Extending the Working Volume of Projection-based Mixed Reality Systems

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Abstract
The working volume of a Mixed Reality (MR) system – which superimposes the real environment with computer-generated virtual content – strongly depends upon the output/display device used. Single screen projection systems like the Barco Baron Table or the FakeSpace ImmersaDesk M seem rather limited regarding their working volume when compared with the CAVE, which is the only projection-based MR installation providing a wide range of viewing directions. We show how the working volume of such projection based MR systems can be extended by tracking not only the user, but also the projection screen and demonstrate how the tilting mechanism of a standard Barco Baron Table can be used to enlarge the range of usable viewing directions of the system. We also give a description of the complete calibration procedure and set-up necessary to employ this concept with any movable back projection system.

Keywords:
Mixed Reality, projection table, calibration, field of view, off-axis projection, tracking

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality

1. Introduction
The working volume for applications running on a Mixed Reality (MR) system is mainly constrained by two factors: the working volume of the tracking system and the used output/display device. Today there exist tracking systems, e.g. optical tracking systems, which have quite large working volumes (and also high precision), therefore the display device often becomes the main constraining factor regarding the working volume of an MR system.

Only optical- and video-see-through head-mounted-displays (HMD) and CAVEs (ideally six-sided) allow the user to fully explore the working volume covered by the tracking system. In the first case the user normally can explore the whole working volume covered by the tracking system with a horizontal field of view (FOV) of between usually 25 up to 80 degrees, depending on the utilized HMD device. In the case of the CAVE the user is also able to explore the whole working volume (typically equivalent with the physical volume of the CAVE) with a FOV just marginally restricted by the worn shutter glasses, but at the cost of a massive, rather expensive infrastructure.

When looking at more cost-effective single screen back projection systems like the Barco Baron Table or the FakeSpace ImmersaDesk M1, the working volume is inherently constrained by the location and orientation of the device’s projection screen. But if we employ a mechanism to re-orient the projection system (like the tilting mechanism of the Barco Baron table) or even move the whole set-up by using castors, tracking the projection screen itself significantly enlarges the working volume and hence enhances the applicability of these devices for MR systems (Figure 1).

Thereby the navigation through the working volume is divided into two distinct tasks: Firstly, the simple movement of the user wearing head-tracked shutter-glasses, and secondly re-orienting the projection system for coarse changes of working volume and viewing direction. The user normally just moves around the working volume while viewing and interacting with its content. When the user reaches an extreme position of the volume and sees the screen under an acute angle, the FOV becomes too limited
(Figure 5, b) and the user re-orient the screen for a better viewing angle (Figure 5, d).

2. Related Work

Previous work described approaches that concentrated on MR setups/systems, where either the display surface moves with the user, but the position and orientation of the display surface relative to the eyepoint is fixed (for devices like HMDs) \(^7, \, 8, \, 9\), or the display surface is considered static during runtime and only the eyepoint is being tracked (CAVE, typical projection system setups) \(^6, \, 11, \, 12\).

Our approach differs from these approaches insofar as both, the user’s head and the display surface are tracked simultaneously but independently. Therefore the user may adjust the position and orientation of the display surface (as far as the device allows him to) during runtime to explore a larger working volume. By applying this technique to e.g. movable projection tables like the Barco Baron Table, the applicability of such devices for MR systems can be enhanced.

3. System Description

Our prototype system (Figure 2) consists of a swivel-mounted Barco Baron Table\(^4\) with shutter glasses synchronized by an infrared emitter, an ART Optical Tracking System\(^3\) with 3 cameras and a PC running our own Studierstube\(^1\) MR system. Tracking markers are mounted on both the Baron Table and the shutter glasses.

This setup enables the user to move around freely to explore the application’s content presented within the MR system’s working volume, since she is not obstructed by any cables.

Table 1 shows the horizontal FOV for different viewpoints in front of the Barco Baron Table, whereas a distance of 1 to 1.5 meters can be considered typical.

<table>
<thead>
<tr>
<th>Distance from display surface</th>
<th>0.5 m</th>
<th>1 m</th>
<th>1.5 m</th>
<th>2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display surface normal through eyepoint near center of display surface</td>
<td>105°</td>
<td>66°</td>
<td>47°</td>
<td>36°</td>
</tr>
<tr>
<td>Display surface normal through eyepoint near edge of display surface</td>
<td>69°</td>
<td>52°</td>
<td>41°</td>
<td>33°</td>
</tr>
</tbody>
</table>

Table 1 Horizontal FOV for different user poses

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4. The (Studierstube) Off-Axis Camera Model

Since the Studierstube system is based on the Open Inventor toolkit (Strauss et. al.\textsuperscript{5}), the viewing parameters for a scene are specified within a camera node. Open Inventor supports only orthographic and (on-axis) perspective pinhole cameras, so in order to be more flexible in regard to defining viewing parameters, especially when concerning projection setups, a new camera model was introduced to the Studierstube System implemented as extension to the Open Inventor toolkit (SoOffAxisCamera node).

Whereas the common perspective camera model describes the viewing volume relative to the camera’s eyepoint, the basic principle of the SoOffAxisCamera (Figure 4) is the decomposition of the camera model into two mutually independent logical parts:

- the eyepoint (or viewpoint) and
- the projection plane (or projection area).

The eyepoint describes the position of the viewing pyramid’s apex and can be placed arbitrarily in 3D-space. The parameters for the projection plane specify a rectangular area, whose corners represent the intersection points of the projection plane with the viewing pyramid’s edges. Like the viewpoint, the projection area can be placed arbitrarily in space. Hence it is placed independently from the viewpoint. The projection area is specified by three parameters:

- position
- orientation and
- size

The 3D-vector position specifies the location of the center of the area. The rotation given by orientation (usually defined as quaternion due to Open Inventor conventions) specifies the orientation of the projection plane, defined as rotation from its default orientation. At the default orientation, the positive z-vector is equivalent to the plane’s normal and the positive y-vector is equivalent to the plane’s up-vector. The size given by a 2D-vector specifies the size (width, height) of the area. Hence it also specifies the aspect ratio of the camera. The (horizontal) FOV, which is often used in a camera model, is implicitly specified by eyepoint and projection plane properties of the Studierstube off-axis camera model.

As mentioned above the eyepoint and the projection plane can be positioned independently from each other and define (in conjunction with the near and far plane) a viewing frustum. If the eyepoint lies within the positive half-space of the projection plane, the camera will render the scene, otherwise the camera is not valid, because the viewpoint lies “behind” the projection plane, hence the scene will not be rendered. For the special case, where the eyepoint lies on the normal through the center of the area, the camera will render like a usual perspective pinhole camera.

To achieve stereo perception with the Studierstube system two virtual cameras must be specified separately. Hence the distance between the eyepoint-position of the left and right eye camera implicitly gives the inter-pupillary distance.

5. Calibrating Mobile Projection Systems

To achieve correct calibration of the mobile projection table, i.e. proper alignment of virtual and real environment, we apply an extended version of the calibration procedure for static projection systems described previously\textsuperscript{2}. The prerequisites for this procedure are:

- Projection screen and
- tracker sensor attached to table must lie within working volume of tracking system.
- Tracked stylus with calibrated hotspot must be available.

5.1. Overview of the calibration process

We want to retrieve the correct viewing parameters for the Studierstube off-axis camera model, i.e. the correct virtual camera, which ideally recreates the user’s view of the display device. Since for a given projection setup the position and orientation of the projection plane remains static relative to the coordinate system of its attached tracker sensor, the calibration of the viewing parameters for a projection setup is divided into two steps:

1. Calibration of projection plane parameters relative to table-tracker
2. Calibration of eyepoint-position relative to head-tracker

5.2. Calibration of projection plane parameters

The position and orientation of the display screen relative to its tracker sensor and the display area actually utilized by the device are determined by this task. This is done by projecting reference markers near the four corners of the screen and measuring their position by touching the displayed markers with the tip of a tracked stylus and pressing the stylus’s button while simultaneously sampling the position and orientation of the table-tracker. The sampled position is then transformed from world-coordinate-system to table-coordinate-system. Hence the calibration procedure is
After the positions of all four markers have been retrieved, the position and orientation (offsets) of the projection plane in table-coordinates as well as its width and height can be calculated (Figure 3).

As mentioned earlier the projection plane typically remains static relative to the coordinate system of its attached tracker sensor, hence the calibration of the projection plane usually has to be performed only once per setup.

The calibration of eye-point-position has to be repeated on a per user basis to achieve optimal results, since every two users have different inter-pupillary distances and wear the shutter-glasses differently.

6. Results

The markers needed for the optical tracking system are mounted on the frame of the projection screen, so that the whole pivoting range of the Baron Table is traceable by the tracking system.

As shown in Figure 5, the working volume is extended considerably, so that the models presented in the demo application are viewable from many different angles, which would not be achievable with a static placement of the Baron Table.

Since the tracker markers are also measured in real-time (60Hz) and the viewing parameters of the virtual cameras are calculated accordingly, tilting the table can be performed while viewing the environment. The adjustment for optimal viewing is therefore an interactive and simple process.

A further advantage of this system lies in its increased stability: when the tracking system is moved relative to the table or vice versa the system stays correctly calibrated, which would not be possible if only the tilt of the table would be tracked (e.g. by a mechanical tracking device).

7. Conclusions and Future Work

At the moment we are only using one degree of freedom of movement of the screen, but we are going to mount castors on the table (Barco already offers a movable version of the Baron Table, but for our tests we employed an older, unmovable version) for easy rotation and translation of the whole projection surface, which represents a hardware modification only, since the implementation of the calibration procedure described in this paper already supports correctly calibrated full six-degree-of-freedom movement of the display device.

The calibration procedure introduced previously was adapted to support the registration of setups with independently tracked projection plane and eye-position. Our approach can be applied not only to the setup described in this paper, but also to any MR system including a display device, which supports stereo output and is conveniently movable, e.g. even a simple CRT-monitor or an auto stereographic tablet PC.
Figure 4 View Volume and Viewing Projection for a SoOffAxisCamera node

Figure 5
Left column: Baron table at varying angles;
Right column: resulting view for the user. Note that the field of view changes, but the projection of the content stays the same.
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