1 Solution Description

The 3D cubic puzzle is implemented in a head-coupled cubic display, pCubee[6], that allows users to view a 3D scene from different sides. The display is compact and light enough to be held in one hand by an average adult user. By coupling the display with a 3D stylus, pCubee supports the bimanual Kinetic Chain (KC) model [4] for the cubic puzzle task. Users can hold pCubee in their nondominant hand and the stylus in the dominant hand to manipulate the puzzle pieces. Doing the puzzle in pCubee allows us to explore the bimanual stylus interaction scheme the display affords. Figure 1 shows the setup of our system.

Our solution involves puzzle pieces with simulated physics inside pCubee, which we refer to as the “working space”. Each of the puzzle pieces can be picked up and manipulated by a rendered virtual stylus while also reacting to the movement of the pCubee display. The “solution space” in which the users place the puzzle pieces is located at the center above the pCubee floor within the “working space” and is represented by a wireframe boundary. We conducted two user studies to evaluate performance with two different puzzles. Below we describe the interaction design of our cubic puzzle solution, the hardware and software involved and also the results and findings from the two experiments.

2 Interaction

We experimented with different interaction mechanisms that have been proposed for a 3D display using a stylus, including ray-tracing based manipulation [3] and virtual stylus extension [2]; however, due to monocular-only viewing and magnetic tracking distortions in the current pCubee prototype, it was difficult to achieve the desired sense of “connectedness” between the physical and virtual domains.

Instead, we designed a set of interaction schemes that have potential in precisely manipulating puzzle pieces and other virtual objects using the stylus and pCubee bimanually. These interactions can be classified into four stages in our cubic puzzle solution: direct selection and manipulation, large rotation, placement and correction.

2.1 Direct Selection and Manipulation

We employ a physical-to-virtual stylus mapping that is one-to-one but offset by a certain distance. Users can work with the physical stylus in an area in real space detached from the “working space” while visualizing the interaction inside pCubee. The orientation mapping is direct and allows for bimanual rotation control of the virtual stylus within pCubee: in this case, the virtual stylus’s orientation is “attached” to the physical world, allowing users to either operate the physical stylus or rotate pCubee to adjust its relative orientation within the “workspace space”. The position mapping is also one-to-one, but we impose certain restrictions to better support multi-screen visualization and interaction with a tangible display and a detached stylus. First, we constrain the virtual stylus to always be within pCubee’s boundary, which allows users to “drag” the physical stylus workspace to any desired locations as needed. Second, we constrain the relative position of the virtual stylus to be fixed to any display movements, which prevents users from losing track of the virtual stylus due to unwanted yet unavoidable translations when rotating pCubee to view different sides.

The virtual stylus acts as a 3D cursor in the “working space” for selection. When the tip of the stylus intersects with a puzzle piece, the piece is outlined in green wireframe to indicate that it is ready to be selected. Users tap the stylus button once to select the piece to enter a direct manipulation mode. In this mode, the selected puzzle piece is attached to the tip of the stylus and is directly manipulated as described in the mapping above. To drop a selected piece back to the “working space” or to place it onto the “solution space”, users tap the stylus button once.

2.2 Large Rotation

Performing large rotation using a one-to-one mapping with the physical stylus is challenging due to the attached cable and limited wrist rotation. We provide a drag-and-clutch mechanism to allow users to rotate a selected puzzle piece in the direction to which the stylus is being dragged while the button is pressed. A virtual arcball is rendered over the piece to indicate entering of the large rotation stage.

Both position and orientation of the piece remain fixed relative to pCubee in this stage. The clutching mechanism allows users to release the button while repositioning the stylus and the display as needed to further rotate the piece along any desired axes. Users can either drop the piece by tapping the stylus button or select the piece again by hovering over and holding down the button until the piece is outlined in green, then releasing the button.

2.3 Placement

We implement a snapping mechanism to aid users to place the pieces in the “solution space”. First, we identify the closest axis-aligned orientation of the selected puzzle piece. Then, we find the closest empty slot in the “solution space” that the axis-aligned piece
can be fit into. If the distance between the closest slot and the center of the puzzle piece is within 1 unit (each puzzle piece is formed with a series of 1-unit cubes), we render a white wireframe in the “solution space” as a visual guide to indicate the possible placement location. The piece is snapped onto the location if released while the visual guide is shown.

2.4 Correction

Pieces that have been placed onto the “solution space” can be selected and removed; users can also rapidly shake pCubee to reset and drop all the placed pieces back onto the “working space”.

3 HARDWARE

pCubee consists of five 5-inch VGA (640x480 pixels) resolution LCD panels mounted into a wooden box-shaped frame. It uses perspective and motion parallax from both head and display movements to provide 3D depth cues to users. The cubic display measures 146x120x146 mm and weights 1.3 kg (2.87 lbs); it is attached to a small 120x96x36 mm base to make it easier to grasp. The host computer connected to pCubee is an Intel Quad Core, 3.0 Ghz Windows XP machine with two dual-output Nvidia GeForce 9800 GX2 graphics cards which drive the rendering for pCubee.

pCubee uses a wired electromagnetic tracking system (Polhemus Fastrak) to track the display and the user’s head position for head-coupled perspective rendering [1] and a stylus for precision manipulation. The head tracking sensor is mounted on an adjustable head gear, while the display tracking sensor is embedded on the base of the display. The stylus is a Polhemus pen-shaped sensor with a single embedded button.

4 SOFTWARE

We use OpenSceneGraph (OSG) for rendering of the cubic puzzles inside pCubee. Texturing and shading are added for greater depth cues and realism in the virtual space. We also integrate the Nvidia PhysX simulation engine to create the effects of gravity and physics response from the puzzle pieces. The update rate of the software is limited to 40Hz with the 3 tracking sensors in use.

5 EXPERIMENTS

5.1 Experiment 1: Contest Puzzle

10 novice subjects, who were not familiar with 3D interfaces, and 5 expert subjects, who were more familiar, were recruited for a study that required them to solve a standard contest puzzle. All subjects were given introduction about the interaction schemes and were allowed a 1-minute practice session. Novice subjects performed only a single trial while the expert subjects did three. In each trial, we measured the completion time and also the time spent on each interaction stage. Post-task questionnaires were used to solicit feedbacks about the difficulty and intuitiveness of the interactions, and whether or not features such as highlighting, rotation widgets and snapping were helpful.

5.1.1 Results

Figure 2 shows the times spent on different interactions for trials that were successfully completed by both novice and expert subjects. In total, three novices failed to complete the contest puzzle; two experts failed to complete the initial trial while another gave up entirely after failing the first two trials.

5.2 Experiment 2: Google Puzzle

The same 10 novice subjects also took part in a second study that compared the performance of a real, physical Google puzzle and a virtual Google puzzle in pCubee. We counterbalanced the order of the physical and virtual puzzles and measured total completion time of each; in the questionnaire, we also inquired subjects about the benefits and weaknesses doing the puzzle in each domain.

5.2.1 Results

The average completion times were 147.8s (SD = 121.7s) and 327.3s (SD = 199.6s) for the physical and virtual puzzles respectively, and all subjects were able to complete the trials. While subjects preferred the interactions (i.e. selection, manipulation, placement and correction) available to them in the physical puzzle over the virtual puzzle, perceived performance were equal for both domains (+1 scores on 7-point Likert scales).

5.3 Overall Results

From both experiments, we identify our current selection scheme design to be a bottleneck, which took averages of 41% (317.3s) and 43% (140.6s) of the the total completion times for the contest and Google puzzles respectively. In the qualitative feedback, subjects indicated that the stylus cable limited their ability to freely manipulate the stylus to select the desired pieces. They also commented on the number of functions that were implemented onto a single button, which became confusing; we believe that enhancing the stylus’s capabilities or using a different 3D input device will give us much improved results. An interesting observation is that subjects used pCubee’s physics capability extensively to bring the pieces closer to their views for selection.

Surprising to us was the seldom usage of the drag-and-clutch rotation mechanism, which we found to be important for large rotation during our initial design iterations. Subjects negatively rated the difficulty, intuitiveness and also the rotation widget feature in the post-task questionnaire. We suspect a steep learning curve for the mechanism to be the cause of the difficulty because imagining rotation axes have been shown to be a difficult task [5]; as a result, subjects resorted to direct manipulation to perform both translation and rotation on the puzzle pieces instead. All other interaction stages and helping features, including highlighting and snapping, received neutral to positive scores.

REFERENCES