Off-Axis Stereo Projection and Head Tracking for a Horizontal Display

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ABSTRACT
In this work, a stereoscopic head-tracked horizontal display system is presented. The hardware parts of the system -besides the computer- are, a helmet which is used for head tracking, 3D shutter glasses for stereoscopic viewing, a firewire stereo camera for locating the 3D coordinates of the LEDs on the helmet by stereo calibration, and a wooden table in which a stereoscopic projector feeds 3D images in stereo onto a semi-transparent glass through a full reflective glass. The original software is developed on an Ubuntu Linux system by means of third party open source software. The main purpose of this project is to create a realistic visualization system for 3D models that are often viewed horizontally, such as architectural models or terrain data. The final system applies head tracking by utilizing the images captured in 50 FPS, and renders three-dimensional images in stereo at 1024x768 resolution and 120 Hz.

Categories and Subject Descriptors
H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems – *artificial, augmented and virtual realities.*

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *prototyping, theory and methods, user-centered design.*

I.3.1 [**Computer Graphics**]: Hardware Architecture – *three-dimensional displays.*

I.4.1 [**Image Processing and Computer Vision**]: Digitization and Image Capture – *camera calibration, imaging geometry.*

General Terms
Algorithms, Performance, Design, Experimentation, Human Factors, Theory.

Keywords
responsive workbench, stereo camera, horizontal visualization, head tracking, stereo rendering, augmented reality, off view-axis projection, OpenGL, OpenCV.

1. INTRODUCTION
The concept of a responsive workbench dates back to 1994 [1], when it was designed as a collaborative working environment. It is described as a non-immersive multimedia environment that emphasizes practical usage by object interaction, as opposed to an immersive virtual environment that aims to create realistic emotional experiences by surrounding its participant. Since then, several applications were developed for this interaction medium. Some applications incorporate the examination and manipulation of scientific objects of research and designed objects of production, such as experimentation, education, teleoperation [2], mechanical engineering and physical simulation [3]. In other applications, the workbench is utilized to visualize and evaluate larger structures and geographies, such as applications in architecture [4] and battlefield visualization [5]. It is also possible to use the workbench as a 3D canvas for art [6] and modeling [7].

The main component of a responsive workbench is a horizontal display. These display systems have been used in a wide range of applications ranging from realistic and informative visualizations of 3D worlds to musical instruments based on human-computer interaction. They are based on a traditional working scheme which contains a standard height plane and input / output tools on it. By the introduction of virtual worlds, there has been a focus on the quality of the 3D scenes and the amount of perception manipulation contained within. Our work focuses on the realistic geometric projection of a 3D scene onto the horizontal display and adjusting the view dynamically by tracking the position of the viewer. The adjustment is applied by head tracking based on a helmet having three LEDs on top, with a stereo camera.

2. TOOLS
The hardware components of the system are; a PointGrey Bumblebee2 stereo camera, an InFocus DepthQ stereoscopic projection device, and StereoGraphics CrystalEyes3 shutter glasses. As for the software, we developed our own tracker and renderer that make use of the latest capture drivers and image processing libraries available on Ubuntu Linux 8.04 (libdc1394 and OpenCV respectively). We preferred open source products in our software development environment.
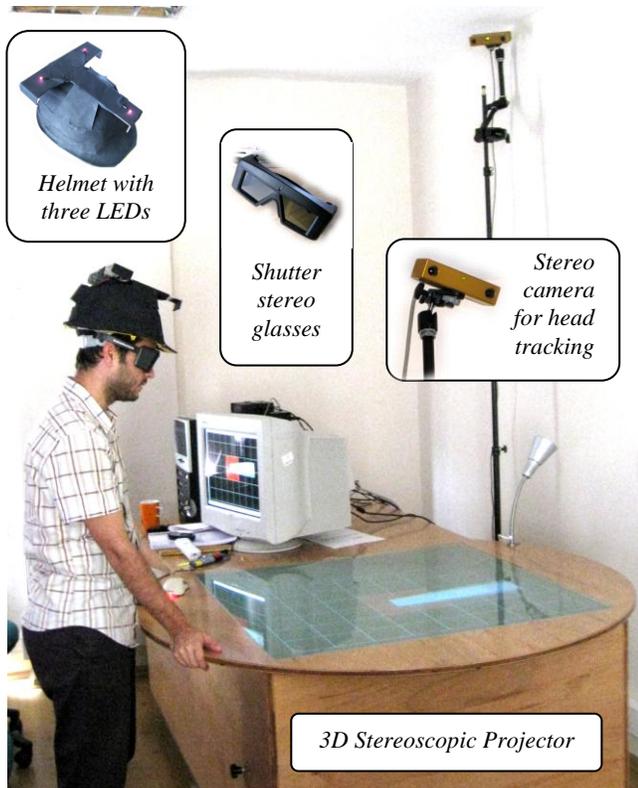
Figure 1. The hardware components of our system

3. THE SYSTEM

The system is based on tracking the head movements of a user with a helmet that carry three LEDs placed at the corners of a triangle, and interpreting the position and orientation information obtained from this tracking for real-time generation of the 3D image in the three-dimensional environment. As the system follows the user's viewpoint in real-time, it instantly renders and presents a 3D image in stereo that creates the 3D illusion from that viewpoint. Thus, the illusion is strengthened by two aspects: The perspective illusion that is obtained by the off view-axis projection from the instantaneous viewing position of the user, and the stereo illusion that is calculated through current viewing angle of the user.

3.1 Types of illusion

The three-dimensional illusion provided by the system is strengthened by two relatively independent aspects. First is the illusion of angled perspective by using asymmetric viewing frustum, which is necessary because the horizontal screen on the workbench is viewed from an unusual angle compared to usual perpendicular viewing angle of a computer screen. Secondly, we determine two camera positions that correspond to the eyes of the viewer to render the scene in stereo to provide an illusion of depth. Both illusions depend on the position and orientation of the viewer.

3.1.1 Illusion of perspective

As the table is viewed from a side angle, in contrast to a TV screen which is viewed frontally, we need a special projection

method. If we use a symmetric view frustum, the viewers will see a skewed scene on the table unless they are looking directly downwards from above the table. Thus, we utilize off view-axis projection, a method in which we use an asymmetric viewing frustum that complies with the viewpoint of the viewer. In this method, the perceived position and looking angle of a viewer can be altered by applying a perspective transformation that exploits the existing knowledge about the viewer's actual position and looking angle, which is provided by the tracked 3D position of the helmet. This method can be considered as the general method of creating perspective illusion, such as the Ames Room. The main limitation of this method is its strong dependence on the viewing point, which is addressed in this project by dynamically adapting the viewing frustum by the real-time tracking of viewer's head.

3.1.2 Illusion of depth

In basic application of the asymmetric frustum, the viewer is assumed to be at a certain point, and this position must be continually tracked in order to adapt the frustum. As perspective projection is non-uniform and sensitive to its inputs, this illusion may easily break down with a small difference in viewpoint. This sensitivity also holds for the distance between the two eyes of a viewer. Therefore, to secure the illusion of perspective, we need an additional measure and take eye separation into account. By rendering the scene separately for each eye of the viewer, we display the scene in stereo through 3D shutter glasses. This improves the realism considerably, as it appeals to the biological depth perception and minimizes the perspective distortion caused by tracking error.

3.2 Components

The functional structure can be examined in four main components:

3.2.1 Obtaining the images from the stereo camera

Initially, we captured stereo images by applying panning (switching between "left" and "right" cameras) in standard RGB mode. This method caused unavoidable shifts in the captured images. Then, we managed to grab and convert the Format7 data structure (particularly supported in stereo firewire cameras) into RGB images by applying Bayer demosaicking by means of the 2.x version of libdc1394. The high-speed algorithm currently provides colored stereo images in 50 FPS through IEEE1394 (firewire) cable.

3.2.2 Detecting LED positions from stereo images

To find the bright points, we applied top hat filtering [8] after applying a thresholding to the colored image based on hue values. As this method was sensitive to small noises, we applied Lucas-Kanade Optical Flow [9] algorithm that is provided in the OpenCV library. This allowed us to develop a robust tracking algorithm.

We initialize the system by manually marking the positions of the LEDs. Then we utilize the tracking algorithm and obtain two-dimensional positions of the LEDs at each frame. These positions are transformed into three-dimensional position and orientation of the helmet by using stereo calibration.

3.2.3 Stereo calibration of 2D points and transformation into 3D coordinates

The 2D positions of the LEDs in the images obtained from the two "lenses" / two "mono cameras" of the stereo camera enables us to calculate the corresponding 3D positions within the coordinate system of the camera. As two cameras are calibrated and aligned inside our stereo camera, we use a simpler geometric model compared to generic models such as epipolar geometry [10]. The geometry is further simplified by the camera planes being parallel and coplanar.

The transformation from the 3D coordinate system of the stereo camera to the 3D coordinate system of the horizontal display (i.e. the table, real world) is obtained by solving the over-determined system consisting of several sample points whose real world coordinates are known. We need a transformation matrix T which satisfies the equation $T\ a = b$, for a stereo camera coordinate a and a real world coordinate b. Solving the over-determined system with least squares method yields the transformation matrix. Finally, we use this matrix to obtain the position and orientation of the helmet at each frame. Then these vectors are used to calculate two viewing positions corresponding to the eyes of the viewer, that are used to render the 3D scene in stereo.

3.2.4 Off view-axis stereo projection (asymmetric frustum) based on three-dimensional position and orientation of the viewer

We converted the three-dimensional position and orientation information to place and orient the two cameras inside the three-dimensional scene rendered in OpenGL. Unlike the usual frontal viewing of a computer screen, horizontal viewing on a visualization workbench involves varying angles of viewing. Therefore, it is necessary to be able to determine the viewing frustum that corresponds to a certain viewing angle, and dynamically adapt it as the user changes this angle [11], [12]. For the horizontal image to create a 3D illusion, we altered the perspective space of the 3D scene by using an asymmetric frustum in OpenGL instead of the usual symmetric frustum which creates an approximate illusion only for a frontal viewer.
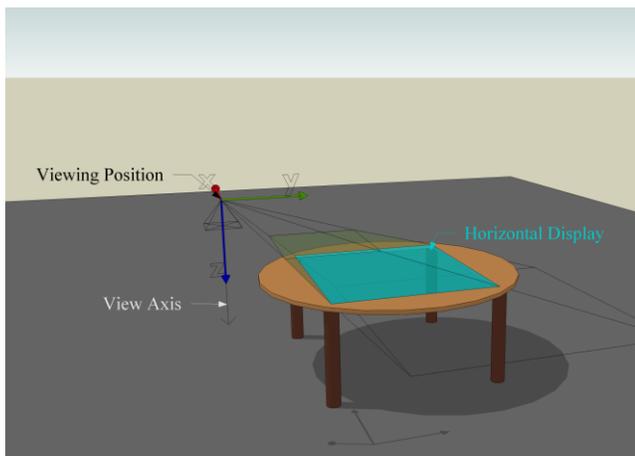

Figure 2. The shape of an asymmetric frustum, used in off view-axis projection method. Position and the usual view axis shown are of the 3D environment camera.

4. CONCLUSION

We implemented a stereoscopic head-tracked system for horizontal display. Head tracking is applied by using a helmet containing three LEDs and tracking these LEDs by Lucas-Kanade Optical Flow algorithm in real-time. Stereo calibration is then applied to the 2D coordinates found on the images. It enables the system to transform these 2D coordinates to their corresponding 3D coordinates. 3D projection is applied in stereo by using the obtained viewing position and orientation, and onto an off view-axis plane, having an asymmetric viewing frustum.
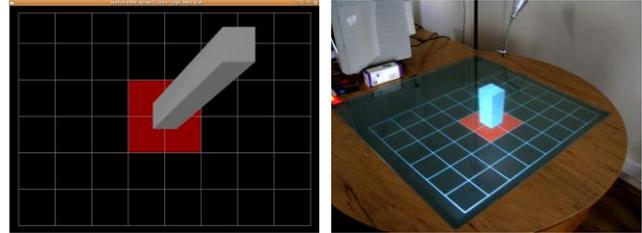

Figure 3. The image on the left shows the off-axis projection of a 3D box. It seems longer than its actual size, because it is not meant to be viewed directly on the screen. The projection matrix is specially calculated for the viewer at the viewpoint of the second image.

The system runs synchronously and in real-time in the main loop, providing an interactive visualization experience despite the narrow viewing angle of the stereo camera. It successfully processes and utilizes the image captured in 50 FPS, and renders the three-dimensional scene in stereo at 1024x768 resolution and 120 Hz.

5. ACKNOWLEDGMENTS

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