Evaluation of an Omnidirectional Walking-in-Place User Interface with Virtual Locomotion Speed Scaled by Forward Leaning Angle

Eike Langbehn[*], Tobias Eichler[†], Sobin Ghose[†], Kai von Luck[†],
Gerd Bruder[*], Frank Steinicke[*]

[*] Department of Informatics,	[†] Department of Informatics,
University of Hamburg	Hamburg University of Applied Sciences
Vogt-Kölln-Str. 30	Berliner Tor 7
22527 Hamburg	20099 Hamburg
E-Mail: {eike.langbehn,gerd.bruder,	E-Mail: {tobias.eichler,sobin.ghose,
frank.steinicke}@uni-hamburg.de	kai.von.luck}@haw-hamburg.de

Abstract: Virtual locomotion is an enabling ability for many tasks in virtual environments (VEs) and denotes the most common form of interaction with VEs. In this paper we present a novel omnidirectional walking-in-place (WIP) locomotion system, which we designed to work in small laboratory environments and is based entirely on consumer hardware. We present our hardware and software solution to 360 degrees omnidirectional tracking based on multiple Kinects and an Oculus Rift head-mounted display (HMD). Using this novel setup we improved on the related work by evaluating leaning as a novel parameter of WIP interfaces. Inspired by observations of changing leaning angles during fast or slow locomotor movements in the real world, we present the Leaning-Amplified-Speed Walking-in-Place (LAS-WIP) user interface in this paper. We present the results of an experiment in which we show that leaning angle can have a positive effect on subjective estimates of self-motion perception and usability, which provides novel vistas for future research.

Keywords: Walking-in-place, locomotion, virtual environments

1 Introduction

Natural locomotion in immersive virtual environments (IVEs) is an important task for many application domains, such as architecture, virtual tourism or entertainment. While head tracking allows users to explore a virtual three-dimensional data set by moving the head or by walking in the tracked real-world workspace, the range of tracking sensors and physical obstacles in the tracked space restrict the maximum virtual space that users can explore by natural body movements. Different hardware and software solutions have been proposed over the last years to address this challenge [SVCL13], e. g., omni-directional treadmills [SRS+11] or redirected walking [RKW01], but still no generally applicable solution exists. There is still a high demand for near-natural locomotion user interfaces in situations where the dominant solutions are not applicable due to spatial constraints [SBJ+10] or cost.

Walking-in-place (WIP) denotes a class of locomotion techniques that enable users to walk through infinitely large virtual environments (VEs) by mimicking walking movements with their body in the real world [SUS95]. In comparison to real walking, WIP interfaces can be used even in very small physical workspaces and the requirements on tracking hardware accuracy and precision are comparably low [SVCL13]. However, providing a WIP interface in which a user can orient the body in any direction in the real world and start walking presents a challenge to WIP tracking technologies, which often do not allow users to turn in the real world or suffer from limited tracking performance in such cases [SVCL13]. Different approaches have been proposed as workarounds in case of such tracking limitations by simulating turning in the VE, such as redirected walking in place [RSS+02]. However, omnidirectional tracking solutions are generally preferred, as are solutions that additionally provide users with a full-body tracked virtual self-representation. We are not aware of any such solution that has been built using consumer-level tracking hardware and used in the context of WIP user interfaces so far. We present our experiences in this paper.

WIP user interfaces have in common that they analyze the gait of users while stepping in-place to initiate virtual movements, but they can differ largely in terms of which gait characteristics their algorithms extract. When stepping in-place the feet show large vertical movements and very limited horizontal displacements, which means that it is not possible to perform a biomechanically veridical one-to-one mapping of physical to virtual walking steps. In particular, this means that it becomes difficult to estimate the step width that a physical foot movement should correspond to in the VE, which controls the speed and thus the distance a user covers while walking. One of the major remaining challenges of WIP user interfaces is the ability to naturally control the virtual walking speed.

Different approximations have been presented such as based on the stepping frequency [WWB10] or amplitude of vertical foot movements [BPJ13] to scale step distances and thus walking speed. However, as far as we know no previous work evaluated interaction effects between the forward or backward leaning angle of the user's upper body and perceived self-motion speed with WIP interfaces. Since slight or heavy forward leaning of the upper body against the horizontal movement direction is a characteristic of runners and sprinters, we hypothesize that a positive correlation exists with increased virtual walking speeds (see also [KRTK15]). Additionally, based on the same arguments we hypothesize that using leaning to scale self-motion speed has the potential to provide an intuitive addition to improve the usability of WIP systems.

The novel contributions of this paper are threefolded:

- We introduce a WIP setup for 360 degrees omnidirectional tracking based entirely on low-cost consumer hardware.

- We propose a novel extension of WIP user interfaces by incorporating leaning angles to scale virtual locomotion speed.

- We show in a user evaluation that the setup and user interface provide a viable virtual locomotion system.

This paper is structured as follows. Section 2 gives an overview of related work on WIP interfaces and tracking challenges, as well as effects of leaning on self-motion perception. In Section 3 we present our hardware and software tracking setup. Section 4 describes our novel WIP interface. In Section 5 we present the user study that we conducted to evaluate our locomotion system. Section 6 concludes the paper.

2   Related Work

In this section we summarize related work on WIP and leaning locomotion user interfaces.

Walking-in-Place   Many different WIP user interfaces have been presented, which differ in inputs, outputs, control of virtual displacements and feedback of virtual locomotion [SVCL13]. Different segments of the user's body can be analyzed to initiate virtual self-motion, such as the feet, shins, knees or head [BPJ13, FWW08, RSS⁺02, SUS95, TDS99, TMEM10]. While early WIP user interfaces triggered discrete virtual steps [SUS95], state-of-the-art systems use the physical body movements as input for algorithms to maintain continuous virtual self-motion, e.g., using sinusoidal velocity profiles [WWB10]. Inspired by real walking gaits, algorithms analyzing the movements of these body parts based on neural networks and signal processing [FWW08], state machines [WWB10] or pattern recognition [TDS99] have helped to reduce starting and stopping latency and improved the smoothness of virtual locomotion.

In order to make the most out of these different algorithms it is important to track the user's body parts with high precision and accuracy, as well as low latency. Different tracking technologies have been evaluated for WIP interfaces, including magnetic [FWW08, SUS95] and optical [UAW⁺99] tracking systems, as well as Wii Balance Boards [WBN⁺11] and Wiimotes [SH08]. However, these solutions usually do not support full-body tracking or suffer from high cost when professional tracking technologies are used. Fewer solutions provide omnidirectional full-body tracking at low cost. One solution focusing on the calibration and coordinate transformation uses multiple Kinect v1 skeletons [WQL14].

Leaning   Different locomotion user interfaces have been proposed that initiate virtual self-motion based on the leaning anlge of the user's torso in the real world when wearing a head-mounted display (HMD) or in CAVEs [GPI⁺15, MPL11]. Such user interfaces are motivated by movements in the real world, which often show people leaning forward when running or driving faster to assume a stable body position in the presence of increased horizontal force during movements in addition to gravitational force. Such static and dynamic leaning poses have been found to affect self-motion sensations during traveling in IVEs [KRTK15]. Notable here is also the SilverSurfer virtual surfboard locomotion user interface [WL11]. While previous user interfaces used leaning alone to initiate virtual movements, we are not aware of any related work that uses leaning in combination with WIP interfaces to scale the virtual locomotion speed.
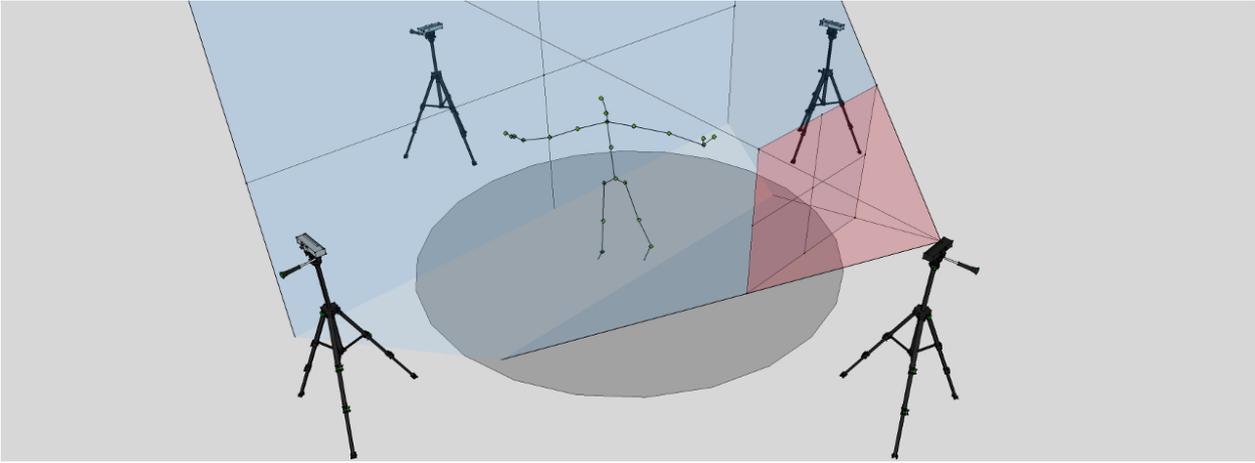
Figure 1: Omnidirectional body tracking setup with four Kinects placed in a circle around the tracking area. The field of view of the front right sensor is marked in blue.

3 Omnidirectional Body Tracking Setup

In this section we present our setup for omnidirectional body tracking based on low cost consumer hardware to recognise stepping in-place. For our omnidirectional tracking setup it was important to be able to track the entire body of the user in order to allow us to extract information about the movements of the user's legs as well as the torso leaning angle. Therefore, we decided to use Microsoft Kinect v2 sensors, which have shown reasonable skeleton tracking performance when the user's body is visible from the Kinect's point of view. To get reliable omnidirectional tracking we fuse the sensor data of four Kinect sensors, which are mounted on tripods and placed in a circle around the tracking area as illustrated in Figure 1. We observed that positioning the Kinect sensors on a circle with 2m radius provides sufficient tracking accuracy and full 360 degrees body tracking, i.e., the user's skeleton is always tracked from at least one sensor.

In order to combine the tracking data of the four Kinects we decided to use one workstation for each Kinect and connected these by a local GBit network. We use an additional workstation for the sensor fusion algorithm, visualization of the tracking data, step detection and logging. We implemented a middleware to transfer the sensor data with a publish/subscribe-based messaging system optimized for low latency and scalability. This platform allows us to change the number of sensors dynamically. In our current implementation we use the J4K library introduced in [Bar13] as Java JNI-Wrapper for the Kinect SDK.

3.1 Calibration

To be able to fuse the Kinect skeleton information all joint data have to be transformed into the same coordinate system. The Kinect sensors can be positioned freely, so we use an automatic calibration method to calculate the 6 degrees of freedom transformation parameters between the local coordinate systems. Therefore, we define the coordinate system of one Kinect as the reference system and calibrate the other sensors one at the time.

We found that it is possible to compute the transformation variables with a simple calibration procedure. We instruct a user to stand in the center of the tracking setup, assume a standard arms-out pose for calibration (see Figure 1), and rotate 90 degrees multiple times. From this data we gain pairs of point sets from the skeleton data of each sensor and the reference system, which we use to compute the rotation and translation parameters to extrinsically calibrate the sensors. To increase the accuracy only joints that are directly visible by both Kinects are used in this process. The transformation parameters are calculated with an overdetermined system of equations with all point pairs utilizing singular value decomposition.

3.2   Sensor Fusion

We implemented a simple sensor fusion approach to calculate a skeleton from the multiple skeleton data sets based on a weighted average method. In our approach we use different heuristics to calculate the weight and improve the sensor fusion. As the sensor data by the Kinect SDK includes information on whether the joints are tracked or guessed, we filter out the guessed joints as long as at least one sensor can track the body part directly. Since the sensor results are most accurate for forward facing skeletons we assign a higher weight to data from sensors that are in front of the body by calculating the angle between the shoulder region of the skeleton and the vector to one of the outer shoulder joints. Furthermore we use multiple constraints to improve the results, e. g., all joints of the skeleton have to be connected by bones with stable length. While this simple approach shows areas for improvement, such as fine-tuning the weights, adding Kalman filters to reduce jitter in the data before sensor fusion, or matching the sensor data to human gait models, pilot tests suggest that the results can already be sufficient for WIP systems.

4   Leaning-Amplified-Speed Walking-in-Place (LAS-WIP)

The LAS-WIP user interface is based on the tracking capabilities of our omnidirectional tracking system (see Section 3). With this setup the user is standing in the center of the tracking space with an upright posture and wearing an HMD that is connected to a laptop in the backpack of the user (see Figure 2). Hence, no wires disturb the user's sense of presence in the VE [Sla09]. In previous versions of our locomotion setup we used a wireless transmission system to provide real-time audiovisual data to the user wearing an HMD, but due to the recent changes in display resolution of HMDs such as the Oculus Rift DK2 it becomes increasingly difficult to find compatible WLAN transmission systems.

For our user interface we expect that accurate tracking data is provided independently of the orientation the user is facing in the laboratory setup. Hence, in our WIP design it is not necessary to introduce an artificial interaction technique to enable the user to rotate in the VE, but instead the user can accomplish rotations just by turning around in the real world. Additionally, this means that the user's hands are not required for virtual locomotion, and thus may be used for orthogonal tasks such as selection or manipulation in the VE. Although

the torso and head orientations are provided by our omnidirectional tracking system, we found that the sensors of HMDs such as an Oculus Rift DK2 provide more precise tracking of the user's head. Hence, we use this headtracking data instead of that of our omnidirectional tracking system to provide the user with feedback to head movements.

4.1 Step Detection

We follow the main literature on implementations of WIP user interfaces in that we detect when the user performs a step in the real world and map it to a forward translation in the VE. Therefore, we had to choose between using the torso or head as reference for forward movements, and we decided on using the head orientation, which is similar to the choice between torso-directed and view-directed steering methods [BKLP01]. Our choice is based mainly on the lower latency and higher accuracy of the headtracking data, but informal tests also suggested that it becomes easier to steer around more difficult paths when using the head instead of having to turn the torso.

With our user interface the user is instructed to step in-place to move forward in the VE. Our step detection algorithm uses the ankle joints of the fused skeleton model to allow as natural as possible locomotion and an accurate detection. A step is detected when the distance of the joints to the floor plane is higher than a threshold. We assume normal step speed and alternating foot movement to filter out false positive detections.

Depending on how rapidly the user raises and lowers the feet during in-place stepping, this results in a change of virtual self-motion speed. Caused by the tracking latency and algorithm we observed a temporal offset between when the user initiates a step and the moment the step generates visual feedback. Overall, our visual feedback is roughly half a step behind the user's movements, which is similar to other WIP implementations with low-cost consumer hardware [WBN+11].

In our system we defined a parameter for the step width in the VE when a user performs an in-place step in the real world. While we designed the user interface in such a way that this parameter could be estimated before a user starts using the WIP system by measuring the typical step width, we observed that an average walking speed of 2m/s already results in acceptable impressions of self-motion. We provide visual feedback to a step by triggering a forward translation based on a velocity profile. The LAS-WIP user interface supports different velocity curves with parameters for ease-in and ease-out velocities during virtual walking, which might be used to fine-tune the feedback for a particular user, if required.

4.2 Torso Leaning Angle

The main novel part of the LAS-WIP user interface is the ability to change virtual walking speeds by changing the torso leaning angle. Therefore, we calculate the leaning angle by computing the difference of the *"spine_shoulder"* and *"spine_base"* joints in the Kinect's skeleton model. We currently do not distinguish between forward or backward leaning, since initial tests suggested that even backward leaning can be interpreted as increased speed, e. g.,
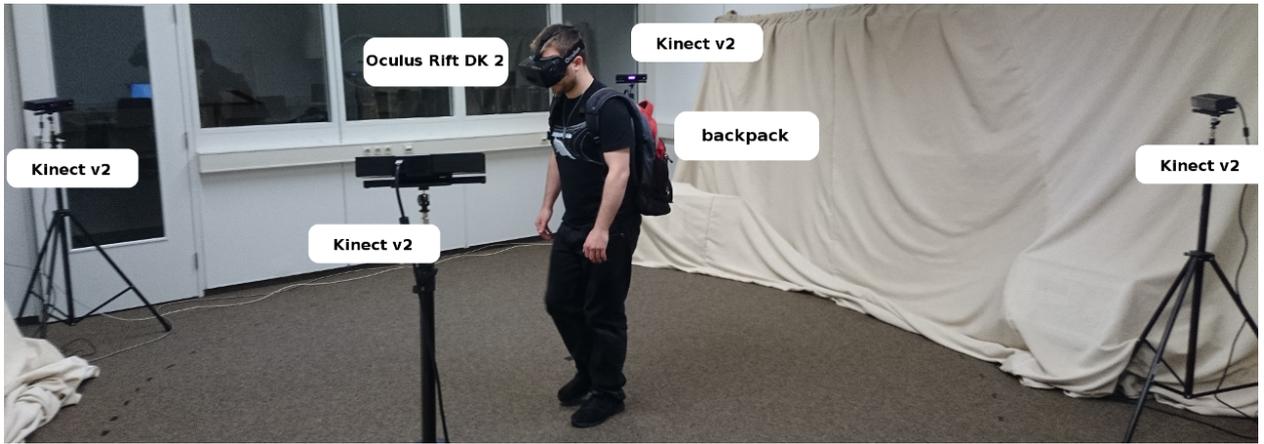
Figure 2: Illustration of the LAS-WIP system: user wearing an Oculus Rift DK2 HMD and a rendering laptop in a backpack, while he is tracked by four Kinect v2 sensors.

when being pressed into the seat when driving fast with a car. However, this point should be evaluated in more detail in future work. Depending on the intended maximum virtual walking speed when leaning, we observed that it is advantageous to define a limit for the leaning angle, or users might start to assume very uncomfortable body poses in order to move faster in the VE. We decided to switch to maximum speed if a leaning angle of θ_{max} degrees or higher is reached to ensure that the body pose remains comfortable; we found a value of θ_{max}=35 degrees to work fine in initial tests. Also, we observed that it is advantageous to define a minimum angle, e. g., θ_{min}=5. Below this angle we do not manipulate the walking speed, which leads to a more stable walking experience on standard walking speed.

5   User Evaluation

In this section we present the evaluation of the LAS-WIP user interface in the omnidirectional tracking setup introduced in Section 3. We compared the leaning angle extension with a traditional WIP implementation, in which the virtual speed is only dependent on the stepping frequency and not additionally on the leaning angle.

5.1   Participants

We recruited 14 participants for our evaluation, 11 male and 3 female (ages from 21 to 36, M=27.9). The participants were students or professionals of human-computer interaction, computer science or engineering. All of our participants had normal or corrected-to-normal vision. 9 wore glasses and 1 participant wore contact lenses during the experiment. None of our participants reported a disorder of equilibrium or binocular vision disorders. 12 participants had experienced HMDs before. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 30 minutes. Participants wore the HMD for approximately 20 minutes. They were allowed to take breaks at any time.

5.2 Material and Methods

We used a within-subjects design, in which we compared two WIP user interfaces: LAS-WIP and traditional WIP implementation without leaning. The order of these tests was randomized and counterbalanced. As dependent variables we measured simulator sickness using the Kennedy-Lane SSQ questionnaire [KLBL93], presence using the Slater-Usoh-Steed (SUS) questionnaire [UCAS99], as well as subjective estimates of preference and experience in a custom questionnaire.

We performed the experiment in an 8m×5m laboratory room. As illustrated in Figure 2, we used a wireless setup. Participants wore an Oculus Rift DK2 HMD for the stimulus presentation and a rendering laptop in a backpack. We used a graphics laptop with an Intel i7 CPU, Nvidia GeForce GTX 970M and 16GB RAM for rendering the VE. The omnidirectional body tracking system was running with four Kinect v2 sensors, each connected to a graphics workstation with Intel i7 CPU, Nvidia GeForce GTX 970 and 16GB RAM. The workstations were connected via GBit Ethernet. The rendering laptop received tracking data via WLAN.

In the experiment we generated virtual step feedback based on a linear velocity function, which consisted of an ease-in and ease-out phase. Each phase lasted 0.5 seconds; the overall duration of a step was 1 second, which corresponds to a walking speed of 2m/s if a mean step frequency of one step per second is assumed. When another step is received during this time, the first step is discarded and the speed is increased from the current level up to the maximum speed. Hence, stepping at the expected frequency results in a uniform movement velocity. We used a velocity scaling factor of 5 for maximum leaning angles, with constraints $\theta_{min}=5$ and $\theta_{max}=35$ (see Section 4).

The virtual world was rendered using the Oculus display mode in the Unreal Engine 4, which corrects for the optical distortions of the HMD. The participants had to walk a periodic path in the VE, which was indicated by a gravel road. The virtual path had a length of ca. 1000m. The path consisted of multiple curvatures so the participants had to turn around and utilize the full 360 degrees tracking range (see Figure 3). The VE was a 3D model of the medieval *Hammaburg*, a castle and adjacent village of the 9th century in Hamburg, Germany. The castle is of significant importance for archaeology, tourism and city marketing. In cooperation with the local archaeological museum we are currently considering different possibilities to create interactive experiences for museum visitors. LAS-WIP with our omnidirectional tracking setup provides one possibility to explore this virtual medieval world.

5.3 Results and Discussion

We measured simulator sickness symptoms before and after each of the two WIP conditions, and we computed the change in simulator sickness.

For the traditional WIP interface we measured an average increase in SSQ scores of 17.63 ($SD = 28.23$) and for LAS-WIP an average increase of 9.88 ($SD = 16.83$), which both are in the range of usual increases in symptoms with an Oculus Rift DK2 HMD over the time of the experiment. We analyzed the questionnaire data with Wilcoxon signed rank tests. We found

Figure 3: Visual stimulus used in the experiment: 3D model of the Hammaburg, a local medieval castle of the 9th century. Participants had to follow the virtual path in (randomized) clockwise or counterclockwise direction.

no significant difference in simulator sickness symptoms between the LAS-WIP user interface and the traditional interface ($Z = 1.22$, $p = .22$). The apparent trend can be interpreted in light of the shorter time participants spent in the VE for LAS-WIP (ca. 7min) compared to the traditional interface (ca. 14min), since the LAS-WIP interface allowed participants to complete the path in the VE at an increased speed.

We measured the participants' sense of presence with the SUS questionnaire, which revealed an SUS mean score of 3.95 ($SD = 1.52$) for the traditional interface and 3.83 ($SD = 1.53$) for LAS-WIP, which both indicate high presence in the VE. We found no significant difference in SUS scores between the two techniques ($Z = 1.30$, $p = .20$). Informal responses, however, suggest that the apparently slightly lower presence with LAS-WIP might stem from an increased concentration of the participants on locomotion in the VE. As one participant remarked, *"Walking slowly gives you more time to look around. With the other technique [LAS-WIP], I was more focused on moving fast along the path and had less time to appreciate the world and smell the virtual roses, so to speak."*

Questioned about which of the two techniques the participants preferred, 12 stated that they would use LAS-WIP, whereas 2 preferred the traditional approach. We additionally collected informal responses, which mainly support the notion that participants prefer to be able to walk faster in the VE than their normal walking speed in the real world, in particular, if it comes at less energy cost than having to step faster. However, they expressed appreciation for the ability to easily reduce speed with LAS-WIP when they had to perform sharp turns in the VE in order to prevent collisions. One participant noted that LAS-WIP did not work well for her due to an occurrence of back strain that she experienced when trying to use that feature, which we have to consider for future work.

Participants judged their fear to collide with physical obstacles during WIP on a 5-point scale (0 no fear, 4 high fear) for the traditional interface on average as 1.0 ($SD = 1.2$) and for LAS-WIP as 0.7 ($SD = 1.1$), $Z = 1.63$, $p = .10$. Questioned about their impression of self-motion with their body in the VE (0 very low, 4 very high) they responded for the traditional interface on average with 1.6 ($SD = 1.3$) and for LAS-WIP with 2.0 ($SD = 1.0$), $Z = 1.73$, $p = .08$. Moreover, they felt that their posture affected their self-motion sensation (0 no, 4 yes) for the traditional interface significantly less with an average of 1.6 ($SD = 1.5$) compared to LAS-WIP with 2.9 ($SD = 1.4$), $Z = 2.57$, $p = .10$. They judged the comfort of their pose during walking (0 uncomfortable, 4 comfortable) for the traditional interface on average as 1.5 ($SD = 1.3$) and for LAS-WIP as 1.4 ($SD = 1.3$), $Z = .51$, $p = .61$. The subjective estimates suggest that LAS-WIP may increase impressions of self-motion, although the estimates are still far from real walking, which is in line with previous research [UAW$^+$99]. The comfort of LAS-WIP seems slightly reduced over traditional WIP, even though both approaches are not judged as particularly comfortable, which provides some vistas for future research.

6 Conclusion

In this paper we presented and evaluated a novel solution to WIP locomotion interfaces. We discussed and presented an omnidirectional tracking setup for WIP user interfaces based on multiple Kinects and a sensor fusion approach that combines the available skeleton data. Using the setup we detailed our novel leaning extension for WIP user interfaces, called LAS-WIP, and presented a user evaluation, which indicates that the leaning extension can improve the usability of WIP user interfaces and also has the potential to improve subjective self-motion estimation.

For future work, we believe that forward leaning is not the only subtle characteristic of fast walking movements, but rather represents one example of different such occurrences which may be leveraged as intuitive speed control methods for virtual locomotion interfaces. Future fields of study may include evaluations of the swinging of the arms during fast walking or differences in head movements along the transveral plane in body-centric coordinates. Besides providing speed control methods, such approaches may also support self-motion speed estimates, which often differ in IVEs from the real world [BSWL12], even if users move by real walking.

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