Comparing Steering-Based Travel Techniques for Search Tasks in a CAVE

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ABSTRACT

We present a novel bimanual body-directed travel technique, PenguFly (PF), and compare it with two standard travel-by-pointing techniques by conducting a between-subject experiment in a CAVE. In PF, the positions of the user's head and hands are projected onto the ground, and travel direction and speed are computed based on direction and magnitude of the vector from the midpoint of the projected hand positions to the projected head position. The two baseline conditions both use a single hand to control the direction, with speed controlled discretely by button pushes with the same hand in one case, and continuously by the distance between the hands in the other case. Users were asked to travel through a simple virtual world and collect virtual coins within a set time. We found no significant differences between travel conditions for reported presence or usability, but a significant increase in nausea with PF. Total travel distance was significantly higher for the baseline condition with discrete speed selection, whereas travel accuracy in terms of coin-to-distance ratio was higher with PF.

Index Terms: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 INTRODUCTION

Navigation is among the most crucial components of every interactive 3D user interface. Two aspects of navigation can be distinguished: travel and wayfinding. Travel refers to the movement from one location to another. Wayfinding is the process of defining a path through the environment. Travel can be classified as active or passive travel, depending on the user's control over the motion. In this work, we address active travel techniques involving *steering*, in which a user constantly specifies the direction of travel. Common techniques [2] are *gaze-directed* steering, whereby the user's view vector is used as direction of motion, *pointing-directed* steering, where hand orientation indicates travel direction, and *torso-directed* steering, which uses the orientation of the user's body. Steering-based techniques often assume that the virtual space is much larger than the available tracked physical space. This is suitable for a Cave Virtual Environment (CAVE) [3] with 3D stereo-projected surfaces. Most researchers believe that active usage of the participant's body, with the real proprioceptive sensations matched by synthetic visual and aural data, strongly affects virtual presence [10]. Therefore, we investigated different travel interfaces, each with a different amount of body movement. We use a CAVE, where the user is surrounded by the virtual scene. No virtual representation of her body is required, since the user can see her real body.

2 RELATED WORK

To classify relevant studies investigating travel techniques, of which most were conducted using head-mounted displays (HMDs), we follow the categorization of Bowman et al. [2]: *exploration* has no explicit goal for movement, *maneuvering* takes place in a local area, and *search* is travel with a specific goal. In an exploration task study, Suma et al. [11] compared real walking with gaze-directed and pointing-directed travel. Participants wearing an HMD were asked to remember objects in a virtual maze. They found that, in general, no condition significantly outperformed the others, though there was a consistent trend of better performance for real walking. Another HMD exploration study by Jeong et al. [4] compared velocity control techniques on an information-gathering task using pointing-directed travel. They found that force-based velocity control based on analog input was more efficient in terms of information gathering, collisions, and ease of use. Arns and Cruz-Neira [1] found that choice of display device and rotation method can have a significant impact on a user's ability to travel in an exploration task. A maneuvering task study by Whitton et al. [14] determined an ordering of locomotion interfaces by their naturalness. In a recent HMD search study by Riecke et al. [7], controlling translations via joystick and rotations via physical orientation led to better performance than joystick navigation, and yielded almost comparable performance to actual walking in terms of search efficiency and time. However, their findings stand in contrast to those of Ruddle et al. [8]. Usoh et al. [13] compared real walking, walking-in-place, and flying in terms of reported presence when participants walked by a virtual ledge. They found that both kind of walkers had a higher subjective presence than flyers.

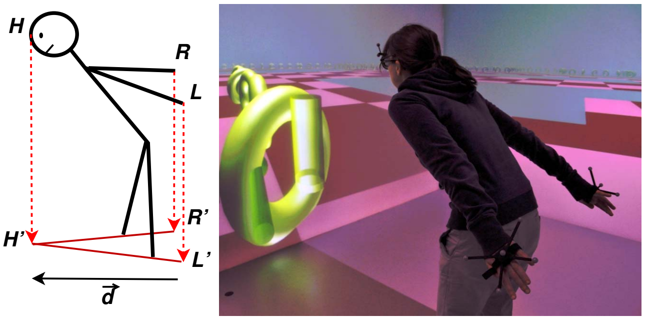

Figure 1: PenguFly (PF): A bimanual body-directed travel technique. The standing user's head and hands are tracked. Their positions are projected onto the ground to define a 2D triangle $H'L'R'$. Travel direction is defined by $\vec{d} = H' - (R' + L')/2$, whereas velocity depends on the length, $||\vec{d}||$.

3 PENGUFLY

We present PenguFly, a bimanual body-directed travel technique with increased body movement (cf. Figure 1). To travel, the user moves her tracked arms and head relative to each other. We named this technique because the pose reminded us of penguins stretching their wings.

Direction Selection Let H, L, R be the position of the user's head (tracked stereo glasses), left hand, and right hand, respectively and H', L', R' their projections onto the ground plane, as shown in Figure 1. The travel direction $\vec{d}$ is given by the vector from the

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IEEE Virtual Reality 2011
19 - 23 March, Singapore
978-1-4577-0038-5/11/$26.00 ©2011 IEEE

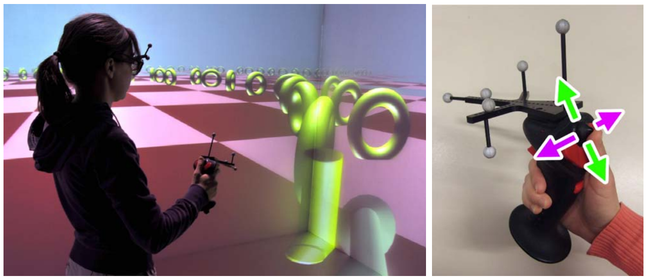

Figure 2: Flystick (F): A user holds a tracked wireless device in her dominant hand. Forward and backward movement in the direction of pointing is activated using a paddle (green arrows). Speed can be adjusted by tipping the paddle to the left or right (pink arrows).

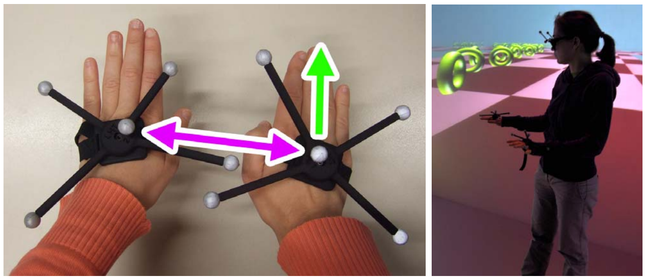

Figure 3: Hand Pointing (HP): Tracking targets are attached to the user's hands. With her dominant hand (here, the right hand) she points in the direction of travel (green arrow) and controls the speed by adjusting the distance between both hands (pink arrow).

midpoint between L' and R' to H', $\vec{d} = H' - (R' + L')/2$. Hence, the user moves forward if she holds her hands behind her head, backward if she holds her hands in front of her head.

Velocity Selection Velocity is selected continuously as a quadratic function $v_{\max} \cdot (||\vec{d}||/x_{\max})^2$ of the projected distance between head and hands $||\vec{d}||$ with maximum velocity $v_{\max}$. The value $x_{\max}$ serves as a normalization constant, determined individually by each user's arm length. For ease of use, we approximate $x_{\max}$ by an initial calibration where the user stands upright with her arms straight at her side. Since we know H, L and R from the tracking system we initially set $x_{\max} = \max\{||H - L||, ||H - R||\}$. Hence, $||\vec{d}||/x_{\max}$ is always in the range between zero and one.

Input Condition The activation and termination of travel is controlled by thresholding the projected distance between head and hands, $||\vec{d}||$. Travel is only activated if $||\vec{d}||$ exceeds a certain threshold t, $||\vec{d}|| > t$. This effectively defines a safety region around the user in which hand movement does not initiate travel. We chose the threshold t as follows: the human body can be subdivided roughly into segments of equal size, where the head is one of them. Since we know the position H of the tracked stereo glasses, we can approximate the total height of the user and from that the size of one body segment. We found that a threshold t of half the size of one body segment works well.

4 USER STUDY

The experiment was a between-subject design and the independent variable was the travel technique. The task was to collect as many coins as possible in a set time, which can be classified as a search task. In all techniques, the user moves in a 2D plane parallel to the ground. For all conditions, the maximum velocity was set to $v_{\max} = 20$ m/s (one ground tile corresponded to 2 meters). Our main hypotheses were that users would perform best with the baseline conditions, but would have more fun and would feel more immersed using PF.

4.1 Participants

We recruited 30 unpaid participants (28 males, mean age = 22.97, SD = 6.28) through email lists and newsgroups. All were able to walk unassisted and had full use of both arms. 15 participants played computer games weekly or more often, eight monthly, five every few months, and only two twice a year or less often. The participants were generally naïve Virtual Reality (VR) users: 25 had never used a VR system before and only five twice a year or less often. The 30 participants were randomly assigned to one of the three conditions, 10 participants in each condition.

4.2 Control Conditions

Flystick (F) Condition F is a steering-by-pointing technique. The participant holds a tracked wireless device in her dominant hand (Figure 2). Direction of travel is selected by hand orientation. A paddle on the device can be pushed up, down, left, or right. The input condition is continuous; the user moves forward as long as she pushes the paddle up, or backward as long as she pushes the paddle down. The velocity is selected explicitly from discrete values by pushing the paddle left (slower) and right (faster). For n discrete steps the ith velocity was $v_{\max} \cdot (i/n)^2$; in the experiment we used $n = 10$. The device is capable of registering only one distinct button press, so the user cannot change velocity and move simultaneously.

Hand Pointing (HP) Condition HP is a steering-by-pointing technique. The participant is equipped with two tracking targets to determine the positions of both hands, as well as the orientation of the dominant hand. The direction of travel is selected by pointing with the dominant hand (Figure 3). The user starts moving as soon as she holds her dominant hand above her waist. Again, we use the segmentation of the human body to approximate the position of the waist at $5/8$ of the body height. The velocity is set continuously through the distance between both hands. This approach is similar to that of Mine et al. [6], except that travel direction is not defined as the ray from one hand to the other. Maximum velocity is reached at a distance of one arm length.

4.3 Equipment

All conditions were tested in a CAVE [3] with four back-projected walls and a floor projected from above. The back wall can be opened. It has a total volume of 3.6m×2.7m×2.7m with A.R.T. infrared optical tracking (update rate: 60Hz, latency: 80–120ms). The system consists of ten passive stereo LCD projectors with 1600×1200 resolution, driven by a cluster of ten Dual-Core AMD Opteron processors with Nvidia Quadro FX 5600 graphics cards. Depending on the scenario, the images were refreshed at 30–50 frames per second. Eye separation for stereo was set to 6cm.

4.4 Measures

As qualitative measures, we assessed simulator sickness using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [5], reported presence using the Steed-Usoh-Slater (SUS) Presence Questionnaire [10], and usability of the travel technique with 20 seven-point Likert scale questions in a usability questionnaire. As quantitative measures, we used distance traveled, task performance, and accuracy. Since participants were asked to collect coins in the virtual world, we defined task performance as the number of collected coins, and accuracy as the number of coins collected per unit distance.

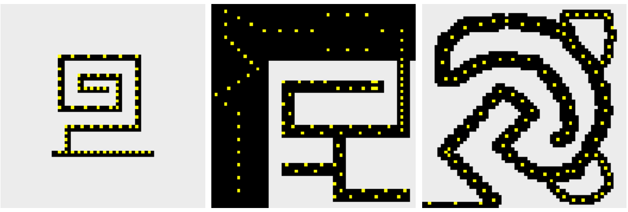

Figure 4: The layouts of the three testing scenarios are represented as discrete pixel images. Ground tiles are black, and ground tiles with coins are yellow.

4.5 Experiment Procedures

The pretesting, experiment session, and posttesting took each participant approximately 45 minutes to complete.

Preexperiment Users read and signed the Informed Consent Form. Then, they filled out questionnaires about demographics, computer use, VR use, and simulator sickness.

Experiment In the lab, the experimenter introduced the CAVE and the equipment specific to the participant's condition. The task of collecting as many coins as possible in a set time was described. The participant's body measures were obtained to normalize speed selection. For 180 seconds, she could practice her travel condition in two training environments. The CAVE was almost completely closed before loading the three testing scenarios, overviews of which are shown in Figure 4.

The user had 45 seconds in the first 64m×64m testing scenario, which had sharp rectangular corners. The second scenario had multiple slalom paths. The third scenario was designed as a continuous path with two secondary loops. The second and third scenarios both measured 128m×128m and were presented for 60 seconds each. Users thus traveled for a total of 165 seconds, with additional 10 second breaks between scenarios.

Postexperiment The participant filled out another SSQ and the SUS. Next, the participant filled out the usability questionnaire and could give general comments, as well as suggest improvements.

5 EVALUATION

There was no significant difference among groups in gaming experience and VR system use. An alpha level of 0.05 was used for significance on all measures.

5.1 Qualitative Measures

Simulator Sickness One participant in the F condition was eliminated from the analysis because his high SSQ score (SSQ=41.44) indicated he was already feeling ill prior to the experiment. Each of the simulator sickness scores (overall simulator sickness, disorientation, oculomotor discomfort, and nausea) was treated with a 2×3 mixed analysis of variance (ANOVA), testing the within-subject effect of time (SSQ score before and after the experiment) and the between-subject effect of travel technique.

The analysis of overall simulator sickness revealed a significant increase of the SSQ score from before to after the experiment for all conditions ($F(1,26) = 6.57, p = .016$). This was also true for disorientation ($F(1,26) = 8.23, p = .008$). It is possible that the nature of the study task, which reinforced traveling with high velocity, is responsible for the rise in disorientation. The analysis of oculomotor discomfort revealed no significant interaction effects. The analysis of the individual measure of nausea revealed a significant interaction effect ($F(2,26) = 3.59, p = .041$). A post-hoc analysis with the Tukey HSD test indicated that participants in the PF condition had a significant rise in nausea (see also Figure 5).

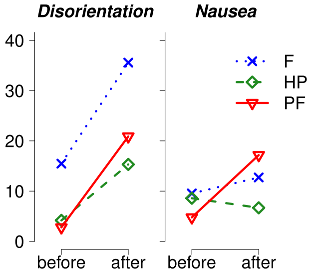

Figure 5: Mean values for disorientation and nausea.

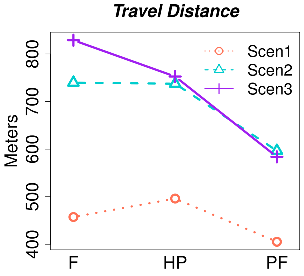

Figure 6: Mean values for travel distance.

Presence A one-way between-subject ANOVA across all travel conditions for the SUS Presence Questionnaire revealed no significance ($F(2,27) = 0.17, p = .84$). The means and standard deviations for each condition are as follows: F: $M = 2.0, SD = 1.56$, HP: $M = 1.7, SD = 1.16$, and PF: $M = 2.1, SD = 1.91$.

Usability Most one-way ANOVAs on each of the usability questions did not reveal significant differences between the travel techniques. "I don't notice any inconsistencies as I navigate" revealed significant differences ($F(2,27) = 5.86, p = .007$). A post-hoc analysis with Tukey HSD showed that participants in the F condition found more inconsistencies than participants in the HP or PF conditions. This could be due to the decoupling of speed and movement in the F condition. Users were experiencing rather large accelerations each time that travel was activated or deactivated by a button press. We did not find significant differences in fatigue between the techniques, but participants traveled for only six minutes, which is probably too short to measure fatigue. Generally, participants gave rather positive ratings for all conditions, which could be due to the novelty of their VR experience.

5.2 Quantitative Measures

The results of the three 3×3 mixed ANOVAs testing the between-subject effect of travel technique and each within-subject effect of distance traveled, collected coins, and accuracy are listed in Table 1.

	interaction	travel technique	measure
distance	$F(4,81) = 1.35$ $p = .26$	$F(2,81) = 11.19$ $p < .0001$	$F(2,81) = 36.8$ $p < .0001$
performance	$F(4,81) = 2.77$ $p = .03$	$F(2,81) = 9.02$ $p = .0003$	$F(2,81) = 25.33$ $p < .0001$
accuracy	$F(4,81) = 1.83$ $p = .13$	$F(2,81) = 9.88$ $p = .0001$	$F(2,81) = 33.27$ $p < .0001$

Table 1: Results of three 3×3 ANOVAs testing the between-subject effect of travel technique and each within-subject effect of distance, coins, and accuracy, respectively. The first column shows the overall interaction effect, the second the main effect for travel technique, and the third the main effect of the respective measure.

Total Travel Distance The analysis revealed no significant interaction effect between distance and condition. The main effect for travel interface was significant, as was the main effect for distance. Post hoc analysis investigating the between-subject effect of the travel technique revealed that the distance traveled in the PF condition was smaller than in the F or HP condition. Since some participants in the PF condition were feeling sick, they may have been inclined to reduce the optic flow by traveling slower and therefore moving less. The F and HP conditions were not significantly different. The mean distance values shown in Figure 6 imply that participants in the F condition were still training during the testing or that the scenario layout influenced their total travel distance.

Task Performance We defined task performance by the number of collected coins. The analysis revealed a significant interaction effect between collected coins and condition. The main effect for travel interface was also significant, as was the main effect for collected coins. These results indicate that the number of collected coins varied across conditions and was affected differently depending on the condition. The means of collected coins for each condition are displayed in Figure 7. Post-hoc analysis investigating the between-subject effect of the travel technique revealed that the number of collected coins in the F condition was greater than in the HP or PF condition. The HP and PF conditions were not significantly different.

Accuracy Coins were laid out to suggest a path to follow, but participants were completely free to choose the way they wanted to travel. Since we did not ask the participants to follow a specific path, we did not analyze the deviation from a perfect path. Instead, we measured accuracy by the number of coins collected per unit distance. Accuracy is depicted in Figure 8. The analysis revealed no significant interaction effect between collected coins per distance and condition. The main effect for travel interface was significant, as was the main effect for collected coins per unit distance. A post-hoc analysis with the Tukey HSD revealed that accuracy in the PF condition was greater than in the HP condition.

6 CONCLUSIONS AND FUTURE WORK

We found that participants covered significantly more distance in the control conditions than in PF. In terms of our accuracy measure (coin-to-distance ratio), participants performed more accurately in the PF condition than in the baseline conditions, and statistical significance was revealed between PF and HP. Participants in the PF condition reported a significant increase in nausea in contrast to the control conditions. This might result from the increased level of body movement in the PF condition. For example, Suma et al. [12] found that real walking in comparison to walking in place increased simulator sickness, in particular disorientation, when wearing an HMD. While it might not be justified to extrapolate from their HMD study to our CAVE study, further work is required to investigate the effect of body movement on simulator sickness.

We found no significant differences in usability between conditions. Most aspects of usability were rated high for all conditions, which may be due the to excitement of the predominantly novice VR participants. Hence, the present study does not support our initial hypothesis that participants using PF have more fun than those using the baseline conditions. Moreover, it let us conclude that in its current form PF is not suitable for a fast-paced search task in a large virtual environment.

In a future user study, several factors need to be improved. The F technique with force-based velocity control would be more suitable as a control condition, since it was found to be more efficient in a comparison of different velocity control techniques [4]. We believe that both training and testing time should be increased: first, to make sure that further learning effects do not occur during testing, and second, to increase the chance to measure a significant change in fatigue. A different ordering of the testing scenarios may be interesting to investigate if participants in the F condition really travel less when there are sharp corners. To compare the scenarios to one another, their design should be similar in terms of time limit and number of coins. Our accuracy measure (coin-to-distance ratio) may not be ideal. It may be better to calculate a deviation from a perfect path. The scenarios should then not contain any crossroads. In particular, the path could also be enclosed by walls such that participants see only the path ahead. Additionally, the number of collisions could be included in the accuracy measure.

Furthermore, we believe that participants' disorientation originates at least partially in their efforts to travel as fast as possible to perform well in collecting coins. Therefore, it may be interesting to investigate simulator sickness in scenarios with no time limits. We found a rather low overall reported presence with no significant differences between travel conditions. Although experimental studies of presence have not found conclusive evidence that higher visual realism is directly related to higher reported presence [9], our scenes may be too simple in terms of dynamics and 3D content. Usability could be tested in a within-subject experiment to get more diverse results among the different conditions; however, simulator sickness and presence would then be more difficult to measure.

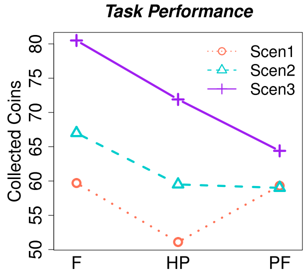

Figure 7: Mean values of collected coins.

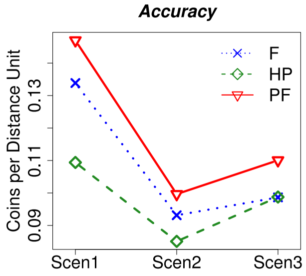

Figure 8: Mean values of coins per distance unit.

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