2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)

Walking-in-Place for VR Navigation Independent of Gaze Direction Using a Waist-Worn Inertial Measurement Unit

Chanho Park* Kyungho Jang† Junsuk Lee‡

Electronics and Telecommunications Research Institute

Abstract

Many techniques have been proposed for navigation using head-mounted-displays (HMDs) in virtual reality (VR). A walking-in-place (WIP) interface for virtual locomotion provides a high presence and an immersive experience in a virtual environment (VE). However, most of the WIP techniques can only navigate users in the direction of their gaze. Other WIP methods considering virtual locomotion direction have complex configurations or are only feasible when the tracking spaces are not limited. This paper proposes a WIP interface independent of gaze direction based on the data analysis of waist-mounted inertial sensors. Our method can navigate in the locomotion direction by calculating the orientation of the pelvis. We experimentally compared two WIP methods using a navigation task that required participants to periodically observe the surrounding VE: (1) Conventional WIP (gaze-based direction) (2) Proposed WIP (pelvis-based direction). While there was no difference in learnability or cybersickness between the two methods, the proposed method had shorter task time and higher efficiency.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction techniques

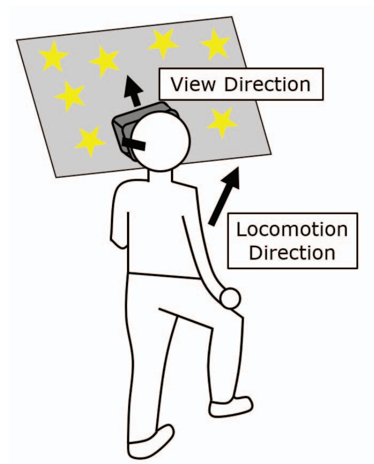

Figure 1: Our WIP technique allows users to walk in the locomotion direction while they turn heads around to see the virtual world.

1 Introduction and Related Work

Navigating a virtual environment (VE) is necessary in almost every 3D interaction task in virtual reality (VR). Using a joystick (e.g. Oculus Touch or HTC Vive Controller) for VR navigation makes it easy to operate and is a common approach. However, this method is not suitable for non-vehicle virtual environments (VEs) and motion sickness is higher in the joystick mode [4]. Natural walking (moving in real space) showed the most realistic interface for virtual locomotion. However, this approach is expensive to configure tracking systems and the tracked space must be the same size as the virtual space [15, 16].

To allow users to perform virtual locomotion in limited tracking space, various walking-in-place (WIP) techniques have been proposed with the users' step-like motions in place as an alternative to the real walking [11]. WIP navigation provides immersive and natural experiences [10] that is almost same as real walking, and it seems to result in better spatial orientation of a VE compared to using a controller [18]. However, most WIP interfaces determine the locomotion direction according to the user's gaze direction [10,12,13,15] which interrupts navigation efficiency because the user's gaze is not free. For example, while we are walking, we can turn our heads around to see the surrounding VE. Other WIP systems distinguished the view direction from the locomotion direction. Feasel et al. [5] detected foot movements using a foot tracker and allowed virtual locomotion in the direction of the chest with a chest-orientation tracker. Wendt et al. [17] attached several LEDs to each shin and used an optical motion capture system to separate the view direction and the locomotion direction (the average of the shins' directions). However, these methods are complicated to configure the hardware system and tracking spaces need to be installed [3, 5, 17]. WIP techniques have also been applied to limited instrumentation (e.g. mobile VR devices). Pfeiffe et al. [9] detected walking from acceleration data of a mobile head-mounted-display (HMD) and separated the head orientation and the body orientation using a low pass filter to allow little head movements. Tregillus et al. [14] used the inertial sensors of mobile HMDs to allow for omnidirectional VR navigation with head tilt. Although these simple algorithms [9, 14] can be configured at a low cost, the methods restrict the users from viewing the VE freely by allowing only partial head movement.

In this paper we propose a WIP interface for VR navigation independent of the user's gaze direction using a waist-worn inertial measurement unit (IMU). Our WIP technique detects steps based on acceleration of the pelvis and determines the virtual locomotion direction using the orientation of the pelvis. Our method can perform a gaze search (searching for a subject by the turn of the head) and virtual locomotion (walking through a VE) at the same time; that way, users can freely see the VEs while walking around in the virtual world (see Fig. 1). We perform a user study to compare our WIP technique (pelvis-based direction) with the conventional WIP technique (gaze-based direction) using an objective and subjective evaluation.

*e-mail: chanho@etri.re.kr
†e-mail: khjang01@etri.re.kr
‡e-mail: leejs@etri.re.kr

2 Implementation

Most previous WIP studies for VR navigation led users to move in the direction of their gaze [10, 12, 15]. The closest related work is proposed by Williams et al. [19]. They proposed a WIP interface

978-1-5386-7592-2/18/$31.00 ©2018 IEEE
DOI 10.1109/ISMAR-Adjunct.2018.00079

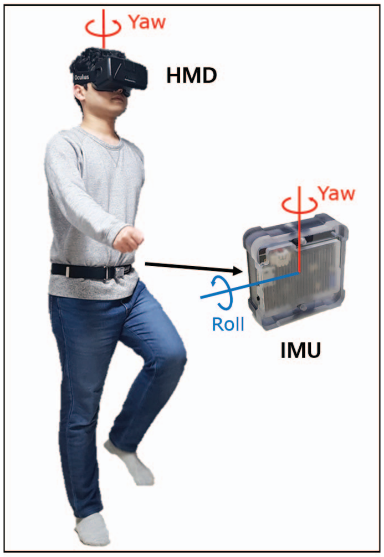

Figure 2: Our system utilizes sensor data from the HMD and waist-worn IMU to provide the view direction and the locomotion direction at the same time.

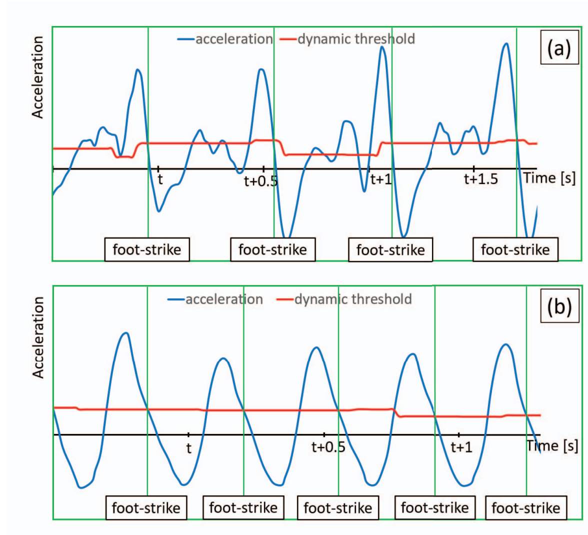

Figure 3: The magnitude of the average acceleration for a WIP movement: (a) Walking mode (b) Running mode

using two Kinect sensors and showed that gaze direction locomotion is better than torso direction locomotion in terms of the users' spatial orientation. However, the experiment was conducted on a simple task that only required users to move towards virtual objects from their memory without vision. And two Kinect sensors are exactly 90 degrees apart and should be installed 2.5m away from the user to recognize the step and the orientation of the body. Compared with related work [19], our approach is a simple configuration based on an IMU, and there is no limit to the space size. Our WIP system provides a natural interface that uses acceleration and orientation data at a 50 Hz frame rate to control the virtual locomotion while allowing head movements to freely view the VE through the HMD (Oculus Rift DK2; 100° field of view (FOV) diagonally). The 9-axis IMU consists of accelerometers, gyroscopes, and magnetometers that are embedded in various wearable devices as well as smartphones and smartwatches. Previous studies [2, 6, 8] applied inertial sensors to several parts of the body (ankle, chest, waist, etc.) for step detection. We adopted the waist as the suitable part for detecting steps and simultaneously tracking the direction of the virtual locomotion. We attached the IMU to the front of a Velcro belt so that users could easily wear it on their waist (see Fig. 2). Additionally, for a variety of VR applications, we evaluated our system through a complex navigation task that not only require walking toward virtual targets but that also perform virtual locomotion while periodically looking at the surrounding VEs which is not considered in the study of Williams et al. [19] (e.g. Users arrive at the target while avoiding obstacles randomly approaching from the side).

2.1 Algorithm

We refer to step detection methods [13, 17, 20] based on inertial sensor data. In a first step, we subtract the contribution of the gravity from the magnitude of the acceleration to determine the user's movement by WIP. We obtain the average of every five acceleration samples. Fig. 3 shows the magnitude of the average acceleration when the user performs WIP ((a) walking mode, (b) running mode). Fig. 3(b) shows a negative slope of the acceleration data in a single step. Using the dynamic threshold (the average of the maximum and minimum values which is updated every 50 samples from the accelerometer) proposed by Zhao [20], we define the timing of the foot-strike as the moment of crossing below the dynamic threshold. However, in the walking mode (Fig. 3(a)), it is difficult to detect foot-strike by dynamic threshold alone, so we use acceleration changes ($acc_{cha} = acc[n] - acc[n-1]$) to detect the exact timing of the foot-strike. We set the range of the acceleration changes $acc_{cha} \geq A_{min}$ for step detection (if $acc_{cha} < A_{min}$, it means that unintended small movements are detected). Once steps are detected, the user's state depends on acc_{cha} per foot-strike as follows:

- If $A_{mode} > acc_{cha}$, walking mode (Fig. 3(a))
- If $acc_{cha} \geq A_{mode}$, running mode (Fig. 3(b))

A_{mode} is determined by comparing the average of acc_{cha} of users' walking and running in place. In the walking mode, we provide the velocity as the default value (V_{min}), and in the running mode, we measure acc_{cha} at the timing of the foot-strike to determine the virtual velocity. Inspired by the velocity equation of Tregillus et al. [13] that is linearly increasing velocity with the time between steps, we set the velocity between $[V_{min}, V_{max}]$ to increase linearly with $acc_{cha} \in [A_{mode}, A_{max}]$ (if $acc_{cha} > A_{max}$, velocity is set to V_{max}) as following equation:

$$V = V_{min} + \frac{acc_{cha} - A_{mode}}{A_{max} - A_{mode}}(V_{max} - V_{min}) \quad (1)$$

Next, we set the moment to stop the step. If every 10 acc_{cha} samples are less than A_{stop}, our algorithm ends the step detection. This algorithm can detect when users perform an unexpected input such as keeping their foot in the air [17]. The changes in the pelvic roll is also used as a factor to determine the stop motion. If foot-strike is not detected for more than 0.5 seconds, we assume that the user has stopped.

The user's view direction is determined by the HMD yaw ($yaw_{head} \in [0, 360])$ which is independent of waist-worn sensor data. On the other hand, the user's locomotion direction is calculated by the yaw which is derived from the waist-worn orientation data (see Fig. 2). To minimize the orientation drift, we calibrate orientation data for every 10 seconds using the magnetometer calibration filter built-in IMU module (E2BOX EBIMU-9DOFV4 [1]). In order to smoothly change the direction of locomotion, we use the average of

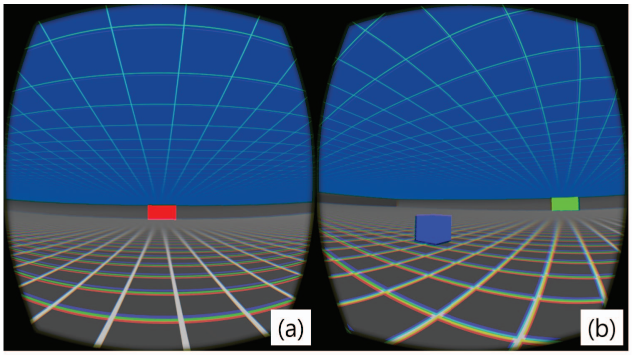

Figure 4: A view of the virtual environment used for the experiment: (a) The color of the rectangular box shown in front of the subject changes according to predetermined conditions. (b) Participants must move to the target (blue cube) while watching the rectangular box.

five yaw samples (yaw_{pelvis}). Finally, we measure the locomotion direction as follows:

- Initialize yaw_{head} and yaw_{pelvis} to be the same when the HMD and the waist-worn IMU are facing the same direction.
- If the difference between yaw_{pelvis} and yaw_{head} is greater than Y_{min}, we allow users to move in the yaw_{pelvis} direction. Otherwise, it is determined that the users want to go straight in the viewing direction, so move in the yaw_{head} direction.

3 Evaluation

Considering the VR application that simultaneously performs the locomotion task and the gaze search task, we designed a complex navigation task that requires the user to get to a target zone while periodically looking at the surrounding VE. The purpose of this experiment was to compare conventional gaze-based WIP (GAZE-WIP) and the proposed pelvis-based WIP (PELVIS-WIP) using performance and subjective evaluation. In our experiment, GAZE-WIP was implemented using the same step detection algorithm as PELVIS-WIP (described in the previous section), but the virtual locomotion direction determined using yaw_{head}. Ten subjects (average age = 26.1 years) participated in our study.

3.1 Instrumentation

Our system used Oculus Rift Development Kit 2 (960 x 1080 per eye resolution at a 75Hz frame rate, 100° FOV diagonally) to view the VEs, and we used the E2BOX EBIMU-9DOFV4 (9 axis IMU with AHRS sensor fusion algorithm) on the waist. We collected sensor data from IMU using wireless serial communication at a 50Hz frame rate. In the user study, participants performed only the walking mode. We set $V_{min} = 2.1 m/s$, $Y_{min} = 1°$ through preliminary experiments. Graphics were rendered using OpenGL.

3.2 Procedure

Participants are located in the center of the virtual room used in the experiment. Fig. 4(a) shows the participant looking straight ahead in the VE. Before the task, the color of the box (box_{color}) is red. The rectangular box shown in front of the subject changes color under the following conditions:

(1) When the task begins, box_{color} changes to green.

(2) After $2s$ to $4s$ (at random) from green, box_{color} changes to yellow.

(3) After $2s$ from yellow, box_{color} changes to red.

Table 1: Quantitative comparison of two WIP interfaces: task time, distance (standard deviation in parentheses)

	GAZE-WIP	PELVIS-WIP
Time[s]	154.49 (43.93)	130.92 (27.91)
Distance[m]	259.38 (19.90)	250.75 (12.22)

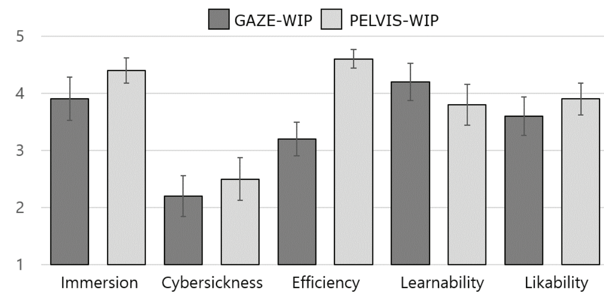

Figure 5: Subjective results for two WIP methods using a 5-point Likert scale.

(4) After $5s$ from red, box_{color} changes to green.

(5) Repeat step (2) to (4).

Each participant takes a front view until the task starts. When the participants hear the start signal, a target (blue cube) appears randomly at a distance from $24m$ away in the range of -90° to 90° (intervals of 20°) around the vertical axis. The target and the rectangular box are inside the FOV in Fig. 4(b), but in some cases the two are not within the FOV at the same time. Our navigation task was performed considering the following conditions:

- If box_{color} is green or yellow, participants can move. Participants should go toward the target.
- If box_{color} is red, participants cannot move. If a step is detected when box_{color} is red, the target is 5m further from the starting point.

When the participants arrive at the target, the first task ends and they automatically return to the starting point, and they wait for the next task while looking straight ahead. They perform the task again in the same way as the start signal. Participants performed 12 tasks (The first two tasks are not reflected in the results) for each WIP method. We measured the time and distance traveled (excluding the time when the box is red). Before the experiment, all the procedure was explained to the participants, and the participants performed two WIP methods so that they were familiar with the setup. We explained to the subjects that the target appears in a random order, while in fact, the target appeared in the same order for each subject (GAZE-WIP: 10°, -50°, 90°, -30°, 30°, 70°, -90°, -10°, 50°, -70°, PELVIS-WIP: 30°, -90°, 10°, -30°, 70°, -50°, 50°, -10°, 90°, -70°). We provided foot-like images as visual feedback that indicated the direction of movement in the VE.

3.3 Results and Discussion

Table 1 shows the navigation time and distance for each of the two locomotion techniques in the experiment. With a repeated-measures ANOVA, we found a significant effect of WIP method on the task time ($F(1,9) = 5.492$, $p = 0.044$) but not on the distance ($F(1,9) = 1.355$, $p = 0.274$). In our analysis of navigation paths, when the rectangular box and the target were not simultaneously within the FOV, we revealed that the participants often stopped walking with

GAZE-WIP when box_{color} was green. Occasionally, they walked in the direction of the box because they saw the box in walking mode. In GAZE-WIP, the participants said that they intentionally stopped and turned their heads to see box_{color}. On the other hand, when considering only the paths where the box and the target appeared within the FOV at the same time, a repeated-measures ANOVA found no significant effect between the two WIP methods for the task time and the distance.

A subjective questionnaire was proposed in which participants ranked each WIP method using a 5-point Likert scale:

- Immersion: Did you actually feel like walking?
- Cybersickness: Did you feel tired during the task?
- Efficiency: Were you able to perform the task efficiently?
- Learnability: Was it easy to learn?
- Likability: If you had this system, would you want to use it?

Fig. 5 shows the summarized results. A Wilcoxon test showed that there was a significant effect of efficiency ($p = 0.003$). No significant effect was found for immersion ($p = 0.266$), cybersickness ($p = 0.375$), learnability ($p = 0.609$) or likability ($p = 0.615$). Before the experiment some participants responded that GAZE-WIP was easy to learn, but after the experiment, they said that it was not realistic because they could not see the surrounding environment while walking. For PELVIS-WIP, two participants said that it was difficult to know their locomotion direction. In the experiment, visual feedback was provided on the floor, but they suggested a first-person view avatar corresponding to their body orientation. Regarding stopping latency, three participants said that it was difficult to stop at the desired timing with the two WIP methods. Our method detected stopping locomotion using only waist-worn sensor data, but it is necessary to analyze the pattern of the movement considering HMD sensor data at the same time.

4 Conclusions and Future Work

In this paper, we presented a walking-in-place (WIP) interface that did not depend on the gaze direction using a low cost IMU worn on the waist. Our experiment compared PELVIS-WIP and GAZE-WIP in a complex navigation task of walking to a target while observing the surrounding environment. The results indicated that there was no significant difference in terms of distance across the two WIP methods, but PELVIS-WIP provided a significantly shorter navigation time and higher efficiency than GAZE-WIP. In future work, we will explore the effect of visual feedback on the locomotion direction when using PELVIS-WIP. In addition, we will explore the effect of FOV on the two WIP techniques in a complex navigation task. We will develop a variety of interfaces for WIP [7] (e.g. strafing or walking backwards).

Acknowledgments

This work was supported by Institute for Information and communications Technology Promotion(IITP) grant funded by the Korea government(MSIT) and Korea Creative Content Agency(KOCCA) grant funded by the Korea government(MCST)(R0132-15-1006, Developing the technology of open composable content editors for realistic media).

References

[1] E2BOX. Available online: http://www.e2box.co.kr (accessed on 18 June 2018).

[2] J. C. Alvarez, D. Alvarez, A. López, and R. C. González. Pedestrian navigation based on a waist-worn inertial sensor. *Sensors*, 12(8):10536–10549, 2012.

[3] L. Bouguila, F. Evequoz, M. Courant, and B. Hirsbrunner. Walking-pad: a step-in-place locomotion interface for virtual environments. In *Proceedings of the International Conference on Multimodal Interfaces (ICMI) 2004*, pp. 77–81. ACM, 2004.

[4] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis. Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence*, 7(2):168–178, 1998.

[5] J. Feasel, M. C. Whitton, and J. D. Wendt. Llcm-wip: Low-latency, continuous-motion walking-in-place. In *Symposium on 3D User Interfaces (3DUI) 2008*, pp. 97–104. IEEE, 2008.

[6] R. C. Foster, L. M. Lanningham-Foster, C. Manohar, and et al. Precision and accuracy of an ankle-worn accelerometer-based pedometer in step counting and energy expenditure. *Preventive Medicine*, 41(3-4):778–783, 2005.

[7] N. C. Nilsson, S. Serafin, M. H. Laursen, and et al. Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *Symposium on 3D User Interfaces (3DUI) 2013*, pp. 31–38. IEEE, 2013.

[8] G. Panahandeh, N. Mohammadiha, A. Leijon, and P. Händel. Continuous hidden markov model for pedestrian activity classification and gait analysis. *IEEE Transactions on Instrumentation and Measurement*, 62(5):1073–1083, 2013.

[9] T. Pfeiffer, A. Schmidt, and P. Renner. Detecting movement patterns from inertial data of a mobile head-mounted-display for navigation via walking-in-place. In *Proceedings of the IEEE Virtual Reality Conference (VR) 2016*, pp. 263–264. IEEE, 2016.

[10] M. Slater, M. Usoh, and A. Steed. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2:3:201–219, 1995.

[11] J. N. Templeman, P. S. Denbrook, and L. E. Sibert. Virtual locomotion: Walking in place through virtual environments. *Presence*, 8(6):598–617, 1999.

[12] L. Terziman, M. Marchal, M. Emily, and et al. Shake-your-head: Revisiting walking-in-place for desktop virtual reality. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST) 2010*, pp. 27–34. ACM, 2010.

[13] S. Tregillus and E. Folmer. Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile vr environments. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI) 2016*, pp. 1250–1255. ACM, 2016.

[14] S. Tregillus, M. A. Zayer, and E. Folmer. Handsfree omnidirectional vr navigation using head tilt. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI) 2017*, pp. 4063–4068. ACM, 2017.

[15] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. B. Jr. Walking ¿ walking-in-place ¿ flying, in virtual environments. In *Proceedings of the conference on Computer graphics and interactive techniques (SIGGRAPH) 1999*, pp. 359–364. ACM, 1999.

[16] D. Waller and E. Hodgson. Sensory contributions to spatial knowledge of real and virtual environments. *In Human Walking in Virtual Environments, Springer*, pp. 3–26, 2013.

[17] J. D. Wendt, M. C. Whitton, and J. Frederick P. Brooks. Gudwip: Gait-understanding-driven walking-in-place. In *Proceedings of the IEEE Virtual Reality Conference (VR) 2010*, pp. 51–58. IEEE, 2010.

[18] B. Williams, S. Bailey, G. Narasimham, and et al. Evaluation of walking in place on a wii balance board to explore a virtual environment. *ACM Transactions on Applied Perception (TAP) 2011*, 8(19):1–14, Aug. 2011.

[19] B. Williams, M. McCaleb, C. Strachan, and Y. Zheng. Torso versus gaze direction to navigate a ve by walking in place. In *Proceedings of the ACM Symposium on Applied perception (SAP) 2013*, pp. 67–70. ACM, 2013.

[20] N. Zhao. Full-featured pedometer design realized with 3-axis digital accelerometer. Analog Dialogue 44, 06, 2010.