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Evaluation of a Bimanual Simultaneous 7DOF Interaction Technique in Virtual Environments

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ABSTRACT

This paper introduces our novel bimanual interaction technique, Spindle+Wheel that provides simultaneous 7DOF. Spindle+Wheel takes advantage of greater finger dexterity, the “bandwidth-of-the-fingers” and passive haptics, by using a pair of precision-grasp 6DOF isotonic input devices rather than using either a tracked pair of pinch gloves or a pair of power-grasped 6DOF isotonic input devices. Two user studies were conducted to show that our simultaneous 7DOF interaction technique outperforms a previous two-handed technique as well as a one-handed scene-in-hand technique for a 7DOF travel task.

Keywords: 3D interaction, 3D navigation, view manipulation, bimanual interaction, input devices, virtual environments

Index Terms: H.5.2 [Information interfaces and presentation]: User Interfaces—Input devices and strategies, Evaluation/methodology

1 INTRODUCTION

Spatial user interaction (UI) plays an important role in Virtual Environments (VE). It allows the user to travel the virtual environment to find a target or investigate a place or a virtual object in the world. These interactions often require 6 degree-of-freedom (DOF): position (xyz) and rotation (yaw,pitch,roll). Examples are 3D object manipulation [18, 15] and view manipulation [16]. Many previous 6DOF one-hand [18, 16, 15] or two-hand [6, 11, 13] techniques have been developed and are widely used in various VE applications. Some spatial UIs require more than 6DOF. The user may want to increase the size of a virtual object to check the object in detail, or she may want to shrink the size to make it fit into the other object. In these cases, the interaction technique requires 1 more DOF: scale.

While many previous two-handed interaction techniques provide simultaneous 6DOF, only a few more recent techniques have supported simultaneous 7DOF [8]. Some previous research shows that controlling more DOF simultaneously improves user’s performance to accomplish 6DOF interaction tasks faster because it reduces transition time to control different DOF [19, 7]. For example, when the user moves a 3D object to a certain 3D location (i.e. translation: x,y,z) she can also rotate the object (i.e. rotation: yaw,pitch,roll) if the technique supports simultaneous 6DOF.

This suggests that simultaneous 7DOF techniques may outperform techniques that require mode switching between the DOFs for tasks that require translation, rotation and scale. For example, using the Mapes and Moshell’s bi-manual technique [6], the user can simultaneously control x,y,z + yaw,roll + scale, but not pitch. Similarly using the one-handed scene-in-hand technique [16], the user can simultaneously control xyz + yaw,pitch,roll but not scale.

2 BACKGROUND AND PRIOR WORK

Mapes and Moshell [6] present a bi-manual technique using 6DOF tracked pinch gloves for adjusting the scale and pose (position + orientation) of an object in an HMD. Two 3D cursors are displayed corresponding to the users hands. The interaction technique is engaged with a pinch gesture. Translating the hands rigidly translates the target object in xyz. Rotating the hands relative to one-another rotates an invisible axis between the two cursors adjusting the target objects orientation via yaw and roll. Expanding or contracting the distance between the hands scales the target up or down. While yaw and roll motions are immediately accessible, pitch about axis between the hands is not supported.

Cutler et al. [2] developed various interaction techniques on the responsive workbench using tracked pinch gloves. They describe bi-manual grab-and-scale. The left hand grabs an object (xyz-only) and as the right hand moves toward/away form the left the objects scales up and down. Their bi-manual zoom is the view manipulation counter-part to their ‘grab-and-scale’. Both are 4DOF: xyz+scale. Their ‘grab-and-twirl’ modifies Mapes-Moshell’s method with the ability to pitch about the axis between the two-hands. In grab-and-twirl, the right hand controls pitch. However, compared to Spindle+Wheel, grab-and-twirl does not al-
low scaling. There are no formal evaluations.

Ulinski et al. [14] explore different two-handed techniques for selecting subsets of volume data. They develop and compare a number of two-handed techniques based on Vguiard’s [4] kinetic chain theory. The authors use equivalent devices as used in this paper. Like Mapes-Moshell, their technique does not support pitch.

Mlyniec et al. [9] add to the Mapes-Moshell’s method a representation of the axis (the “Spindle”) drawn between the cursors with a small sphere at the center point. The Spindle interaction technique is implemented using power-grasped joystick handles called SpaceGrips™ and a desktop VR display. The Spindle improves user understanding of the interaction. In Schultheis et al. [11], Spindle out-performs a mouse interaction technique and 6DOF Wanda technique for a 6DOF docking task and an object construction task. While the interaction technique allows view scale change, the objects that are docked do not need to be re-scaled. So the view scale adjustment is available to augment 6DOF travel and to find a preferred view scale for performing the docking task, but the task does not enforce view scale change. This paper’s experiment the docking task requires adjustment of pose and size.

Song et al. [13] present bi-manual “Handle-Bar” technique using a Kinect to track hands and detect pinch gestures. Their “object manipulation” mode replicates Mapes-Moshell’s 5DOF+Scale technique, but with a visually displayed ‘handle-bar’ representing the inter-hand axis. This appears equivalent to the Spindle [9]. Song et al. make no comparison to either [9] or [6] so it is difficult to distinguish them. The primary difference between the core handle-bar technique and Mapes-Moshell with Spindle appears to be the ability of the user to control the translational offset between the hand locations and the handle-bar. They present a novel “constrained rotation gesture” that does enable pitch. However, this mode (1) disables the other DOFs and (2) rotation is controlled by a crank motion in the plane perpendicular to the pitch axis. Hence these methods do not provide simultaneous 7DOF control.

Jackson et al. [5] use a computer-vision tracked cylindrical prop that allows yaw-pitch-roll but not scale.

Mendes et al. [8] compare five free-hand 3D manipulations on a virtual workbench augmented with multi-touch. Two Kinect’s track head and hands and recognize pinch gestures. In their ‘3-DOF Hand’ technique, the hand that grabs the object performs translation. Rotation of the other hand performs object 3DOF rotation while the inter-hand distance scales the object. So 3DOF Hand provides simultaneous 7DOF. Their fourth condition is Song et al.’s Handle-Bar technique. The ‘Air TRS’ bi-manual technique closely replicates Mapes-Moshell but the rotation center always remains at the object pinched point.

3 Interaction Technique Design

The following description of Spindle+Wheel assumes that the user is right-handed. In the actual experiment, for left-handed users the roles of the left and right buttonballs are reversed. Two 3D semi-transparent sphere cursors are shown corresponding to the buttonballs (Figure 2), but at a comfortable translational offset [12] for our stereo desktop VR system [3].

Pressing and holding a button on the left buttonball engages the exo-centric, travel technique. As in the Mape-Moshell, translating the hands rigidly translates the view point. Moving one hand individually, such as rotating one hand about the other—while keeping their distance constant—rotates the view in yaw and roll. Moving the hands closer or farther apart scales the view. The precise center of scale (or rotation) depends on the hand motion. For instance, holding the left hand still and moving the right hand inward or outward scales about the left cursor; whereas, moving both hands an equal distance inward or outward scales about the spindle center. Following the Spindle of Schultheis et al. [11], a cylinder is drawn between the cursors with a red sphere at the center point (Figure 2).

4 Experiment Hardware and Task Design

The system is a stereoscopic, head-tracked desktop VR setup [3] with Nvidia 3D Vision glasses, a 120Hz LCD 22” monitor and Polhemus Fastrak. The user sits roughly 1 m from the display. Software is written in OpenSceneGraph [17] and our VR API.

The virtual environment is a checker-board ground-plane (Figure 3). It is 40 cm square with half appearing behind the screen and half appearing in front. In the center of the screen is a transparent box of fixed size (white-outlined box) and at a random orientation per trial. Each face is a different color. This cube’s (the “objective cube”) pose remains stationary relative to the screen during travel. At each trial, a second target cube appears at random location on the ground-plane (red-outlined box). This target cube’s location, size and orientation vary randomly across trials. A timer appears in the upper left of the screen. The user must travel to align the target cube with the objective cube. This requires view pose and view scale maneuvering to superimpose the cubes. The target cube comes in 3 sizes: 25%, 100% and 400% of the objective cube’s size. The 25% and 400% cases require the user to scale up or down by 4 or 1/4. Given our ground-plane size, the 25% cube remains easy to see and its orientation is discernable at the farthest distance.

When the distance between the target cube’s corresponding vertices is within a tolerance (0.84 cm) [19] of the objective cube’s vertices, the outline of the target cube turns green and a success sound is played. The user must release the interaction technique engagement button to stop the clock. The user then presses a button to advance to the next trial. A dominant hand button engages the technique and the less-dominant hand does pitch.

All interaction techniques of all experiments use the same button balls (see Figure 1). This avoids introducing confounds such a varying physical form-factors and button layouts or varying tracking system jitter, latency, working volume, etc.

Initially the user holds the buttonballs and rest their elbows on the chair’s arms and the experimenter sets a translational offset [12] that places the 3D cursors in the center of the screen. The 3D cursors and spindle are mapped using absolute position control. However, travel is only engaged when a button is pressed. Based on the ground-plane size and a typical person’s arm reach, a user will typically perform several clutching translation maneuvers to reach the
far side of the ground-plane. Because we are comparing two position control interaction techniques (rather than rate control) for Experiment 1, the target box distance range is restricted to the range of the ground plane. In a proper (large) MSVE larger ranges of travel would occur inducing either a larger number of translation clutches or strategic use of view scale and translation maneuvers. Since our goal is to compare two interaction techniques within the domain of MSVEs, we keep the distance short but use the variation in target box size to force the user to change view scale.

In both experiments, we record task completion time per trial. All participants were trained to use each interaction conditions for about 10 minutes. We use the per-trial median of task completion time for further analysis. The reported F tests use α=.05 for significance. The post-hoc tests that were conducted were Fisher’s least significant differences (LSD) pairwise comparisons with α=.05 level for significance. The qualitative data (fatigue rate) is analyzed by Friedman test with α=.05 level for significance.

5 EXPERIMENTS

5.1 Experiment 1: Spindle vs. Spindle+Wheel

Experiment 1 compares completion time on a 7DOF travel task between the original Spindle technique (but using buttonballs) and Spindle+Wheel. The hypothesis is that Spindle+Wheel will have faster completion time than the original Spindle technique because Spindle+Wheel can control more DOFs.

12 users perform 90 trials (15 trials × 3 box sizes × 2 interaction techniques) each in a within-subject comparison of two interaction technique conditions (Spindle Only and Spindle+Wheel). The two interaction technique conditions are presented in counter-balanced order across the 12 participants. All participants are from the C.S. Department. 10 are males and 2 are females. All participants have (corrected) 20/20 eye vision. All participants have high daily computer usage (6.3 out of 7) and 11 have experience of 3D user interface typically with the Kinect or Wiimote.

We use a 2×3 repeated measures ANOVA. Interaction technique presentation order is the between-subjects factor. Interaction technique (value set \{Spindle+Wheel (S+W), Spindle only (SO)\}), and target box size (value set \{25%, 100%, 400%\}) are the two within participant variables.

5.1.1 Experiment 1: Result

The results show an interaction effect of box size and interaction technique condition on completion time (F (2,22)=4.579, p=.022, $\eta^2=0.294$). There is a simple main effect of interaction technique condition in 25% box size ($F(1,11)=42.845, p<.001, \eta^2=0.769$). S+W ($M=17.8, SD=2.3$) has faster completion time than SO ($M=25.5, SD=4.2$) with 25% box size. There is also a simple main effect of 400% box size ($F(1,11)=6.001, p=.032, \eta^2=.353$). S+W ($M=16.7, SD=3.3$) has faster completion time than SO ($M=19.7, SD=3.4$) with 400% box size. However, there is no simple main effect of 100% box size ($p=.052, M_{SO}=22.2$ vs. $M_{S+W}=18.2$).

The results show a main effect of interaction technique condition on completion time ($F(1,11)=19.431, p=.001, \eta^2=.639$). Overall, as we hypothesized, S+W ($M=17.6, SD=3.5$) has faster completion time than SO ($M=22.5, SD=4.6$).

Participants took a post-survey questionnaire regarding subjective preferences. All (12 of 12) participants preferred the S+W interaction technique over Spindle. When asked whether the S+W is better than the SO for rotation, 10 of 12 participants agreed; one rated the interaction techniques equally and one preferred the SO interaction technique. 9 of 12 participants indicated the S+W is more intuitive; 2 rated the SO interaction technique and one rated both interaction techniques equally.

5.2 Experiment 2: Spindle+Wheel, Spindle+Wheel with Separate Scale vs. One-handed Technique

In Experiment 1, we observed users sometimes accidentally change the view scale during view manipulation even when the trial’s docking task required no scale change. If a travel task does not require any view scale changes, this may reduce user performance. This motivated designing the Spindle+Wheel with Separate Scale technique. In Spindle+Wheel with Separate Scale, one button engages 6DOF manipulation, while a second one engages only the bimanual scale. Both buttons are on the right buttonball.

Further, in Experiment 2 we desire to perform a comparison to a one-handed scene-in-hand technique while holding the device form factor constant. Schultheis et al. [11] compared the Spindle technique (using power-grasped SpaceGrips) to a one-handed technique that used a Wanda device where the Wanda interface used both the Wanda 6DOF tracking as well as the Wanda’s built-in trackball. In Experiment 2, we test against a one-handed technique that uses the same buttonball device as used for our two-handed condition. In our one-handed condition, one button engages 6DOF manipulation using the scene-in-hand metaphor with the right buttonball. For scaling, we know of no prior work that compares rate control vs. position control in this circumstance, so we allow the user to freely choose either one. A second button engages rate controlled scale. A third engages relative position controlled scale. In both cases the center of scale is determined by the cursor’s location when the scale button is first pressed [10].

12 users perform 90 trials (10 trials × 3 box sizes × 3 interaction techniques) each in a within-subject comparison of three interaction technique conditions (one-handed interaction technique, Spindle+Wheel with Separate Scale and Spindle+Wheel). The interaction technique conditions are presented in counter-balanced order across the 12 participants. 8 participants are from the Psychology Department Pool and 4 are from the C.S. Department; 4 are males and 8 female. None of participants conducted Experiment 1. All participants have (corrected) 20/20 or higher vision. All have high daily computer usage (6.08/7). 4 have experience with 3D UIs.

We hypothesize that Spindle+Wheel would outperform other interaction techniques with 25% and 400% box sizes because those require 7DOF. But the one-handed or two-handed with separate scale interaction technique would outperform Spindle+Wheel with 100% box size because it only requires 6DOF.

5.2.1 Experiment 2: Result

For Experiment 2, we use a 3×3 repeated measures ANOVA and use technique presentation order as the between-subjects factor. Interaction technique condition (value set \{One-handed (OH), Spindle+Wheel with separate scale (SWS), Spindle+Wheel (S+W)\}), and target box size (value set \{25%, 100%, 400%\}) are the two within participant variables.

The results of Experiment 2 show an interaction effect on completion time ($F(4,44)=7.924, p=.001, \eta^2=.419$). Contrasts reveal significant interactions when comparing 25% to 100% both for OH compared S+Wi ($F(1,11)=13.902, p=.003, \eta^2=.558$) and SWS compared S+Wi ($F(1,11)=17.639, p=.001, \eta^2=.573$). These also reveal interactions between 100% to 400% both for OH compared S+Wi ($F(1,11)=18.962, p=.001, \eta^2=.633$) and SWS compared S+Wi ($F(1,11)=14.777, p=.003, \eta^2=.573$). Those show that completion time of OH and SWS interaction techniques are faster than S+Wi with 100% but slower with 25% and 400%. As expected (H1 and H2), completion time of OH or SWS is significantly faster than S+Wi with 100%. The most likely explanation is that accidental scale changes with S+Wi decreases performance in docking trials that requires no scale change, i.e. the 100% box size.

There is a simple main effect on completion time of interaction technique with 100% box size ($F(2,22)=7.297, p=.004, \eta^2=.399$). LSD tests show completion time of S+Wi ($M=15.5, SD=6.0$)
is significantly slower than SWS \((M=12.1, \text{SD}=7.6, p=0.036)\) and OH \((M=10.6, \text{SD}=2.9, p=0.004)\). However, completion time between OH and SWS does not differ \((p=0.221)\). With 400% box size, there is also a simple effect of interaction technique condition on completion time \((F(2,22)=4.687, p=0.020, \eta^2_p=0.299)\). LSD comparisons show completion time of \(S+W (M=15.4, \text{SD}=4.0)\) is significantly faster than SWS \((M=18.6, \text{SD}=4.8, p=0.034)\) and OH \((M=19.0, \text{SD}=4.0, p=0.018)\). Completion time between OH and SWS do not differ \((p=0.736)\). Unexpectedly, there is no significant simple main effect on completion time of interaction technique condition with 25% box size \((p=0.484)\). OH and SWS have better performance than \(S+W\) with 100% box size because it does not require any scale changes as discussed before.

Possibly the above changes the overall significance of performance of interaction technique overall three box sizes. Therefore, we break box size down into two groups based on whether a scale change is required and analyze the groups separately. The \(3 \times 2\) (interaction techniques \(\times 25\%\), \(400\%\)) repeated measures ANOVA shows no interaction effect. However, as expected, there is a main effect of interaction technique condition on completion time \((F(2,22)=5.497, p=0.012, \eta^2_p=0.333)\). LSD tests show completion time of \(S+W (M=16.8, \text{SD}=4.7)\) is significantly faster than both SWS \((M=20.4, \text{SD}=5.8, p=0.019)\) and OH \((M=20.2, \text{SD}=5.7, p=0.009)\). This clarifies advantages of \(S+W\) when a task requires a scale change.

6 of 12 participants preferred the \(S+W\); 4 favored the OH, one favored the SWS, and one rated both OH and SWS equivalent. When asked whether \(S+W\) is better than OH for rotation, 6 of 12 participants agreed. For translation, 6 of 12 participants answered that \(S+W\) is better than OH. 7 participants indicated \(S+W\) is better than OH for scaling; 3 rated SWS and 2 rated OH. 6 participants answered OH is the most intuitive overall; 3 answered \(S+W\), and 3 rated SWS. Interaction technique has no main effect on arm fatigue.

6 DISCUSSION

Overall, the differences in results for the 25% and 400% versus 100% sizes are consistent with prior work on lesser 6DOF manipulations that find that when a task requires fewer than 6DOF adjustments adding either physical constraints or virtual geometric constraints to an otherwise 6DOF UI can improve performance by constraining the DOFs that the user does not desire to change.

As mentioned, some users preferred the one-handed interaction technique and rated it more intuitive than the bimanual techniques especially for rotation and we observed that some users performed tasks better with the one-handed technique.

Our results are more nuanced than Schultheis et al. [11] in two respects. Our results distinguish results from the scaling trials from non-scaling trials and secondly, the one-handed interaction technique used in Experiment 2 is a closer one-handed counterpart to our experiment’s two-handed techniques. The one-handed interaction technique of Schultheis et al. is a Wanda device and their UI uses both the embedded tracker’s 6DOFs as well as the Wanda’s track ball. In contrast our one-handed condition uses the exact same device as our two-handed conditions. Overall, our experiments complement their results while at the same time we demonstrate advantages for the “+Wheel” addition.

The subjective results indicate that Spindle+Wheel interaction technique does not induce more arm fatigue than the original Spindle and one-handed techniques. Our desktop VR system allows users to rest their elbows during interaction. Possibly standing VR systems may increase overall fatigue which might increase the difference between one and two-handed interfaces.

7 CONCLUSION AND FUTURE WORK

This paper presents, Spindle+Wheel, a bimanual 7DOF interaction technique. Our experiments show a statistically significant advan-