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EMPIRICAL EVALUATION OF MAPPING FUNCTIONS FOR NAVIGATION IN VIRTUAL ENVIRONMENTS USING PHONES WITH INTEGRATED SENSORS

Amal Benzina[1], Arindam Dey[2], Marcus Tönnis[1] and Gudrun Klinker[1]

[1]Fachgebiet Augmented Reality
Technische Universität München
Fakultät für Informatik Boltzmannstraße 3, 85748 Garching b. München, Germany
{ benzina; toennis; klinker }@in.tum.de

[2]School of Information Technology and Mathematical Sciences
University of South Australia
Adelaide, South Australia 5001, Australia
arindam.dey@unisa.edu.au

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Abstract. *Mobile phones provide an interesting all-in-one alternative for 3D input devices in virtual environments. Mobile phones are both touch sensitive and spatially aware, and they are now part of our daily activities. We present Phone-Based Motion Control, a novel one-handed travel technique for a virtual environment. The technique benefits from the touch sensitivity of the mobile phone to change the viewpoint translation in virtual environments, while the orientation of the viewpoint is controlled by built-in sensors in the mobile phone. The travel interaction thus separates translation (touch based translation control) and rotation (steer based rotation control), putting each set of degrees of freedom (DOF) to a separate interaction technique (separability). This paper investigates, how many DOF are needed to perform the travel task as easy and comfortable as possible. It also investigates different mapping functions between the users actions on the mobile phone and the viewpoint change in the virtual environment. Therefore, four techniques are implemented: rotate by heading, rotate by roll, rotate by roll with fixed horizon, and a merged rotation. Each technique has either 4 or 5 DOF and different mappings between phone and viewpoint coordinates in the virtual environment. We perform a user study to explore different aspects related to the travel techniques in terms of DOF and mapping functions. Results of the user study show that 4 DOF travel techniques are advantageous for traveling in VE. Also the participants subjectively preferred the use of mobile roll as the desired mapping to control the viewpoint heading in the VE.*

1. Introduction.

Nowadays, we are living in a technologically rich, heterogeneous, and ubiquitous computing world, where we need to interact with different devices like large displays. Recent introduction of 3D game controllers like the Wii has spread the general acceptance of 3D spatially aware input devices and user interfaces that generally imitate the user interactions in the real world. Mobile phones have shown to be promising as 3D input devices. Mobile phones provide a rich set of features enabling us to interact with virtual environments. As an application, we are using a visualization system [5] that renders high resolution 3D geographical data on a large display. The aim of the project is to provide the engineers with user interfaces for the visual exploration of 3D geological structures and terrain data. Traditional input devices are not appropriate for interaction with large high-resolution displays [4]. The engineers need a mobile solution to interact with the VE that can be in different physical locations. They also require a small, wireless, and convenient input device to control the viewpoint. Another pseudo requirement is that only one hand of the user should be able to use the system so that fatigue of very long use can be distributed over both hands. The second hand can hence execute additional activities, such as manipulation of simulation parameters or selection of area of interest in the terrain.

The increasing availability and the ubiquity of mobile phones with various integrated sensors and touch sensitive displays provide a broad design space. Although sensors of various kinds with higher accuracy are available, mobile phones offer an all-in-one integrated and compact solution. Having both, built in sensors and a touch screen available, creates a large and diverse design space.

This paper presents the design of a novel interaction paradigm for navigation in VEs and provides an extensive user study to investigate the dimensionality and the mapping functions of the user interface to perform the travel task in the VE. Indeed the DOF is an important property of an input device and influences greatly the acceptance of the input device as a user interface [10]. Users have difficulties controlling all 6 DOF [17]. Zhai also showed that users mostly use translation and ignore rotation and only after a learning phase that 80% of the users could control both translations and rotations effectively using all 6 DOF. Furthermore, transfer functions have to be appropriate as defined by [10], to obtain a more intuitive control. They also highlighted that the match of the transfer function to the properties of the input device is the appropriate mapping.

Therefore, following the recommendations of Hinckley et al. [13] to constrain the dimensions (i.e., degrees of freedom) of an input device to a certain meaningful value, we developed a one-handed system that has been outlined in an earlier works [2]. The navigation task distinguishes between translation and rotation, putting each set of DOF to a separate interaction technique. For translation, more specifically, for controlling the direction of the viewpoint, we use the touch capability of the display of the phone. For rotation we employ the motion sensors to make it spatially aware. With the separation between the translation and the rotation, four travel techniques with different DOF and mappings have been developed and tested in an initial study [2]. The study aimed on collecting information about the general quality of the techniques and brought insights about drawbacks in technical matters. The findings were used to improve the system to yield a mature system for testing in this work. In this work we investigate through the user study two, very important and decisive, properties of the navigation user interface: DOF and mapping functions.

This paper has two main contributions. First, four novel interaction techniques are proposed to use a mobile phone as a 3D input device to travel in VEs. Second, results of a rigorous user study investigating the DOF and the mapping functions of the mobile phone used as a 3D input device for a travel task in VE are presented. The results provide valuable insights about the effectiveness of different DOF and the mapping between the input device and the VE.

The next sections cover first the related work and then develop our concept. Then, the four travel techniques with the respective DOF and the mapping functions are presented. In the following section, the outcome of the formative shaping process is illustrated. Then we present the user study we conducted. Results of the user study are then presented and discussed. Finally, we conclude the paper by directing towards the future work.

2. **Related Work.**

Handheld and multi-touch capable devices, and mobile phones have been used recently for various interaction techniques, often for travel tasks. The sensors embedded in mobile phones and built-in cameras have been used for sensing the users' gestures or what was called in several publications sensing-based interaction or travel [14].

2.1. **Sensing-based interaction within handheld devices.** Hinckely et al. [11,12] investigated different sensing techniques for mobile interaction with spatially aware mobile devices and demonstrated several new functionalities. They used touch sensors, accelerometers or what they call tilt sensors, and proximity sensors to introduce functionalities such as recording memos when the device is held vertically, switching between portrait and landscape display modes by changing the device orientation, power management of the device when the user picks the device up and starts using it, and scrolling the display using tilt. Their usability study showed that a careful usage of the phone integrated sensors is necessary to deliver a mobile interaction that is as simple and pleasant to use as possible. In an earlier works, Hinckley et al. [13] presented a survey of previous research on spatial input techniques. They gathered some interaction techniques involving 3D input devices and presented a design framework for the development of interaction techniques using spatial input devices. Accelerometers have also been used to control mobile 3D games, and [15] describe how accelerometers provide the feature of a no-button control for mobile games. They discuss that tilt motion is suitable for mobile phones for a 3-D graphics first-person driving game 'Tunnel Run'. They compare the game user experience with a traditional phone joypad interface and with a tilt interface in two phases. Their results show that the tilt interface was more attractive and fun to play. Rohs and Essl [14] presented three sensor technologies in small-scale handheld devices for spatial tracking: camera-based tracking, optical motion estimation, and accelerometer and magnetometer readings for tilt and rotation detection. They performed a comparison of user performance using the three sensor technologies to navigate in a map. The evaluation procedure consisted of the users searching 10 individual targets in sequence using each time one of the three navigation techniques and hence each time a sensing technique. Accelerometer and magnetometer sensing showed good performance just below optical marker grid tracking. Others explored different physical operations, such as contact, pressure, tilt and motion, that can be applied to handheld devices for navigation tasks in mobile phones [6,16]. Zhai [8] introduced the TinyMotion prototype that tracks the users hand movements by analyzing image sequences captured by the phone built-in camera. They found out that their TinyMotion method could be quite reliably used for text-input and gaming. They also made an analytical comparison between their camera phone based motion sensing TinyMotion and accelerometers. They mentioned that even though the accelerometers, to the contrary of the TinyMotion, will not have any influence from illumination conditions and require a fairly low processing power on the mobile side, they might suffer from a higher accumulative drift error.

2.2. **Sensing-based travel in VE using handheld devices with external resources.** Zhai presented in his thesis an extensive job to investigate the human performance using various 6DOF interfaces, taking into consideration among others the device resistance, transfer function, and input display formats. He analyzed many devices, but the mobile phone is not part of the investigated input devices. Zhai investigated the relation between the sensed property and the transfer function [17]. He also shows that isotonic sensors work better for position control techniques, while elastic sensors and isometric sensors should be used with rate controls. According to Zhai's work, travel tasks use mostly rate control, thing that we took into consideration in our design of the interface. Boring et al. [19] introduced and compared three different interaction techniques for continuous control of a pointer located on a remote display using a mobile phone: scroll, tilt, and move. The interaction in their work is more about selection on a large display, but the results can be related to our approach for traveling in VEs, because especially the tilt technique uses acceleration sensors. The evaluation showed that users applying the move and tilt techniques perform the selection task faster, but they also suffer from higher error rates. The paper by Jeon et al. [20] presents user interaction especially for object selection and manipulation using camera built-in mobile phones in large display environments. They proposed three approaches: motion flow based, marker-object based and marker-cursor based. Bednarz [21] introduced an interaction technique in immersive virtual environments. They used the iPhone to get the orientation data pertaining to accelerational and rotational attributes, such as, pitch, roll and yaw as well as the touch screen for navigation and manipulation of virtual objects in an immersive VR mining environment. Kulik et al. [1] introduced a one-handed input device for 3D interaction called two-4-six. They analyzed the specific interaction task to choose a specific spatial arrangement of the sensors in the input device, and discussed the required DOF in appropriate combinations. They provided 6 DOF for the travel task with a separation between translation and orientation. Also Hinckley et al. [13] pointed out that it is important to look at the number of available DOF for the interaction task, and to relate this to the ability of the users to control the DOF simultaneously.

3. Phone Based Motion Control.

We introduce a novel one-handed travel technique in a VE. We call it the *Phone-Based Motion Control* technique, since the travel in the VE is completely performed using a mobile phone with integrated sensors as a 3D input device.

As our travel technique aims for the exploration of large scale data sets, for long distance movements it is better to employ a rate control instead a position control during the travel to avoid unnecessary clutching that decreases performance. This has been discussed in the work of Casiez et al. [3] where they presented a prototype RubberEdge position-rate hybrid control device for selection task. They also discuss in their work the fact that position control provideS better precision performance, but since in our work we are dealing with travel tasks where clutching would have a dramatic influence and fine precision is not that crucial. With a spatially aware mobile device, we can provide up to 6 DOF; however, as mentioned earlier we want to answer the question of whether or not more DOF contribute to a better execution of the travel task. The control of the VE viewpoint is divided into two parts. We use the *touch screen* of the mobile phone to control the *translation* of the viewpoint, and the *built-in sensors* to control the *orientation* of the viewpoint. For translation, a *touch based translation control* technique is conceptualized. For rotation, the orientation of the device is mapped to the orientation of the viewpoint in the VE, defining the *steer based rotation control* technique.

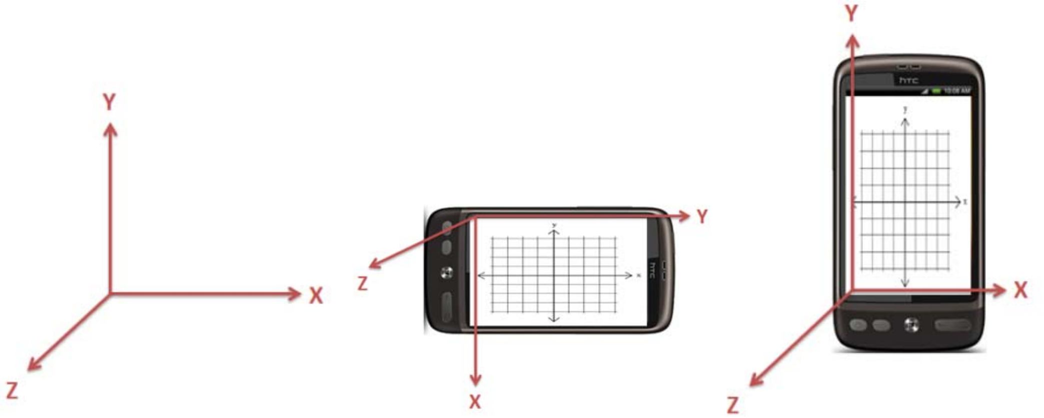
In addition to the separability, we aim to make the mappings between the user actions on the mobile phone and the effect or reactions onto the viewpoint in the VE smooth and meaningful. The main underlying principle here is that a translation maps to a translation and a rotation, or more specifically, a tilt, maps to a turn or a rotation in the VE.

Before introducing our approaches, conventions on the coordinate systems used in later concepts are illustrated and the general activation model of the interaction techniques is introduced.

3.1. Conventions of coordinate systems.

To ease understanding in the following paper sections, we define the coordinate systems, both of the mobile phone and the VE.

(1) **Coordinate system of the mobile phone touch screen:** The coordinate system is aligned to the phone screen. The origin of the coordinate system is the lower left corner of the screen. The X-Axis extends horizontally and to the right, the Y-Axis extends vertically and to the upper direction, and the Z-Axis extends outside the front of the screen (see Figure 1(b) and Figure 1(c)).



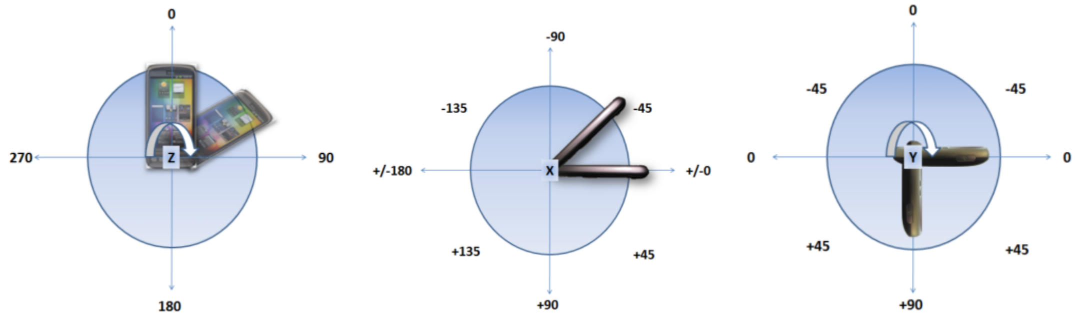
(a) VE coordinate systems (b) Landscape coordinate system (c) Portrait coordinate system

Figure 1. Coordinate system

(2) **Coordinate system of the mobile phone (sensors):** Many programming interfaces of mobile phone functionality internally fuse the readings from built-in sensors, in most cases a 3-axis accelerometer sensor and a magnetic field sensor. Accelerometers cannot be used for rotation around the Z-Axis. The gravitational field of the earth can provide an absolute reference and rotation relative to the gravitational field can be measured reliably. Other rotations are only measurable if more than one sensor is built into the phone. At the moment, most mobile phones only provide one sensor for acceleration. This is the reason behind combining both, the readings from the 3-axis accelerometer and the magnetometer, to get the orientation around the three axes. The three angles representing the orientation of a mobile phone are usually heading, pitch, and roll, as described below:

   (a) *Heading* or *Azimuth* represents the orientation around the Z-Axis. It represents the angle between the magnetic north direction and the Y-Axis. The angle ranges from 0 to 359 where 0 indicates north, 90 east, 180 south and 270 west directions as shown in Figure 2(a).

   (b) *Pitch* represents the orientation around the X-Axis. The angle ranges from -180 to 180, positive angle when the Z-Axis moves toward the Y-Axis as shown in Figure 2(b).



(a) The heading orientation (b) The pitch orientation (c) The roll orientation

Figure 2. Orientation sensor readings

    (c) *Roll* is defined as the representation of the orientation around the Y-Axis. The angle ranges from -90 to 90; positive angle when X-Axis moves toward the Z-Axis as shown in Figure 2(c).

(3) **Coordinate system of the virtual Environment:** The coordinate systems of the VE are depicted in Figure 1(a). The X-Axis extends to the right, the Y-Axis increases upwards and the Z-Axis extends into space from the center of the screen towards the viewer.

Since the coordinate systems of the mobile phone and the VE are not the same, we transform the coordinates accordingly and also depending on whether the user is holding the mobile phone in the portrait or landscape side. For simplicity, in this paper all examples are considering the phone in the portrait mode.

3.2. **Activation state of travel mode.** The user needs to trigger a dedicated action on the mobile phone to activate the start or to end the motion in the VE; otherwise, the viewpoint would change continuously, every time the user moves the hand holding the mobile phone whether intentionally or not. As the system uses accelerometer and magnetometer readings, we need to calculate the relative rotation of the mobile phone. For this reason, we need an initial rotation angle of the mobile phone. Therefore, we use the touch capabilities of the mobile phone (touch or release) as indication to maintain the system control for activation and deactivation of the traveling action. To stop steering and translating, users have two options: either to remove the thumb from the screen to enter a smooth deceleration phase, or to set the mobile phone back to its start orientation and in parallel to move the finger to the start position on the screen. We also implemented a short tap on the screen to allow the user to stop instantly if needed to avoid overshooting a target position in VE.

3.3. **Touch based translational control.** As the thumb moves over the display, the relative displacement of the finger to the initial touch-down position is calculated. The mobile direction vector is hence calculated indicating the viewpoint motion direction. The finger displacement on the mobile screen is mapped to a translation in the virtual environment. The users can press any initial point on the screen and move the finger in any direction. Not having a conceptual start-stop button for motion control is beneficial in terms of avoiding accidental clicking on the button. Users can perform activation and translation without looking at the mobile screen; they can keep their eyes on the VE as desired. As long as the thumb is still pressing the touch screen does the translation continue in the indicated direction.

The mobile displacement vector is then sent asynchronously to the VE server application where the displacement of the viewpoint in the VE is calculated. The VE vector is calculated by multiplying the mobile displacement vector received from the mobile with the elapsed time between each two frames to obtain a smooth motion.

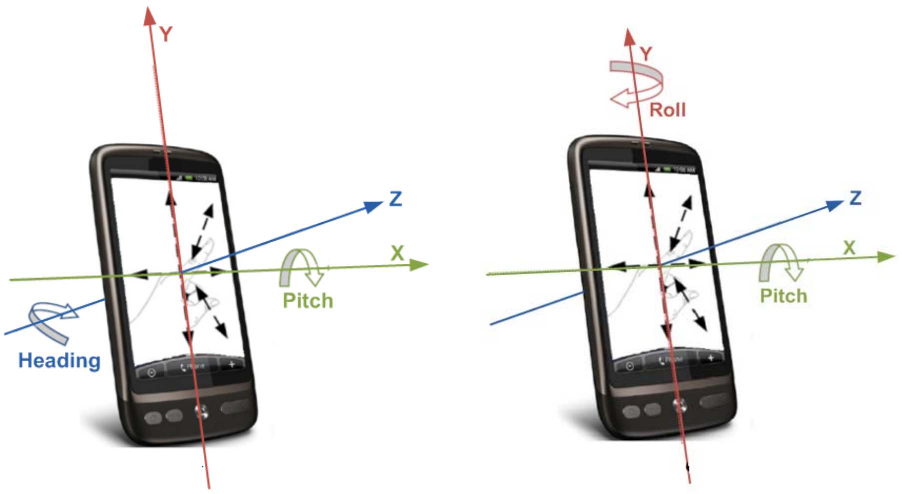
3.4. **Steer based rotation control.** The orientation is controlled by tilting the mobile phone. The sensors in general provide angles for heading, pitch and roll. We calculate the difference between the initial orientation value (once the thumb presses the mobile screen) and the current orientation at each point in time. The delta orientation of the mobile is then mapped to the viewpoint orientation speed in the VE. The delta angles are first “filtered“ and then sent to the VE, where the angles are multiplied by the elapsed time between each two frames and added to the previous VE orientation values (heading, pitch and roll). As a result we obtain a smooth transition from one orientation state to another.

The orientation sensor is a virtual sensor, provided by the phone programming interface, combining the readings from both the 3-axis accelerometer sensor and the magnetic field sensor.

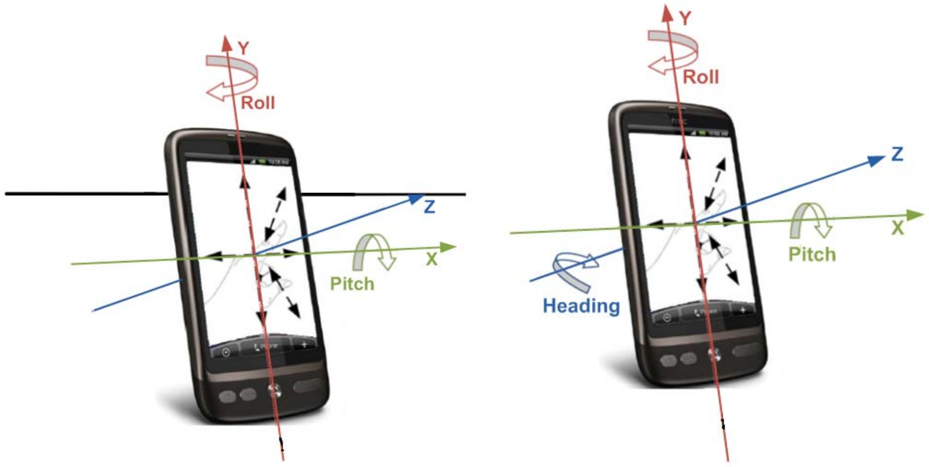
Three techniques are implemented for the steer based rotation control with different number of degrees of freedom and different mapping functions. A fourth technique is a combination of the rotate by heading and the rotate by roll technique, having the maximum number of DOF used.

(1) **Rotate by Heading Technique**: This technique simulates a bicycle or walking metaphor. In this technique heading and pitch of the mobile are mapped to heading and pitch of the VE application. The roll is not used, and the horizon in the VE remains horizontal. The user has to rotate or tilt the mobile around the Z-Axis (up vector). Since the coordinate system is relative to the mobile phone, as shown in Figure 1, rotating the mobile using the hand wrist or the lower arm will not make a difference in sensor readings for the heading; see Figure 3(a).

(2) **Rotate by Roll Technique**: The rotate by roll technique is simulating an airplane metaphor. The change in the mobile roll is mapped to both, heading and roll, in the VE. The change in the roll values generates an animation in the VE to make the user



(a) Rotate by heading (b) Rotate by roll



(c) Rotate by roll with fixed Horizon (d) Merged rotation

FIGURE 3. Steer based rotation control techniques

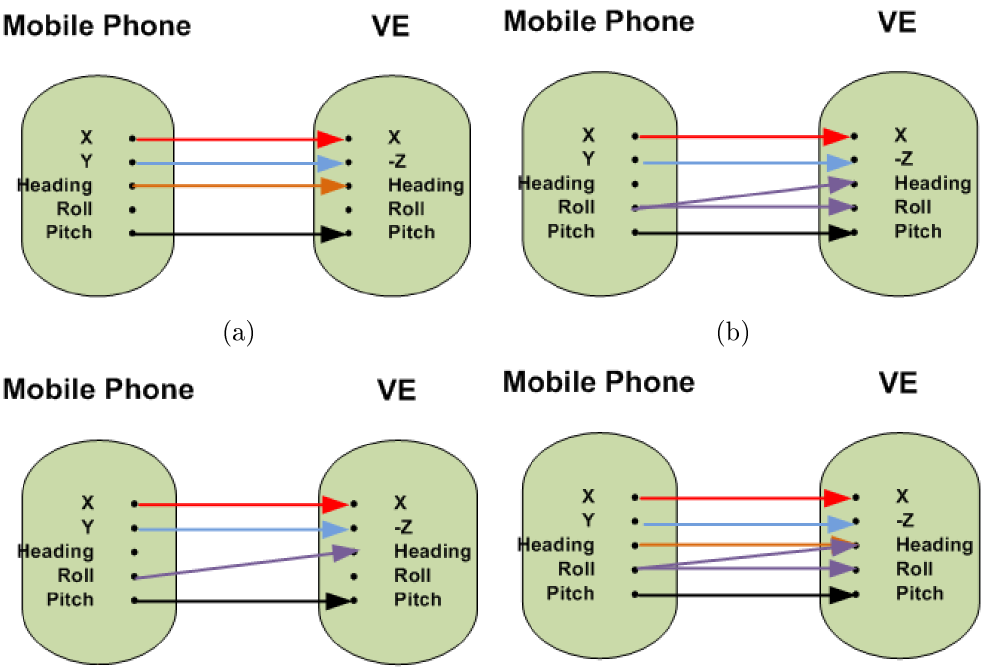
feel like flying. Here, the mobile pitch is mapped to the pitch of the viewpoint in the VE; see Figure 3(b).

(3) **Rotate by Roll with Fixed Horizon Technique**: The rotate by roll with fixed horizon technique is similar to the rotate by roll technique; the only difference is that the horizon remains aligned horizontally. Hence the mobile roll is mapped only to the heading of the VE and the mobile pitch is mapped to the pitch of the viewpoint in the VE. This technique simulates a car steering behavior; see Figure 3(c).

(4) **Merged Rotation Technique**: This technique is a merged combination of the Rotate by Heading and the Rotate by Roll techniques. Both the heading and the roll values from the mobile phone are mapped to the heading in the VE. The delta heading is the average of the delta heading and the delta roll. The mapping of the mobile phone roll to the roll in the VE generates a flying effect. The mobile orientation on the three axes (heading, roll and pitch) is mapped to the VE orientation of the viewpoint (heading, roll and pitch); see Figure 3(d).

3.5. **Travel in a virtual environment.** With the translation and rotation mechanisms at hand, users can travel through the VE freely. The touch translation combined with the four rotation techniques gives the four travelling techniques for investigation in a user experiment. With these techniques at hand we investigate the suitability of different DOF for maintaining exploratory travel tasks and inspect different coordinates' mapping between the phone tilt and the VE rotation.

(1) **Touch Translation and Rotate by Heading Technique**: In this technique four DOF in the mobile device (translation (X, Y) and rotation (heading, pitch)) are mapped to four DOF in VE (translation (X, −Z) and rotation (heading, pitch)); see Figure 4(a).



(a) (b)

(c) (d)

FIGURE 4. (a) Rotate by heading, (b) rotate by roll, (c) rotate by roll with fixed horizon, (d) merged rotation

(2) **Touch Translation and Rotate by Roll Technique**: In this technique four DOF in the mobile device (translation (X, Y) and rotation (roll, pitch)) are mapped to five DOF in VE (translation (X, –Z) and rotation (heading, roll, pitch)); see Figure 4(b).
(3) **Touch Translation and Rotate by Roll with Fixed Horizon Technique**: In this technique four DOF in the mobile device (translation (X, Y) and rotation (roll, pitch)) are mapped to four DOF in VE (translation (X, –Z) and rotation (heading, pitch)); see Figure 4(c).
(4) **Touch Translation and Merged Rotation Technique**: In this technique five DOF in the mobile device (translation (X, Y) and rotation (heading/roll, roll, pitch)) are mapped to five DOF in VE (translation (X, –Z) and rotation (heading, roll, pitch)); see Figure 4(d).

4. **Formative Shaping of Travel User Interface.**

Evaluating user interfaces during development facilitates stability and usability. Following [18], we integrated discussion partners and test subjects at early stages to discuss drawbacks and to identify further issues. This formative shaping during system development helped us learn about behaviors of test users in terms of used dimensionality while performing the travel task.

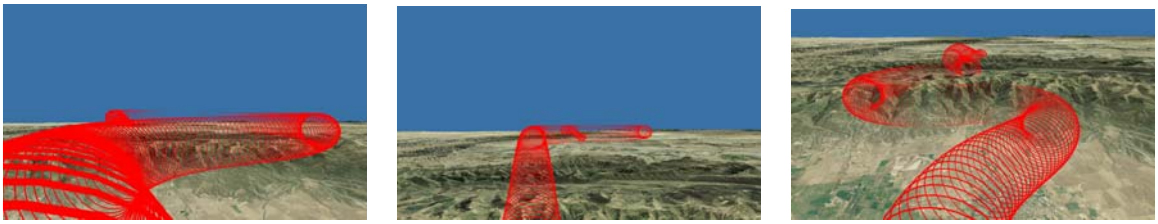
4.1. **Intermediate implementation.**

An intermediate implementation of the touch based translation control technique, was a small modification of the finger walking in place (FWIP) [9] for one handed interaction. The users had to keep "rolling" their thumb to control the viewpoint translation. In other words, we simulate the behavior of a mouse scrolling wheel on the screen such that the user will have to "roll" the virtual wheel on the screen to control the translation in the (X, Y) plane (2 DOF) depending on the movement of the scrolling. Early observations of the users, however, showed that the majority never used the scrolling method. The users, for example, moved the thumb forward on the screen and expected the translation to continue, like with a virtual joystick. Moreover, when this "virtual scrolling wheel" was used at the same time with the steer based rotation control, users had trouble controlling translation and rotation of the device simultaneously. To move forward and to steer at the same time in a sharp turn, most users first had to roll their thumbs for the virtual mouse wheel on the screen to translate, then stopped, and steered the mobile device. Users translated and steered sequentially. Also, due to the continuous finger rolling to simulate the "virtual scrolling wheel", we noticed a clear cross influence between the touch and orientation sensors. While rolling the finger, the users were unintentionally also changing the accelerometers roll readings as they could keep their hands stable. Therefore, we modified the touch based translation control technique to support a "joystick" metaphor, as described in Section 3.3. This modification was instantly accepted by the users, as it removed the undesired sensor cross influence and it relieved the users from hand fatigue. With the new implementation, they did not have to move their thumbs extensively. Small displacements on the screen were enough to perform the translation.

5. **User Study on Steering Metaphors.**

In this user study, we performed a *mixed-factorial* evaluation to compare the performance of the different steering techniques (rotate by roll, rotate by roll with fixed horizon, rotate by heading, and merged rotation) with their different DOF and mapping functions in terms of Accuracy, Errors, Time, and Steering Quality. The overall design goal of this experiment is to evaluate whether users could complete a given travel task better with less or more DOF as presented through our steering techniques. We have also collected data to analyze whether the mapping functions had an influence on the performance. Twenty participants (18 male), ages ranging from 22 to 36 years (M = 27, SD = 3.8), were recruited from the student population of the university. All of the participants had normal vision.

5.1. **Experimental environment.** The mobile device used for the evaluation is an HTC Desire phone. The mobile phone provides a multi-touch display, a 3-axis accelerometer, and a digital compass. The mobile phone runs the Android operating system [7]. The work is evaluated on 3D terrain visualization environment [5]. We used a 3D TV (50") during the evaluation, and the participants had to wear shutter glasses for the 3D effect and semi-immersivity in the VE. The lighting condition of the environment was controlled and remained identical throughout the entire experiment. To be able to carry out the evaluation we drew three different tunnels; we call them *paths*, with different steering complexities in the VE application as shown in Figure 5. However, all of the paths had an equal length of 98km. The coordinates of the paths were taken from a prerecorded flight. The recording was done using a keyboard for the translation and a mouse for the orientation in the VE. In this way the four techniques have the same fairness of travel. Each of the tunnels was composed of rings having a diameter of 2000 meters at 250 meters interval.



(a) Straight paths and two large turns and no change in the pitch

(b) Mixture of sharp and moderate turns along with a straight path

(c) Sharp turns and frequent change in the pitch

FIGURE 5. Path complexities: (a) simple path, (b) moderate path, and (c) complex path

5.2. **Experimental task.** Participants were placed in front of the 3D TV at a distance of 1 meter during the evaluation. The display was placed at a convenient height and fixed throughout the experiment. However, participants were allowed to move their body freely during the experiment. There were two repetitions for each participant, and in each repetition participants had to travel through nine tunnels (permuted) (see Figure

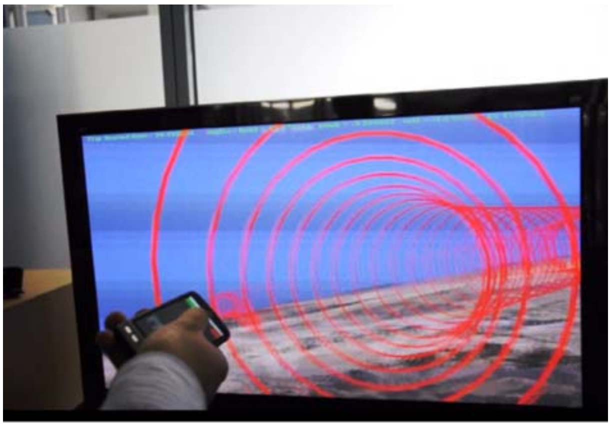


FIGURE 6. Evaluation tunnel

6) using the assigned steering technique. We have randomly distributed participants in four groups. They were instructed to be within the tunnel as much as they can and reach the end of the tunnel as quickly as possible. Participants were allowed to take a rest between each repetition. Participants were provided with a training session to try out the experimental technique before the experiment. Data collection for each trial started when a participant entered the tunnel from the start point, and ended when she reached the end of the tunnel.

5.3. **Variables.** There were four independent and five dependent variables in this experiment. The entire experiment was based on 4 (techniques) × 3 (paths) × 3 (speeds) × 2 (repetitions) × 5 (participants per technique) = 360 data points.

5.3.1. *Independent variable.*

- **Steering Technique** ∈ {Rotate by Roll, Rotate by Roll with fixed horizon, Rotate by Heading, Merged Rotation} *between subjects*
  Please see Section *Steer Based Rotation Control* for detailed description of the four steering techniques used in this experiment. Each group of participant performed their experimental task using only one technique.

- **Path Complexity** ∈ {Simple, Moderate, Complex} *within subjects*
  We have designed three different paths with varying complexity namely Simple, Moderate, and Complex. The paths were verified by a panel of researchers in our group to ensure the quality of the paths are appropriate for their respective levels. We have carefully designed the paths and verified them with a pilot study to avoid any unrealistic turns that could force participants to cause errors.
  Simple: In this type of path we have carefully manipulated the curves to have moderate complexity at the turns (large turns). Along the entire path were just two turns, straight paths and minimal change in the height along the path. See Figure 5(a).
  Moderate: Moderate path had a mixture of sharp and moderate turns along with a straight path. We also varied the height along the path more than that of the Simple path. See Figure 5(b).
  Complex: This type of path had all sharp turns and frequent change in the pitch. See Figure 5(c).

- **Speed** ∈ {Slow, Medium, Fast} *within subjects*
  Increasing speed decreases the accuracy of traveling in a VE. We were interested to know how the increasing speed affects our four novel techniques. We have systematically varied the speed: Slow (20km/sec), Medium (35km/sec), and Fast (50km/sec).

- **Repetition** ∈ {1 to 2} *within subjects*
  We have crossed the variables Path and Speed to achieve nine unique stimuli and then permuted these nine conditions to each participant in one set of trials. A same set of nine trials was repeated two times for each participant resulting in having the participants to perform eighteen different trials, where they traveled through one path in each of them. Participants were allowed to take a break between two trials and also a longer break after each repetition.

5.3.2. *Dependent variable.* As dependent variables we measured Accuracy, Error, Time and Steering Quality.

Accuracy: We measured the accuracy of traveling using these steering techniques with Equation (1).

$$\text{Accuracy} = \frac{\text{Time}_{\text{in}}}{\text{Time}_{\text{total}}} \times 100\% \tag{1}$$

Hence, an accuracy of 100% is perfect.

Error: The number of times participants went outside the tunnel's rings during each travel was measured as an Error.

Time: In each trial the time to reach the end of the tunnel was measured in Seconds. The stopwatch started when the participant entered through the first ring of the tunnel.

Steering Quality: We decided to measure a composite measure that takes all aspects of the travel into account and call it *Steering Quality*. It was measured using the following Equation (2).

$$\text{Steering Quality} = \text{Error} \times \text{Time}_{\text{out}} \times \text{Deviation} \tag{2}$$

where Deviation is the *area* covered outside the tunnel during each travel. Hence, 0 is the veridical steering quality and lower values indicate higher quality.

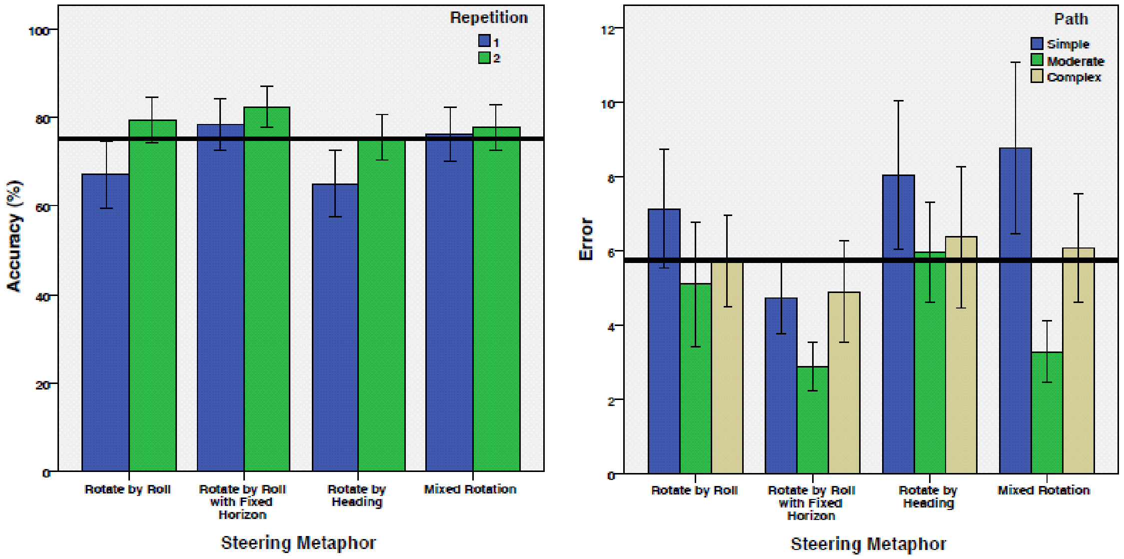
5.4. **Hypotheses.** Initially we have hypothesized the following.
[**H1**] Overall, performance will increase with the increase of DOF in the techniques as participants will have more flexibility in the traveling task. Hence, Merged rotation will be the best among all of the techniques.
[**H2**] The higher the speed is and the more complex the tunnel is, the worse the accuracy for the travel task is.

5.5. **Results.** To analyze the effect of four steering techniques on the dependent variables we ran a set of mixed factorial ANOVAs, one for each of the dependent variables using the statistical package SPSS. Once getting a significant main effect through the ANOVA, we used Tukey's HSD post-hoc test to analyze between-subject effects (Techniques) and pairwise comparisons with Bonferroni adjustments for within-subject effects (Path, Speed, and Repetition).

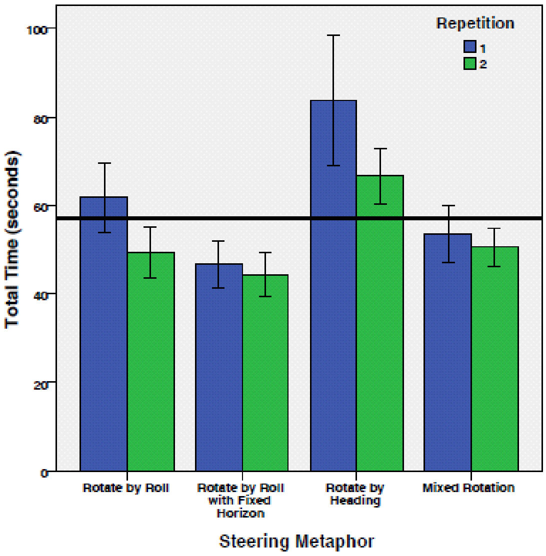
Accuracy: The analysis did not show a significant main effect of Technique $F(3, 16) = 1.071$; $p = .389$; ${\eta_p}^2 = .167$ (see Figure 7(a)). However, among all of the techniques Rotate by Roll with fixed horizon was the best (M = 80.44, SD = 17.61) and Rotate by Heading was the worst (M = 70.28, SD = 22.21). **Error:** There was a significant main effect of Technique on Error $F(3, 16) = 3.51$; $p = .04$; ${\eta_p}^2 = .397$ (See Figure 7(b)). In this case also, Rotate by Roll with Fixed Horizon (M = 4.17, SD = 2.9) was significantly ($p = .03$) better than Rotate by Heading (M = 6.79, SD = 4.77). Expectedly, there was main effect of Speed ($p < .001$) as Slow speed being significantly better than both Medium and High speeds. We have found a main effect of Path on Error ($p < .05$). Interestingly, Moderate path (M = 4.3, SD = 3.41) had significantly ($p = .02$) better performance than both Simple (M = 7.17, SD = 4.96) and Complex (M = 5.77, SD = 4.04) paths. Surprisingly, the Simple path had most errors.

Time: Steering techniques had a significant main effect on the total time $F(3, 16) = 5.244$; $p = .01$; ${\eta_p}^2 = .496$ (See Figure 7(c)). Rotate by Roll with Fixed Horizon (M = 45.48, SD = 16.92) was significantly ($p = .008$) faster than Rotate by Heading (M = 75.15, SD = 38.52).

Steering Quality: Though Rotate by Roll with fixed horizon was the best technique in terms of steering quality, ANOVA did not report any main effect of steering techniques on steering quality ($p = .13$). Expectedly, Path had a significant main effect on Steering Quality $F(1.42, 22.74) = 9.13$; $p = .003$; ${\eta_p}^2 = .363$ (Greenhouse-Geisser adjustment), and so had Speed $F(2, 32) = 9.396$; $p = .001$; ${\eta_p}^2 = .37$. While the Moderate path had



(a) Accuracy (b) Error

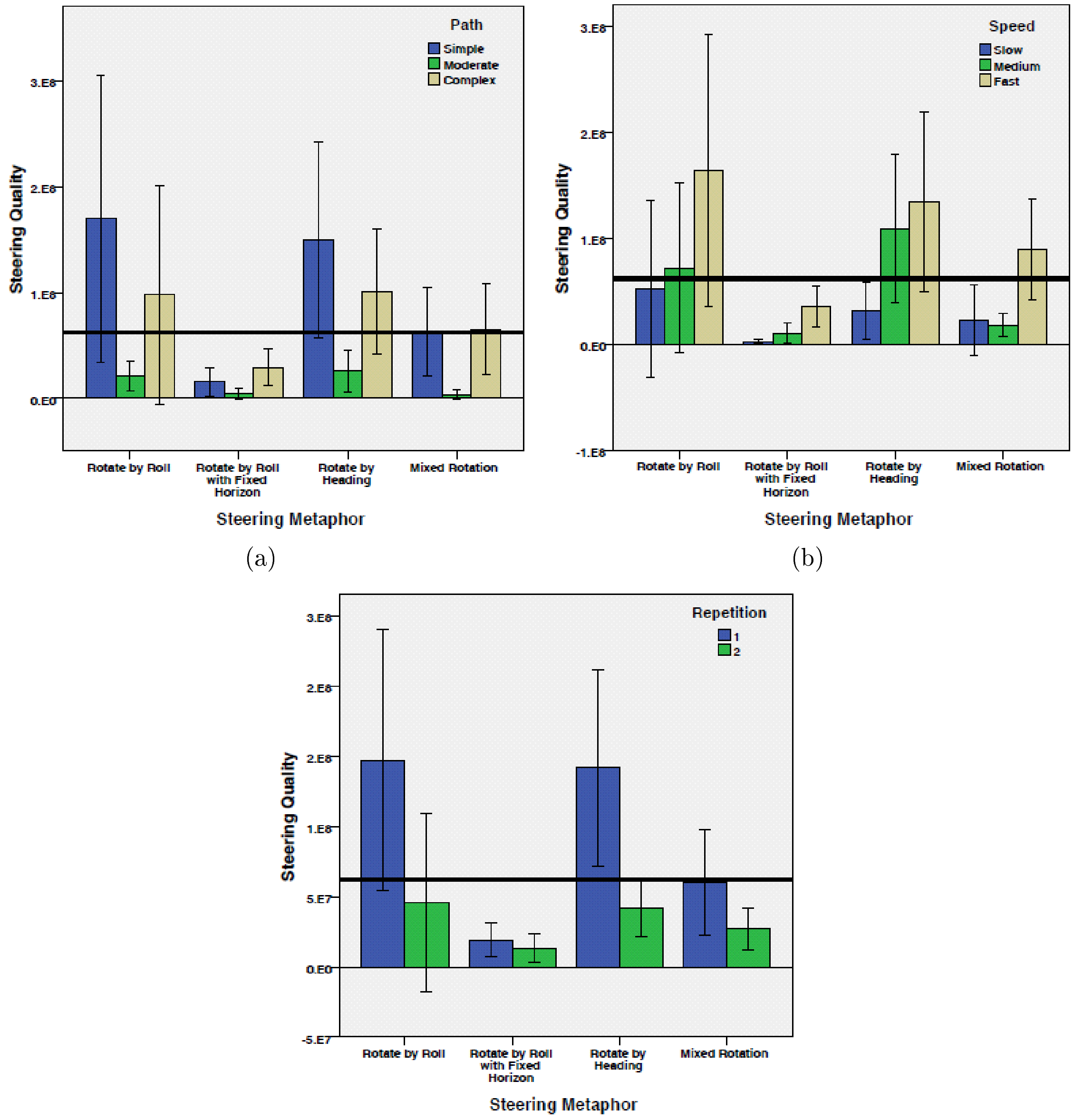


(c) Time

FIGURE 7. Rotate by roll with fixed horizon appeared to be the best alternative among all of the techniques experimented in terms of Accuracy (a), Error (b), and Time (c). Moderate path had significantly less Error. Thick black lines represent the overall mean and whiskers represent ±95% confidence interval.

significantly better steering quality than other paths (see Figure 8(a)), High speed had significantly worst quality than both of the other speed levels (see Figure 8(b)).

5.6. **Discussion.** We considered all of the performance metrics (Accuracy, Time and Error) at the same time, because it is not sufficient to draw any conclusions without looking at all those aspects together. Accuracy gives an indication of the percentage of the time users spend steering inside the tunnel with respect to the the total time. However, we need to know how many times users exited the tunnel, and what is the area of the path they covered outside the tunnel until they steered back inside the tunnel. Therefore, we calculated the steering quality as a product of the deviation, time, and error. From



(a) (b)

(c)

FIGURE 8. Rotate by roll with fixed horizon had the highest steering quality among all of the steering techniques. The thick black line represents the overall mean and whiskers represent ±95% confidence interval.

the results presented in the previous section, we can draw the following conclusions: The *rotate by roll with fixed horizon*, seems to have the best performance in general, it is also the most consistent technique. This is due to the fact that the performance of this technique shows consistent results through both repetitions, in other words even though the learning effect is the smallest among all the techniques, the first repetition is already better than the second repetitions of all the other techniques. Moreover, rotate by roll with fixed horizon, has more stable results even in different speeds and path complexities. Interestingly, despite the fact that the rotate by roll technique and the rotate by roll with fixed horizon have the same DOF, the only difference is the fact that with rotate by roll with fixed horizon the roll is mapped to both the heading and the roll in the VE, the later performed better than the earlier. In other words, the roll dimension in the VE provides a nice animation to simulate flying, but does not improve steering quality. This is due to the fact that participants in rotate by roll with fixed horizon had a fixed frame (i.e., the horizon) during their traveling task and it was easier for them to constantly relate their current orientation with that fixed frame. Hence, this worked as a visual cue and helped them to maintain orientation. Also, some test users mentioned that they felt some kind of dizziness due to the fact that roll was changing in the VE. Another interesting observation is the fact that all techniques performed worst in all performance metrics (time, error, steering quality) with the simple path. A simple path had the characteristics of containing straight paths and only two wide turns. It is worth mentioning that we identified the path to be *simple*, since it has mostly straight paths elements. However, it appeared to be difficult to steer in a straight path, meaning it was challenging for the participants to hold the hand still, and not to change the rotation of the mobile phone, even if we introduced thresholds and separated the translation and rotation on different sensors. When the speed is fast, the Accuracy of the four techniques is almost the same and around 50 percent; in other words, the users were almost half of the time outside the tunnel. This was expected, because when the speed is too high, the performance of steering experiences a negative impact.

On a more subjective level, we observed the following. Even though, we expected the use of the mobile phone heading to steer left and right in the VE to be more natural and intuitive than the use of roll, because this is actually how humans turn left and right in the real world. However, the opposite showed to be true. When using the rotate by heading technique and rotating the mobile phone over the Z-Axis, the users complained about wrist fatigue. We think that the reason behind that could be the fact that rotating the hand over the wrist joint is not a too common hand movement. Other participants used the rotate by heading technique and used their elbow to change the heading; they expected a larger change in the heading value compared with using their wrist. This is not the case as the delta change in the heading value is the same (the sensor coordinate system of the mobile phone). On the other hand, while using the roll to control the heading, participants felt that the rotation over the Y-Axis is easier, e.g., a *screw driver* movement, and they could take better control of the roll change. In addition to that, in the merged rotation technique, participants disliked the fact that they could not separate the heading control from the roll control in the VE. As a result, participants were not able to turn left using only heading. With this technique, a heading change was inseparable from a roll change with the mobile phone and vice versa.

Analyzing the sensors readings for the merged rotation, users actually used mostly the roll to control the heading. When the heading value was below a certain threshold, only the mobile roll was used to control the heading in the VE. We could also notice that during the user study and the observation of the users' hand gestures.

6. Conclusion and Future Work.

Incorporating mobile phones as self-contained input devices for travel control tasks in VEs is a challenging task. Especially the built in sensors are not yet perfectly suitable for sensing in all DOF.

To investigate the usability of phones with an "appropriate" number of DOF and mapping functions, we developed a concept for a one-handed travel technique. We use the touch capability of the mobile phone for translation, and the built-in sensors in the mobile phone for VE viewpoint rotation control. To gain experience about the self-referring combination of the number of DOF that can be handled by a user and the variety of mapping functions, we developed four differing interaction techniques for traveling and shaped them in formative studies. The four travel techniques are: rotate by roll, rotate by roll with fixed horizon, rotate by heading, and merged rotation. Each technique has either 5 or 4 DOF and different mappings of the phone coordinates to the VE viewpoint coordinates.

We performed an empirical user study to investigate the number of DOF that are necessary to travel in a VE as easy as possible and to study the different coordinates mappings. The results of the user study show that the rotate by roll with fixed horizon technique with 4 DOF provides good performance, and shows strong acceptance and favoritism among the users. Also the usage of the roll in the mobile phone to control the heading in the VE seems to be the desired or appropriate mapping. Finally, we find that an extra not needed dimension in the VE could also make a significant difference in terms of performance, in our case the VE roll. In other words, an extra dimensionality does not lead automatically to better control, and could hinder the performance and the acceptance of the user interface.

In the future, we are planning to compare both the rotate by roll techniques with classical existing systems, like joysticks. Especially that joysticks benefits greatly from the elastic resistance. Also, we will enhance the technique by adding some more visual cues showing for example what gestures users actually execute on the mobile phone. Visual guidance when the users leave the tunnel will also be investigated. Some participants also mentioned the fact that haptic feedback on the mobile phone when they hit the tunnel borders would be beneficial. Finally, we are planning to perform further subjective evaluations and to estimate the fatigue factors.

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