumstances.

3 DESIGN AND IMPLEMENTATION

Since the overall experience is the key to engaging people into VR. We argue that the technique for reducing cybersickness should not introduce other side effects such as additional discomforts or lower immersions. Our goal is to use head vibration to reduce motion sickness while enhancing the VR experience. There are two reasons why we choose head vibration: First, the head is more sensitive to vibration [44]. Walkingvibe and BCV have shown its effectiveness, and they both suggest that vibration to the head is likely to be conducted to the vestibular system, landing the effect of reducing sensory mismatch. Second, the head vibration can also be seen as a haptic cue that helps the user to make connections between real-life experience and virtual presence in VR. As long as the mental model is established, it is possible to further reduce motion sickness and increase immersion.

3.1 General model of vibrotactile feedback

To generalize the design, we parameterize the vibration pattern into three components: *event*, *mapping*, and *threshold*. *Event* is the selected timing that we apply stimulation. A good choice of timing can help the user connecting the haptic cue and the *event*. If the brain cannot comprehend the timing of the event, it will see the vibration as interference and decrease the user's immersion. A *mapping* from *event* to vibration intensity and the stimulated position of the head can further enhance the connection. Since the sensitivity to vibration varies between individuals, we let users set the lowest intensity they can feel (min_i) and the highest intensity they can endure (max_i), and then maps the intensity of *events* into this range. Setting *thresholds* is for preventing overstimulation to the brain. When the skin receives long-term sustained stimulation, the brain tends to see it as noise and ignore it, nullifying the effect of the stimuli afterward. *Thresholds* can make the feedback occur only when a *event* happens and bypass certain intensity, thus ensure the brain aware of the haptic cues all the time.

3.2 Design concept

In reality, all locomotions, excluded walking and running, can be seen as the body being carried by some moving vehicle. This vehicle could be bicycles, cars, skies, or skateboards, depending on the locomotion itself. In this study, only 2D locomotion is considered. We observed that in the locomotion, the most intensive *events* to the human body is when inertial forces, or pseudo forces, take places. For example, when sudden accelerations or sharp turns happen on vehicles like buses or cars, our bodies would tilt in the opposite direction immediately. These situations are also the ones that cause the most severe motion sickness [18]. Vestibular sensing system consists of two parts: semicircular canals (SCC) and otolithic organs. SCC takes the role of sensing rotations, while otolithic organs respond to linear accelerations [17]. Both vestibular signals are lost during VR locomotion, causing strong mismatches. Thus, selecting the inertial force as *events* for feedback might compensate for the lacked vestibular signals. We then choose to apply vibrations when accelerations, deceleration, left turns, and right turns happen, which are the most common in locomotion, with the patterns corresponding to the four directions of inertial forces.

3.3 Details of vibrotactile design

We refer to Oliver [2] for the position of vibrators on the head, choosing the two outer sides of the forehead and the bottom back of the head (Figure 1ab). These four positions are far away from the ears enough for reducing the discomfort to the vibrations and yield the four sides of vibration that could be distinguished clearly on the head. The two vibrators on the back(LB, RB) are activated when having backward inertial force (e.g. accelerating). Activate the two on the front(LF, RF) when the inertial force leans forward (e.g. deceleration), left ones(LF, LB) when the inertial force shift left (e.g. right turns), and right ones(RF, RB) when the inertial force shift right (e.g. left turns).(Figure 1c) Note that the position of vibrations will subject to change when the user's head turns. For example, if the user turns his head to the right, the inertial force caused by acceleration may shift to the right side of the head. Thus, the RF and RB are activated.

Figure 2: (a) Image of the user in the pilot study. (b) The city scene used in the pilot study.

To increase immersion, we map the vibration intensity to the magnitude of the inertial force in the *events*. We use G-force as a measure of how people sense inertial forces. Hence min_i and max_i defined in the previous paragraph are correspond to the *lower threshold* that humans are sensible and the *upper threshold* that humans can endure. According to Cheung [10] , the lowest G-force human can sense is around 0.005G to 0.1G. In the pilot study, we found that the vibration would be overly frequent when the *lower threshold* is below 0.15G, so we take 0.15G as the final *lower threshold*. For the upper one, we observed that the G-force in a normal car ride is less than 1G since an inertial force over 1 G will most likely result in a turnover. Also, it takes 2.8 seconds from 0 to 100 km/h with 1G acceleration, which is over the power of a regular car. Thus we set the *upper threshold* to 1G. In summary, when navigating in the virtual environment, the vibrators are inactive if the G-force is below 0.15G and constantly output max_i when G-force is above 1G. We take linear interpolation for the vibrator intensity if the G-force is between these two values, so the user can fell the force varying.

3.4 Vibrotactile prototype

For comfort and easy wearing purposes, we plug four ERM vibrators(Parallax, 12 mm coin type, 3.3 V, 90 mA, 9000 rpm) into the sponge of the face cushion on HMD.(Figure 1ab) We attach Arduino Nano to the front of HMD and connect it to USB type-c port on the HTC Vive Pro. The VR content is made with unity v2019. The viewer's acceleration of locomotion is computed frame-wise. When the magnitude is over the *lower threshold*, it calls Arduino to output the corresponding vibration pattern as mentioned before. The vibration motors are controlled by PWM signals range from 100 to 240 that can produce 90Hz to 185Hz of vibration frequency.

3.5 Pilot study

We conducted a pilot study to have better insights on how users think about the vibrotactile feedback in two scenarios (active vs passive). 12 participants were recruited. They were asked to navigate through the city along a certain path indicated by green halos.While half of them could control their movement, half of them took the ride passively. All participants finished the ride twice, one with head vibration applied and one without.

Judged from the users' feedback, their opinions on the vibration were positive. Most users reported improvement of both realism and immersion, and they generally felt less discomfort. However, some claimed that the vibration acted like interference due to the high intensity. We observed that when two directional inertial forces occur at the same time, three of four vibrators will be stimulated. Some participants who are sensitive to the intensity may feel discomfort. We then decided to provide one-directional vibration at a time and turns will have a higher priority to be stimulated. We also observed more sickness in passive mode than in active mode. This is also suggested by the prior work [39] showing that passengers in a car are expected to obtain more sickness than the driver, as they might have difficulties predicting car conditions such as the timing of brake. Moreover, in active mode, the timings of accelerations, brakes, and turns differ from person to person due to driving habit differences, thus the stimuli in the experiment cannot be controlled well. In the end, we will only include the passive mode in the evaluation.

4 FUTURE WORK

We will continue conducting a within-subject three-session multi-day experiment to test the effectiveness of reducing cybersickness and the subjective measures of realism, immersion, and enjoyment between three conditions: a) the unmodified condition, b) applying bone-conducted vibration, and c) assisting with head vibration.

However, our technique only considers the four directions of inertial force for now and is only applicable to 2D locomotion. We may consider using [2] to realize the mapping directions of 3D forces and even the transferring process of the force in the future.

5 CONCLUSION

This paper proposed an approach to alleviate cybersickness in VR locomotions by a haptic feedback design that gives head vibrations corresponding to the events of inertial force in the VR environment. We conducted an pilot study to evaluate how user opinions about vibrotactile on head and most of them gave postive feedback. We will do the evaluation and put our effort into investigating the feedback design of self-rotations and 3D locomotion in the future.

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