Handsfree Omnidirectional VR Navigation using Head Tilt

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ABSTRACT

Navigating mobile virtual reality (VR) is a challenge due to limited input options and/or a requirement for handsfree interaction. Walking-in-place (WIP) is considered to offer a higher presence than controller input but only allows unidirectional navigation in the direction of the user's gaze–which impedes navigation efficiency. Leaning input enables omnidirectional navigation but currently relies on bulky controllers, which aren't feasible in mobile VR contexts. This note evaluates the use of head-tilt –implemented using inertial sensing– to allow for handsfree omnidirectional VR navigation on mobile VR platforms. A user study with 24 subjects compared three input methods using an obstacle avoidance navigation task: (1) head-tilt alone (TILT); (2) a hybrid method (WIP-TILT) that uses head tilting for direction and WIP to control speed; and (3) traditional controller input. TILT was significantly faster than WIP-TILT and joystick input, while WIP-TILT and TILT offered the highest presence. There was no difference in cybersickness between input methods.

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 [8, 23]. Low-cost VR smartphone adapters, like Google Cardboard [4] have the potential to bring VR to the masses, but their current input options are limited [32]. Positional tracking input generally delivers the most immersive experiences with a low possibility of inducing cybersickness [33, 28]. Positional tracking generally isn't available on mobile VR platforms, as it is computationally intensive and requires a depth camera to reliably track movement, which aren't available on smartphones. Another constraint for Cardboard is the lack of a head-strap; which forces users to hold the adapter with both hands and limits the rotation speed of the head to the torso to minimize cybersickness [4]. Though useful– this constraint prevents using a controller for navigation.

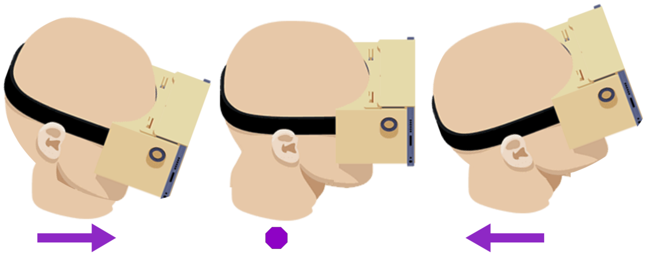

Figure 1. Head tilt is used to indicate the direction of travel

Walking-in-place (WIP) closely mimics walking, e.g., users provide step-like motions while remaining stationary [29]. WIP closely approximates real walking input in terms of performance [25] and presence [27]. Compared to a controller, WIP is handsfree; offers higher presence [33]; improves spatial orientation [19]; and is less likely to induce cybersickness [16], because of the generation of proprioceptive feedback. However, a controller allows for 360° omnidirectional navigation, where WIP only navigates users in the direction of their gaze. This impedes navigation efficiency, for example, if a user wants to back up a little bit, it requires them to turn around, move forward, turn around again and then move to where they want to be. Because prior studies [25, 13, 27, 37] have only evaluated navigation tasks that include forward motion, they find a similar performance for WIP as controller input. However, these results are misleading, as VR navigation also contains lateral movements [15] and controller input outperforms WIP as it allows omnidirectional navigation.

As a result of bipedalism, humans lean their body in the direction they walk; to align with the gravitational vertical [14]. Leaning interfaces exploit this characteristic and are widely used, for example, in popular hoverboards. Leaning interfaces have been explored for virtual navigation [36, 22]. Like a controller they offer omnidirectional navigation with a significant difference that leaning interfaces are handsfree. Controller input is faster but leaning interfaces offer a higher presence [36] because they generate vestibular feedback. Current leaning interfaces are difficult to enable on mobile VR platforms, as they rely on bulky sensors [36, 22, 12].

This note explores augmenting gaze-based navigation with head-tilt input to enable handsfree omnidirectional VR navigation. Because head-tilt is similar to whole body leaning, we anticipate that similar to prior results [36] it could offer a higher presence than controller input. To improve WIP, we evaluate a hybrid method (WIP-TILT) that uses head tilt to indicate a direction of travel and WIP to control locomotion speed. WIP-TILT is novel in that it offers both proprioceptive and vestibular feedback and thus approximates real walking input much more closely than current WIP implementations; which could improve presence and reduce cybersickness.

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BACKGROUND

Because we focus on mobile VR contexts, we survey locomotion techniques that offer handsfree input.

Leaning interfaces offer handsfree omnidirectional VR navigation and though they don't stimulate proprioception like WIP, they generate vestibular feedback, which was found to be beneficial to presence [36]. Laviola [20] explores leaning input to enable handsfree navigation in a 3D cave, but no comparative user studies were performed. ChairIO [6] 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 presence [22]. Both De Haan [12] and Valkov [34] explore the use of a low cost Wii balance board to enable 2 DOF leaning input for VR navigation. Though they use commercially available hardware, no comparisons with other techniques are made. Joyman [22] 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 a joystick to be more efficient with no difference in error. Joyman was found to be more fun, offer a higher presence and generate better rotation realism than joystick input. Wang et al. [36] 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 [35] and found a frontal stance to offer a better performance.

WIP [26] offers handsfree locomotion and a higher presence than a controller [33]; it also allows for better control over velocity [31]; and offers better spatial orientation [19]. Various WIP implementations exist but these rely on external cameras [26, 38, 30] or bulky hardware [37, 11, 7] which aren't feasible to use in mobile VR contexts. In previous work, we developed VR-step [32]; a WIP implementation that can be facilitated on mobile VR platforms using existing inertial sensors. A user study with 18 participants compared VR-step to a gaze activated auto-walk technique and found no differences in performance or reliability, though VR-step was found to be most intuitive and have a higher presence. A current limitation of WIP is that it only offers unidirectional navigation.

A criticism of existing WIP studies [25, 13, 27, 37] is that they have mostly included navigation tasks that use a straight/forward trajectory [31], which isn't very realistic for many VR applications. In a previous study, we analyzed free form navigation in a 3D virtual environment [15] and found that pure forward motion only constitutes 47% of used inputs –where forward+lateral and lateral input were used 37% and 15% correspondingly. Prior studies did not detect a significant difference in performance between WIP and controller input, but one could argue that because they don't evaluate lateral navigation, these results are not representative for VR navigation in general and WIP is likely to perform worse.

Most closely related to our work is the following. Graveyard [1] and Slender [3] are Cardboard apps that use head tilt for navigation. Concurrent to our previous work [32], Pfeiffer [24] presents a WIP implementation using inertial sensing, which allows backwards navigation when the user tilts their head backwards. A similar mechanism is available in Gravity Pull [2]; a VR puzzle game that we developed to illustrate VR-step. Both WIP implementations offer bidirectional navigation, where in this note omnidirectional navigation is explored.

IMPLEMENTATION OF HEAD-TILT NAVIGATION

An upward vector $\vec{o}$ is defined and initially points straight upwards (aligning with the negative gravity vector $\vec{g}$) when the user looks straight ahead. When the user tilts their head vector $\vec{o}$ changes with it. 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 figure 2). Because the user wears a smartphone on their head, both $\vec{o}$ and $\vec{g}$ can be measured using its gyroscope.

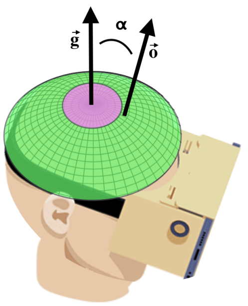

Figure 2. head tilt defined using vectors.

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. Either full 360° navigation can be implemented or it can be mapped to four cardinal directions, as users may associate this more with how a joystick works. Once α exceeds threshold p, we could immediately move the user with a predefined velocity V. Alternatively, we can interpolate the velocity between 0 and a value q that is reached for some maximum value of α to allow users to control their velocity and to allow for more precise navigation. The value chosen for p needs to be considered carefully, as it determines how much freedom user has to look around versus the amount of effort, i.e., head tilt that needs to be provided for navigation. Given the likelihood of certain types of input 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 limiting looking around, a better solution is to decouple direction provision from velocity manipulation using a state transition. Given the limited input options of mobile VR, a handsfree solution includes augmenting WIP with head-tilt, where step input triggers velocity and head-tilt determines direction. WIP-TILT is unique in that it generates both proprioceptive and vestibular feedback; and thus more closely resembles real walking input –which could offer higher presence than WIP or leaning input. There is some evidence that proprioceptive feedback generated using WIP [16] can minimize visual-vestibular induced cybersickness. With postural instability also being a cause [17]; adopting a more natural head pose during VR locomotion might further minimize the occurrence of cybersickness.

EVALUATION

Previous work [22, 36] 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 an improved version of WIP (WIP-TILT) that we described. The performance, usability, presence and the ability to induce cybersickness of both input techniques are compared to conventional controller 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 that featured an analog thumbstick.

Virtual Environment

Our navigation task was inspired by a complex navigation task that tests the robustness of a bipedal robot [10]. 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 users to use lateral movements rather than just steering forward. 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 placed such that there was a minimum space of 2 obstacle-widths between them, to prevent unavoidable collisions. Object avoidance tasks can be found in many 3D games. Navigating backwards illustrates WIP's current limitation, but this scenario was not evaluated as backwards input is rarely used ($<$1.2% [15]).

Each corridor was 170 meters long. 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. To implement our navigation task, an Android app was built using the Unity 5.0 game engine and the Google Cardboard SDK. Both TILT and WIP-TILT were implemented as described in the previous section. Using experiments, we found a value of $p = 9^\circ$ to work best. WIP was implemented using an algorithm presented in [32] and which was available as a Unity plugin [5].

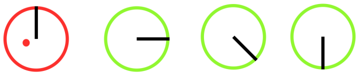

Figure 3. Reticle shows: 1) no 2) right 3) right-back 4) back motion.

The virtual locomotion velocity of WIP depends on step frequency but to minimize 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 (i.e., average human walking speed). We did not apply any low-pass filtering to translate raw joystick and tilt values to velocity. To provide feedback on navigation, we created a reticle that indicates the direction of movement (see Figure 3).

Procedure and Data Collection

We used a mixed design where we assigned participants to three 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) [18]; a standardized questionnaire that quantifies various aspects of simulation sickness. Before the trial, basic demographic information was collected using a questionnaire and participants filled in an SSQ to get a baseline reading.

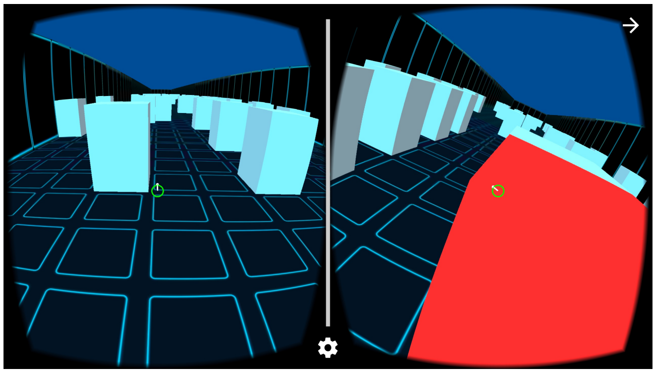

Figure 4. Left: navigation task showing corridor with the obstacles the participant users must navigate. Right: when colliding with an obstacle it turns red and becomes sticky; requiring users to navigate laterally.

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 cardinal directions for a few seconds and upon successfully completing this task 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 ran through five different corridors where we measured the task completion time and the number of collisions with the obstacles. Every participant navigates 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 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 participants 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. All participants had prior experience with navigating 3D environments using a controller.

	TILT	WIP-TILT	joystick
Time(s)	30.74 (4.2)	44.11 (17.7)	43.03 (16.8)
Obstacles(n)	5.05 (4.8)	5.99 (3.4)	6.84 (5.1)
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).

Results

A Grubbs test was used to filter outliers (5 for trial time, 3 for obstacles) and the average results for trial time, obstacles hit and SSQ scores are listed in table 1. A one-way MANOVA found a statistically significant difference between locomotion techniques for trial time and obstacles hit ($\boldsymbol{F}_{4,456} = 10.133$, $p < .001$, Wilk's $\lambda = .843$, partial $\varepsilon^2 = .082$). There was homogeneity of variances, as assessed by Levene's Test ($p > .05$). Tukey post hoc analysis found a significant difference between TILT and Joystick for both trial time ($p < .001$) and obstacles hit ($p = .021$) and between TILT and WIP-TILT for trial time ($p < .001$) but not for obstacles hit ($p = .195$). There were no differences in trial time ($p = .961$) and obstacles hit ($p = .611$) between joystick and WIP-TILT.

A Kruskal-Wallis did not find significant difference ($p > .05$) 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 [18].

We asked users to rate each method in terms of efficiency, learnability, accuracy, likability, and presence using a 5 point Likert scale. The results are summarized in Figure 5. A Kruskal-Wallis test found a significant difference for efficiency ($\chi^2 = 9.04, p = .001$), learnability ($\chi^2 = 8.81, p = .001$), likeability ($\chi^2 = 8.81, p = .001$) and presence ($\chi^2 = 13.59, p < .001$). Mann-Whitney post hoc tests found a significant difference between TILT and WIP-TILT for efficiency ($p = .002$), learnability ($p = .017$), errors ($p = .015$), and likeability ($p = .024$). There were significant differences between TILT and joystick for likeability ($p = .007$) and presence ($p = .002$).

We also asked users to rank navigation methods on efficiency, presence 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 have highest presence and 5 TILT , with 6 stating no preference. 12 participants liked TILT the best, and 6 joystick and 4 WIP-TILT,and 2 had no preference. A χ^2 test found the rankings for efficiency ($p = .001$), presence ($p = .005$) 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. Participants liked how natural and realistic WIP-TILT felt, but some participants complained about drifting, and felt nervous about WIP when not being able to see the real environment.

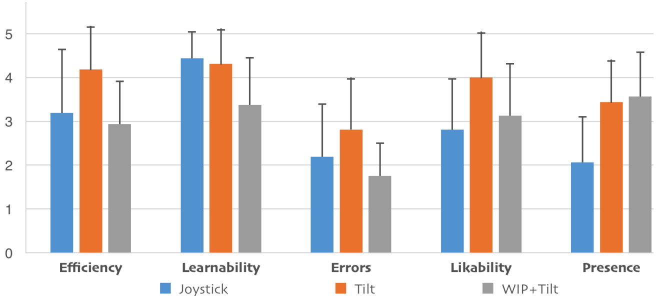

Figure 5. Avg Likert scores and standard deviation for each method

DISCUSSION AND LIMITATIONS

Because locomotion velocities were paired, we anticipated no difference in performance, so TILT's superior performance was unexpected. On average, TILT finished each trial 14 seconds faster with 1-2 fewer obstacles hit than the other two methods. With TILT, users only needed to tilt their head forward to move, and lean left or right to make small corrections. WIP-TILT requires more physical effort as in addition to steering with their head, participants also had to actively provide step input with their legs to maintain speed. Though participants were most familiar with joystick input, it ended up having the worst performance and also received the lowest rankings.

Another significant result is that we found no difference in performance between WIP-TILT and joystick input. This is a good result given that previous WIP studies have not evaluated lateral motions [25, 13, 27, 37] while lateral motions are typically used in VR navigation [15]. This result makes WIP-TILT– an improved version of WIP–a feasible alternative to joystick input especially considering that it is handsfree and requires no instrumentation.

Regarding presence, because WIP-TILT generates both proprioceptive and vestibular feedback, we expected this to be higher –based on previous results [36, 16]. Participants ranked WIP-TILT to have the highest presence, though they felt that it was harder to learn and that it was the least accurate.

Regarding cybersickness, the data did trend towards what we expected, e.g., higher cybersickness scores in the disorientation subscale overall, and higher scores for joystick input. However, there ended up being no significant differences between the three input methods. This result contradicts prior studies [16, 9, 21] that found joystick input to lead to significantly higher cybersickness scores. Overall there was a low incidence of cybersickness because participants may not have been exposed to VR long enough to induce it. In addition, 83% of our participants already had VR experience and the use of a high-end mobile VR headset (Gear VR) may have alleviated known causes such as latency and frame rate.

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 that we previously observed [32], but for this study we observed much higher amount of movement drift. Sustained head tilt could offset the user's natural balance enough to exacerbate the movement drift problem.

Currently, a joystick is the most commonly used input device for mobile VR. Our study however, demonstrates that TILT offers a significantly better performance and both TILT and WIP-TILT offer a higher presence than using a joystick. TILT is currently already available in two popular shooter (>100k downloads) Cardboard games [1, 3]. For shooter games TILT is feasible but for VR applications such as Puzzle games, 3D Realty and Museum apps, TILT is not practical because it limits the user's ability to look around. For those cases, it may be preferable to use WIP-TILT or have users trigger head-tilt movement using a button. With recent advances in mobile hand-tracking, e.g., Leap Motion, it is likely that in the near future a controller won't be available to be used for VR locomotion, as users may prefer using hand input. Because positional tracking is limited by available tracking space it doesn't doesn't allow for virtual locomotion at scale. Future work will focus on evaluationg a hybrid locomotion technique that lets users switch between real walking input to either TILT or WIP-TILT to navigate beyond the confines of the available tracking space.

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