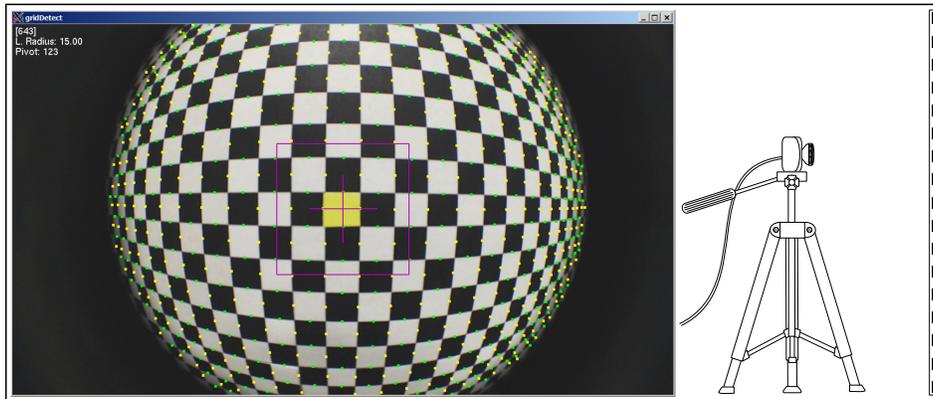


Automated Calibration of Display Characteristics (ACDC) for Head-Mounted Displays and Arbitrary Surfaces

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ABSTRACT

In this document we present a method for calibrating head-mounted displays and other display surfaces using an automated, low-cost camera system. A unique aspect of this method is that the calibration of geometric distortions, field of view, and chromatic aberration are achieved without the need for a priori knowledge of the display system's intrinsic parameters. This method operates by capturing and storing the pixel space locations of a series of real world control points. These control points are then used as ground truth references by which virtual space transformations can be automatically generated for a display system.

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1 INTRODUCTION

A common problem faced by users of head-mounted displays (HMDs) is the need to calibrate the display such that imagery viewed through it is geometrically comparable to that seen in the physical world. For see-through displays this problem can be solved somewhat easily since the real world is visible along with computer generated imagery. However, non-see-through displays, such as those commonly used for virtual reality applications, are considerably more difficult to calibrate. Calibration procedures can also be cumbersome processes involving meticulous alignments and multiple measurements.

In this document, we present a method for fast, automated, and low-cost calibration of head-mounted displays that requires no a priori knowledge of the underlying configuration of the display system. In addition to HMDs, this method can also be used to calibrate arbitrary, continuous display surfaces including monitors, projection screens, and curved projection surfaces, though these are not the primary focus of this document. Our method uses a single camera and wide angle lens to capture a series of real world reference points. These points are then used in conjunction with a fast screen scanning procedure to develop a correction scheme that counters geometric distortions present in the display system.

2 RELATED WORK

The calibration of non-see-through HMDs can be troublesome since they lack a means by which to easily compare the virtual and real worlds. The lack of visible ground truth within the virtual environment may make geometric distortions less noticeable despite their presence. Nevertheless, there is sufficient motivation for accurate calibration, since distortion is still present in these HMDs. Wide field of view HMDs typically have 8-10% distortion [1]. Uncorrected distortions in HMDs may cause physiological symptoms such as nausea and premature fatigue[1, 2]. Additionally, distortions may cause perceptual disparities between the virtual world and the real world, such as differences in distance judgments[3]. The calibration techniques that exist for non-see-through HMDs

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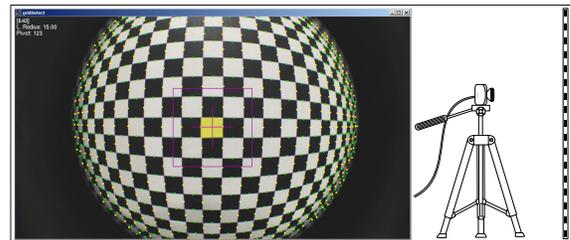


Figure 1: The camera and grid apparatus used for calibration.

typically rely on stock camera parameters or estimated camera parameters based on assumptions regarding the display's design[2, 4]. The method described here does not rely on modeling the camera parameters of a display but instead estimates the gross distortions (optical or otherwise) that are present in the system.

3 METHODS

3.1 Calibration Apparatus

The apparatus used to implement this calibration method, shown in Figure 1, consisted of an off-the-shelf Logitech HD Pro Webcam C920, a tripod, a generic fish-eye lens intended for use with a cellular phone camera, and a Dell Precision M6600 laptop computer. Excepting the computer, all necessary components cumulatively cost under \$100 USD. Though it is possible that better results may be achieved with higher-end equipment, we feel it is an important contribution of this document to emphasize that a reasonable calibration can be achieved without significant financial investment.

3.2 Step 1: Mapping Real Space to Camera Space

The most critical step in this procedure is establishing a ground truth measurement of the real world. This step is crucial because errors here will propagate to counter-distortion schemes generated in further steps. As shown in Figure 1, we printed a large grid of alternating black and white 1cm squares. Using standard computer vision techniques, we recorded the pixel space coordinates of all discernible real world positions. This provides a mapping between real world space and the camera space. The distance from the camera to the real world grid must be recorded to future reference in Step 3.

3.3 Step 2: Mapping Camera Space to Virtual Space

In this stage, we perform a screen scanning procedure, see Figure 2, to determine correspondences between camera and virtual space. To begin, the camera used to capture the real world grid is placed at a reasonable, forward looking eye position in front of an eye piece of the head-mounted display. Once the camera is aligned with the eye piece, a virtual scene is rendered that consists simply of a black background and a single white line. The field of view and aspect ratio at which the scene is rendered is important only in that it must be recorded for future reference when rendering your calibrated virtual environment. These values can otherwise be considered arbitrary. The white line then scans across the screen twice, once horizontally

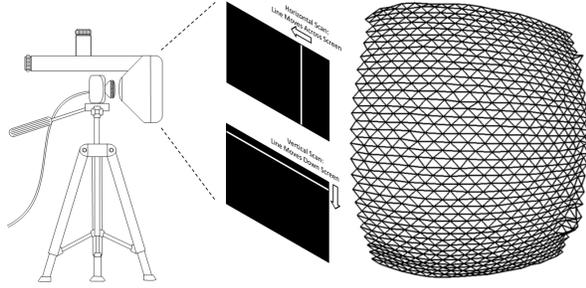


Figure 2: The camera and HMD configuration for the scanning phase of the calibration procedure (left). Example counterdistortion mesh acquired from a Socket HMD (right).

and once vertically. The camera space coordinates for each of the previously captured real world control points is monitored to determine if that pixel is being illuminated by the white line. If so, the virtual space position of the line is stored as corresponding to that particular real space position. This analysis is done on a frame-per-frame basis. Once the vertical and horizontal scans have completed, each real space control point that was illuminated will now have a corresponding virtual space position.

3.4 Step 3: Rendering the Calibrated Environment

The real space to virtual space correspondences generated in the previous step now define a deformed surface that, when rendered in the virtual environment, will reproduce the surface defined by the real world calibration grid. This grid will now need to be triangulated and rendered as a mesh, see Figure 2. We must now use a two pass rendering procedure. The first pass renders the virtual scene to a texture. The second pass displays the first pass texture mapped on to the calibrated mesh. For simplicity, we will refer to the virtual scene that we wish to render without distortions as the *ideal environment* and the environment containing the mesh upon which the ideal environment will be texture mapped as the *calibrated environment*.

Since OpenGL's camera model is essentially equivalent to that of an on-axis pinhole camera, we must render our ideal scene not to match the actual height and width of our mesh since the properties of the display system may require off-axis views in order to be viewed free of distortion. Instead, we must determine the absolute value of the maximum extent along both the X and Y axes from the mesh's real world origin. We will refer to these as X_{rMax} and Y_{rMax} . The aspect ratio of our ideal scene will then be:

$$aspect = X_{rMax}/Y_{rMax}$$

To calculate the vertical field of view for the ideal environment, we must recall the real world distance at which the reference grid was placed, as recorded in Step 1. We will call this parameter Z_r . The vertical field of view for the ideal environment is then given by:

$$FOV_{vertical} = 2 * atan(Y_{rMax}/Z_r)$$

Once the ideal environment has been rendered to a texture, this texture can be mapped onto the counterdistortion mesh. To accurately do this, a 2D texture coordinate for each vertex must be calculated. This is rather straightforward with the coordinates for any vertex i defined as:

$$X_i = (X_r + X_{rMax}) / (2 * X_{rMax})$$

$$Y_i = (Y_r + Y_{rMax}) / (2 * Y_{rMax})$$

The ideal environment can now be texture mapped onto the counterdistortion mesh in the *calibrated environment*. The calibrated environment consists solely of the texture mapped counterdistortion mesh. It is very important that the field of view and aspect ratio used to render the calibrated environment match those used during the scanning phase. Otherwise, the view of the virtual environment, as seen on the counterdistortion mesh, will no longer be accurate.

3.5 Chromatic Abberation Correction

A property of lens-based optical systems is that light of varying wavelengths is refracted differently across the field of view. This error, called chromatic aberration, results in a rainbow-like separation of the light emitted from the display surface in an HMD. The calibration method, as described above, focuses on the combined position of the red, green, and blue color channels, using a single pass of a white line to generate a counterdistortion mesh. Extending the method detailed above, chromatic aberration can be measured, modeled, and corrected using a three-pass procedure. One pass each would be used for the red, green, and blue color channels, changing the color channel referenced during real world localization and the color of the reference line used during scanning. This yields an counterdistortion mesh for each color channel. Each color channel from the texture of the ideal environment can then be mapped to its respective mesh, and the three meshes can be blended together to form a composite image that, when viewed through the display, will result in a chromatically correct image.

3.6 Arbitrary Surfaces

Though this calibration technique was developed primarily for use with head-mounted displays, we found that it is also quite effective in calibrating most arbitrarily placed display surfaces. A notable difference between HMDs and most other display surfaces is that the display plane within the HMD is typically stable relative to the eye's position and moves with the user's head. This is often not the case for other display systems. However, for displays where the user's viewing position is well defined and relatively predictable, this method should be quite effective.

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