Handsfree Omnidirectional VR Navigation using Head Tilt

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ABSTRACT
Navigating mobile virtual reality (VR) environments is a challenge due to limited input options and a requirement for handsfree input. Walking-in-place (WIP) input is more immersive than controller input but WIP only allows unidirectional navigation in the direction of the user's gaze. Leaning input enables omnidirectional VR navigation but relies on bulky controllers, which aren't feasible in mobile VR contexts. This note explores the use of head-tilt to allow for handsfree omnidirectional VR navigation on mobile VR platforms. Head-tilt can be implemented using inertial sensing and requires no additional sensors, and allows users to specify a direction of travel by tilting their head. A user study with 24 subjects compares three input methods using an obstacle avoidance navigation task: head-tilt alone (TILT), WIP with tilt (WIP-TILT), and traditional controller input. TILT was significantly faster and less error prone than both WIP-TILT and controller input, while WIP-TILT was considered most immersive. No differences in cybersickness between input methods were detected.

ACM Classification Keywords
I.3.7 Graphics: 3D Graphics and Realism–Virtual Reality;

Author Keywords
Virtual reality; locomotion; mobile VR; walking-in-place; head-tilt; simulator-sickness; games; inertial sensing

INTRODUCTION
Virtual reality (VR) has recently enjoyed significant commercial success, but virtual navigation has remained a challenge [7, 21]. Low-cost VR smartphone adapters, like Google Cardboard [1], have the potential to bring VR to the masses, but their input options are limited [28]. Using positional tracking for VR navigation generally delivers the most immersive experience [24] with a low possibility of inducing cybersickness [29, 25]. Positional tracking input isn't feasible on mobile VR, as it generally requires external instrumentation or high-end depth cameras to reliably track movement. Another constraint for Cardboard is the lack of a headstrap, meaning that users need to hold the adapter with both hands. This is to limit the rotation speed of the head and minimize cybersickness, but it also bars the use of a controller.

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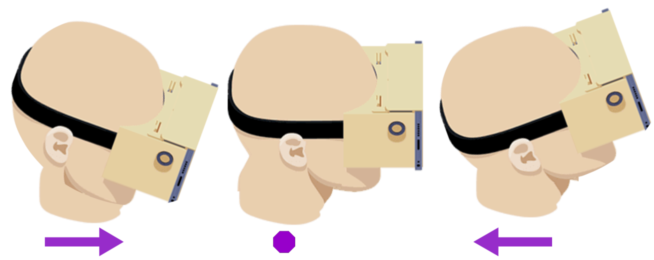

Figure 1. Head tilt is used to indicate the direction of travel

Walking-in-place (WIP) [23] most closely approximates positional tracking in terms of immersion [24, 35] and efficiency [22]. Compared to a controller, WIP is more immersive [24], allows for better spatial orientation[17]; and reduces cybersickness [15]. However, where a controller offers 360° omnidirectional movement, current WIP implementations only navigate the user in the direction of their gaze. This leads to inefficient navigation for certain scenarios. For example, when a user wants to back up a little bit, it requires them to turn around, move forward and turn around again.

When walking, humans naturally lean their body and head in the direction they travel [13]. Leaning interfaces exploit this natural characteristic and are widely used, for example, in popular hover-boards. Both controller and leaning interfaces offer omnidirectional navigation, but the latter is handsfree and also maintains equilibrioception, i.e., sense of balance, which has found to increase immersion [34]. Leaning interfaces have been explored for virtual navigation [34, 20], but such interfaces are difficult to facilitate on mobile VR platforms, as they rely on bulky external hardware [34, 20, 11].

This note explores augmenting gaze-based navigation using head-tilt to enable handsfree omnidirectional VR navigation. Because head-tilt is similar to whole body leaning, we anticipate it could maintain equilibrioception, and thus potentially be more immersive than joystick input. To address one of the current limitations of WIP, we evaluate a novel WIP implementation that uses head-tilt input (WIP-TILT) to allow for omnidirectional navigation. This is a novel locomotion method that provides both proprioceptive and equilibratory feedback. Head-tilt input can be facilitated using inertial sensing on mobile VR platforms and does not require any extra instrumentation. We make the following contributions: (1) a detailed description of how to implement head-tilt for VR navigation and what tradeoffs to make; and (2) quantitative and qualitative results from a user study with 24 subjects that compares TILT, WIP-TILT, and controller input.

BACKGROUND

Currently, controllers are most commonly used for VR navigation, but because they don't offer proprioceptive and vestibular feedback they offer low immersion [6] and carry a higher risk of inducing cybersickness [15]. Various virtual locomotion techniques exist, but because we focus on mobile VR contexts, we survey methods that offer handsfree input.

WIP [23] is handsfree and as efficient as controller input [12]; but it is more immersive [24]; allows for better control over velocity [27]; and better spatial orientation [17]. Various WIP implementations are available but these rely on external cameras [23, 37, 26] or bulky hardware [36, 10, 5] which aren't feasible to use in mobile VR contexts. VR-step [28] is a WIP implementation using inertial sensing that is available on mobile VR platforms, without any extra sensors. A user study with 18 subjects compared VR-step to an auto-walk technique and found no differences in performance or reliability, though VR-step was found to be more immersive and intuitive. A limitation of current WIP implementations is that they don't support omnidirectional navigation.

Leaning interfaces offer handsfree omnidirectional VR navigation and though they don't stimulate proprioception like WIP, they maintain equilibrioception, which has found to be beneficial to immersion [34]. Laviola [18] explores leaning input to enable handsfree navigation in a 3D cave, but no comparative user studies were performed. ChairIO [3] embeds sensors in a single legged stool with a tilting spring mechanism to allow for 3 degrees of freedom (DOF) leaning input. Some results from user studies are reported, but it has been argued that seated leaning interfaces have limited immersion [20]. Both De Haan [11] and Valkov [30] explore the use of a low cost Wii balance board to enable 2 DOF leaning input for VR navigation. Though these approaches use low-cost commercially available hardware, no comparisons to other techniques are made.

Joyman [20] is a 2 DOF leaning interface inspired by a joystick. It embeds an inertial sensor in a wooden board with metal handrails that is placed inside of a mini trampoline. When a user leans in a direction the board elastically tilts in the same direction. A user study with 16 participants compares Joyman to joystick input and found joysticks to be more efficient with no difference in error. Joyman was found to be more fun, more immersive and offer better rotation realism than joystick input. Wang et al. [34] explores the use of a leaning based surfboard interface that offers 3 DOF leaning input. A user study with 24 subjects compares two different modes (isometric/elastic) and found the elastic mode to offer higher intuition, realism, presence and fun but was subject to greater fatigue and loss of balance. A follow up study evaluated frontal and sideways stance [33] and found a frontal stance is best.

Closely related are also the following approaches. Handsfree input is often required to make computers more accessible to users with severe motor impairments but who still retain dexterity of the head. Head tracking has been explored to let quadriplegics control a mouse pointer on the screen [4].

IMPLEMENTATION OF HEAD-TILT NAVIGATION

The implementation of head-tilt was largely inspired by the Joyman leaning interface [20], which imagines the user's body to be a joystick. Our approach differs as we appropriate the head into a joystick. An upward vector $\vec{o}$ is defined as pointing straight upwards (aligning with the negative gravity vector $\vec{g}$) when the user looks straight ahead. The angle α between $\vec{o}$ and $\vec{g}$ is defined as: $\alpha = \vec{o} \cdot \vec{g}$ and is 0° when there is no tilt (see figure2). Because the user wears a smartphone on their head, both $\vec{o}$ and $\vec{g}$ can be measured using its gyroscope.

Several tradeoffs should be considered when mapping head-tilt to virtual motion. When using only head-tilt as input for navigation (TILT), we sacrifice some freedom of being able to look around. When α exceeds a predefined threshold p the user's avatar will move in the direction of vector $\vec{m}$, which is the projection of $\vec{o}$ onto the XZ plane.

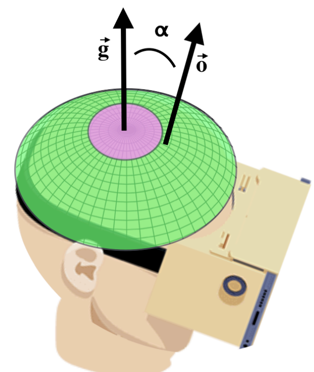

Figure 2. defining head tilt using vectors

Once α exceeds threshold p, immediate acceleration to a predefined velocity V might cause cybersickness, certainly for lateral movements [32]. It might be better to gradually accelerate to V or interpolate the velocity between 0 and a value q that is reached for some maximum value of α to allow for more precise navigation as users can control their velocity. The value chosen for p determines how much freedom a user still has to look around versus the amount of head tilt that needs to be provided for navigating. This requires a careful tradeoff; requiring too much tilt is inefficient and limits users' ability to see where they are going where a low value of p doesn't allow users to look up or down. A previous study that analyzed free form navigation in VR [14] found that forward motion (47%) or forward+steering (37%) are the most frequently used inputs. Given these results, one could implement different values of p depending on what quadrant $\vec{m}$, lies, e.g., implement a small value for p for forward tilt and larger values for the other directions as these are less likely to be used and users cannot see in those directions anyway.

To avoid this tradeoff altogether, looking around and triggering motion should be decoupled using a state transition. Given the limited input options of mobile VR we developed a solution that can enable this handsfree. When augmenting WIP with head-tilt (WIP-TILT), detected step input can act as a trigger for navigation, while still allowing users to look around when they do not walk. WIP-TILT is unique in that it combines the best of WIP and leaning interfaces, as it generates both proprioceptive and equilibratory feedback; which could potentially be most immersive.

EVALUATION

Previous work [20, 34] has only evaluated full body leaning interfaces. In this note we evaluate head-tilt for navigation using a mobile VR headset. Specifically, we evaluate head-tilt by itself (TILT) and a modified version of WIP (WIP-TILT). The performance of both input techniques is compared to conventional joystick input.

Instrumentation

We used the Samsung Galaxy S7 smartphone and the Samsung Gear VR adapter. This setup offers a 1280x1440 per-eye resolution at 60Hz with a 96° FOV. For the joystick input, we used a SunnyPeak Wireless Bluetooth Controller.

Virtual Environment

Our navigation task was inspired by a complex navigation task that tests the robustness of a bipedal robot [9]. Participants have to navigate through a large corridor with obstacles (chest-height rectangles) protruding out of the ground. These obstacles were positioned in a way such to encourage user to use lateral movements rather than just steering forward motion. When a user collides with an obstacle, the obstacle turns red and a large amount of friction was applied, to force participants to navigate entirely left, right, or backwards to stop colliding with the obstacle. The obstacles were also placed so that there was always a minimum space of 2 obstacle-widths between them, to prevent unavoidable collisions. Each corridor was a 170 meters long and five different corridors were generated and we made sure each one was traversable. Figure 4 shows the corridor and a visualization of colliding into an obstacle.

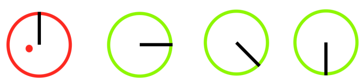

Figure 3. Reticle shows: 1) no; 2) right; 3) right-back; 4) back motion.

To implement our navigation task, an Android app was built using the Unity 5.0 game engine and the Google Cardboard SDK. TILT and WIP-TILT were implemented as described in the previous section. Using experiments, we found a value of $p = 9°$ to work best. WIP was implemented using an algorithm presented in [28] and which was available as a Unity plugin [2]. The virtual locomotion velocity of WIP depends on step frequency but to minimize for any differences in performance the maximum velocity for both WIP-TILT,TILT and joystick input was set to 8m/s, which is reached with a step frequency of 2 steps a second (average human walking speed). To provide feedback on navigation, we created a reticle that indicates the direction of movement (see Figure 3). For the joystick task, the reticle shows the direction in which the thumb stick is pressed.

Procedure and Data Collection

We used a mixed design where we assigned participants to 3 different groups, each group testing and evaluating two of the navigation methods. Group 1 evaluated WIP-TILT and TILT, group 2 evaluated WIP-TILT and Joystick, and group 3 evaluated TILT and Joystick. Within each group, we controlled for order effects by counterbalancing the order of navigation methods. To collect information about cybersickness, we used the Simulator Sickness Questionnaire (SSQ) [16]; a standardized questionnaire that quantifies various aspects of simulation sickness. Before the trial, basic demographic was collected using a questionnaire and participants filled in an SSQ to get a baseline reading. Prior to each trial, participants

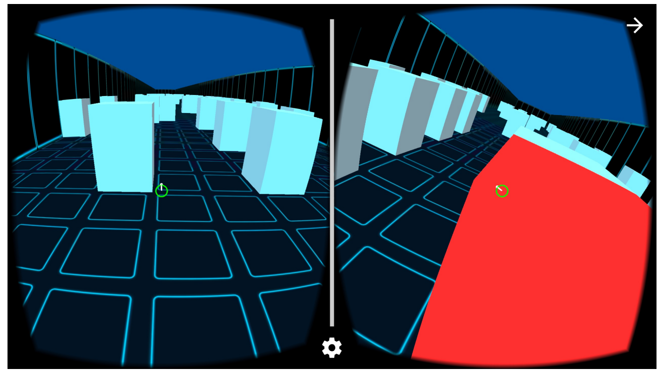

Figure 4. Left: navigation task showing corridor with the obstacles the participant users must navigate through, Right: when colliding with an obstacle it turns red and becomes sticky which requires users to navigate laterally.

performed a training task to familiarize them with the navigation task.

User studies were held in a large open lab space free of any obstacles or interference, and participants were fitted with the VR headset. Participants found themselves in a large open virtual space where a built in tutorial explained how the reticle works. The tutorial asks users to navigate in each one of the 8 primary directions for a few seconds and upon successfully completing this they moved on to the main navigation task. The navigation task asks users run through a corridor as fast as they can without hitting any obstacles. Each participant needed to run through the five different corridors where we measure the task completion time (seconds) and the number of collisions with the obstacles. Every participant runs through the same sequence of five corridors. After each trial participants took off the headset and filled in an SSQ, as well as a questionnaire to collect qualitative feedback about the navigation method they just experienced. They then rested for 10 minutes before doing the second trial using their second navigation method.

Participants

We recruited 25 participants (6 females, average age 26.33, SD 4.5) for our study. Individuals who self-reported [31] to have previously experienced simulator sickness were excluded from participation, as they were at a higher risk of not completing the study. None of the subjects self-reported any non-correctable impairments in perception or limitations in mobility. One person with no VR experience dropped out due to cybersickness after the first trial and their results are not included in our analysis. User studies were approved by an IRB. Nine participants owned a VR headset. Five of participants had no VR experience, and fourteen reported having some VR experience while six reported having lots of VR experience.

Results

The average results for trial time, obstacles hit and SSQ score for each navigation technique are listed in table 1. There was a statistically significant difference between navigation methods as determined by a one-way ANOVA ($F_{2,427} = 20.78, p = .000$). Post-hoc tests found a significant difference between

	TILT	WIP-TILT	joystick
Time(s)	31.22 (5.2)	45.36 (20.9)	44.83 (20.1)
Obstacles(n)	5.05 (4.8)	6.35 (4.1)	7.06 (5.4)
Nausea	26.83 (34.4)	29.22 (18.9)	30.41 (28.4)
Oculomotor	19.42 (23.0)	17.06 (12.8)	21.79 (24.0)
Disorientation	30.45 (29.7)	28.71 (32.7)	35.67 (49.8)
SSQ-total	28.28 (30.8)	27.58 (17.0)	32.26 (34.6)

Table 1. Quantitative results (standard deviation).

TILT and Joystick for both trial time ($p = .017$) and obstacles hit ($p = .000$) and between TILT and WIP-TILT for both trial time ($p = .000$) and obstacles hit ($p = .034$). There were no differences in trial time ($p = .869$) and obstacles hit ($p = .349$) for joystick and WIP-TILT. Overall TILT was significantly faster and better in avoiding obstacles than the other two methods. We did not find significant difference in total and sub-SSQ scores between methods. The average total severity scores, which had a maximum possible value of 235.62, would rank between no and mild cybersickness [16].

We asked users to rate each method in terms of efficiency, learnability, accuracy, likability, and VR immersion using a 5 point Likert scale. The results are summarized in Figure 5. A one-way ANOVA found a significant difference for efficiency ($F_{2,45} = 5.09, p = .001$), learnability ($F_{2,45} = 7.33, p = .002$), errors ($F_{2,45} = 4.08, p = .002$), likeability ($F_{2,45} = 5.17, p = .001$) and immersion ($F_{2,45} = 10.39 p = .000$). Post-hoc tests found a significant difference between TILT and WIP-TILTfor efficiency ($p = .005$), learnability ($p = .0013$), errors ($p = .0005$), likeability ($p = .0026$), and immersion ($p = .000$). There were also significant difference between TILT and joystick for learnability ($p = .0045$) and immersion ($p = .0006$).

We also asked users to rank navigation methods on efficiency, immersion and likeability and we aggregated results. 12 participants thought TILT was most efficient, and 3 WIP-TILT ,8 joystick and 1 having no preference. 13 participants ranked WIP-TILT to be most immersive and 5 TILT , with 6 stating no preference. 12 participants liked TILT the best and 4 TILT ,6 joystick and 2 having no preference. A χ^2 test found the rankings for efficiency ($p = .001$), immersion ($p = .005$) and likeability ($p = .003$) to be statistically significantly different.

General feedback included: users liked the joystick's ease of use, but felt it did not feel realistic, and felt it was "more jerky and less smooth" when compared to TILT. For TILT, some users said they needed to tilt forward more than they would like, and some commented that it didn't feel realistic, but they generally thought that it was easier to use and more accurate. For WIP-TILT, participants liked how natural and realistic it felt, but some participants complained about drifting, and felt nervous walking-in-place when not being able to see the real environment.

DISCUSSION AND LIMITATIONS

We did not expect to see any significant differences for performance, especially since locomotion velocity was set to the same value, so it was interesting to see how much better TILT performed. On average, TILT finished each trial 15 seconds faster and with 1-2 fewer obstacles hit than the other two methods. With TILT, users only needed to lean forward to move, and lean left or right to make small corrections, while using WIP-TILT they had to actively provide step input to maintain speed. Participants were most familiar with joystick input, but surprisingly performed the worst with it and also ranked it the lowest. Participants seemed to like TILT the most across all criteria other than immersion. Because WIP-TILT generates proprioceptive and equilibriotary feedback, we expected it to be most immersive. Participants ranked WIP-TILT to have the highest immersion, but felt that it was harder to learn and was the least accurate, which conflicts with another study [27] that found WIP to be more accurate than joystick input.

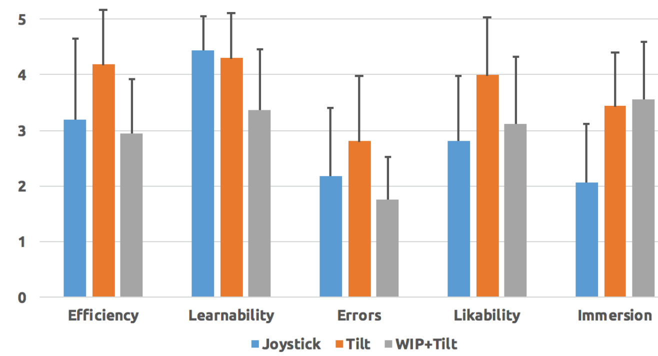

Figure 5. Avg Likert scores and standard deviation for each method

We did not detect any significant differences for cybersickness between the three input methods. This does seem to be contrary to other studies [15, 8, 19], which found significantly higher cybersickness scores for joystick input than with other control methods. For our experiment, we may not have had users exposed to VR long enough to induce cybersickness.

WIP input require participants to walk deliberately with a "bounce" in their step, which may not have felt natural for everyone. Some participants also tended to drift from a central position while walking-in-place, sometimes moving so far that we had to actually stop them mid-trial and reposition them. This might have lead to higher average task completion times. Drifting is a known problem with WIP [28], but we observed much higher amounts of movement drift with the WIP-TILT method. It's possible that by requiring the user to tilt their head in a direction, we offset their natural balance enough to exacerbate the movement drift problem.

While TILT was most liked, it's important to note that TILT may not be ideal for all VR situations. In VR applications that require the user to look vertically to see targets or to just experience the environment, the tilt-only control is not ideal as any tilt of the head up or down will result in motion.

Overall our study suggest that TILT is a viable input method for handsfree virtual locomotion that significantly outperforms a joystick, which is currently the most commonly used input device for mobile VR.

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