CHARACTERIZATION AND CORRECTION OF SPATIAL MISALIGNMENT IN HEAD-MOUNTED DISPLAYS

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ABSTRACT

CHARACTERIZATION AND CORRECTION OF SPATIAL MISALIGNMENT IN HEAD-MOUNTED DISPLAYS

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A toolset was developed for characterizing and correcting spatial misalignment in head-mounted displays. A hardware system consisting of two cameras and various rotation and translation stages was used to emulate the ocular position of most human observers. A checkerboard pattern was displayed on the HMDs and matched to a reference pattern through an image registration process. The HMD image registration process is carried out after the effects of camera distortion and keystone effect are removed. The registration process is repeatable with a standard deviation of less than one HMD pixel.

The relative misalignment between left and right eyes was fairly small in the center of the displays, and increased near the edges and corners. Small rotations simulating an imperfectly aligned HMD had little effect on the misalignment present. The introduction of vergence angles did have a large effect on misalignment. Several methods were used to correct misalignment, including different corrections for the left and right eyes, and the use of a composite correction incorporating different
correction maps in different local regions of the display. Both of these methods showed improve uniformity and rectilinearity in test images displayed on the HMD. The composite correction map did show noticeable global variations. The luminance of an HMD was also characterized, showing higher luminance in the center of the display than in the corners by a factor of three.
ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

1.1 Background

1.1.1 Head-Mounted Displays

Head-mounted displays (HMDs) provide an image to a user in a helmet-mounted or head-mounted form factor. HMDs typically consist of a display device and optics that produce an image in front of the user’s eyes [1]. Various configurations of HMDs exist:

- Monocular HMDs provide an image to one of the user’s eyes, biocul ar HMDs provide the same image to both eyes, and binocular HMDs provide different images to each eye. These configurations are shown in Figure 1.
- HMDs can be see-through (also known as transparent or augmented reality), enabling the user to view imagery from the HMD overlapped with the real world. HMDs can also be opaque (also known as virtual reality), providing the user only with the imagery from the HMD within its field of view.
To maintain binocular vision, the eyes move in a coordinated manner to maintain vergence. For an object placed at infinity, both eyes point straight forward. For objects at closer distances, eyes converge towards each other horizontally to maintain focus at a single point in space. The eyes can also move outwards horizontally, known as divergence. Dipvergence occurs when one eye moves upwards and one eye moves downwards in the vertical direction. Convergence is easily tolerated by the human eyes, while divergence and dipvergence are tolerated to a much lesser degree [1, 2, 3]. The levels to which convergence, divergence, and dipvergence can be tolerated has been evaluated in literature, but the recommended values vary wildly [2, 4]. Tolerable levels given for convergence range from 0.3 to 47.0 mrad, 0.3 to 20.0 mrad for divergence, and 0.3 to 10.0 mrad for dipvergence [4]. The rationale for these specifications is often not given [4]. These various types of ocular alignment are shown in Figure 2.
Misalignment in biocular or binocular HMDs can result in blurry or doubled images [1, 5]. Slight misalignment may not be visible due to the vergence/fusion capabilities of the human ocular system, but may still introduce eyestrain or visual fatigue [1, 2]. Greater levels of misalignment can result in doubled images or possibly suppression of the imagery to one eye [1]. Even if visual fatigue is not present immediately upon donning an HMD, it may present after sustained use [1, 2]. Recent research shows
that recommended tolerance limits for optical misalignment vary widely and, furthermore, that the results of many of the studies were based on short viewing durations [6].

1.1.4 HMD Characterization

Various methods of measuring and calibrating spatial distortion in HMDs have been utilized [7, 8, 9, 10, 11]. These methods measure distortion of an HMD on-axis without evaluating the effects of different distortions when viewing the displays off-axis. They also do not consider the relative misalignment between left and right imagery, but rather only align the imagery of each eye to a reference pattern. These methods, however, generally work quite well for viewing scene content in the majority of virtual and augmented reality applications when precision alignment between the left and right eyes is not critical. Methods of correcting the distortion include fitting several parameters of the HMD optics (focal length, radial distortion, center of display, spherical aberration, etc.) [7, 9, 11]. Parametric approaches typically do not account for distortions due to effects such as manufacturing tolerances (tooling marks, thermal gradients, etc.). Non-parametric approaches such as B-splines and radial basis functions [12] can account for aberrations of HMD optics as well as other effects such as manufacturing tolerances.

Luminance of HMDs has been characterized through the use of spectroradiometers and luminance meters. These results have shown that luminance is generally highest in the center of the display and drops towards the edges [13, 14]. The degree of drop-off is dependent on the specific HMD.
1.1.5 Optical Aberrations

Aberrations in optical systems occur due to deviation from the paraxial optics model. These aberrations can be separated into spatial and chromatic aberrations. Only spatial aberrations will be evaluated in this effort. The aberrations can be expressed as the deviation from an ideal spherical wavefront through the use of Zernike polynomials. The even Zernike polynomials are given by (1) and the odd polynomials are given by (2).

\[ Z_n^m(\rho, \theta) = R_n^m(\rho) \cos(m\theta) \]  
\[ Z_{-n}^{-m}(\rho, \theta) = R_n^m(\rho) \sin(m\theta) \]  

Where \( \rho \) and \( \theta \) are the radial and azimuthal coordinates, \( m \) and \( n \) are integers, and \( R \) is a radial polynomial. \( R \) is given by (3) for cases in which \( n - m \) is even and by (4) for cases in which \( n - m \) is odd.

\[ R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s(n-s)!}{s!(n+m-s)! \left(\frac{n-m}{2}-s\right)! \left(\frac{n-m}{2}+s\right)!} \rho^{n-2s} \]  
\[ R_n^m(\rho) = 0 \] 

The sum of these Zernike polynomials can be used to express the shape of the actual wavefront. (5) describes the wavefront for the first several Zernike polynomials, which describe common types of optical aberrations.
\[ W(\rho, \theta) = Z_0 + Z_1 \rho \cos \theta + Z_2 \rho \sin \theta + Z_3 (2\rho^2 - 1) + Z_4 \rho^2 \cos(2\theta) \\
+ Z_5 \rho^2 \sin(2\theta) + Z_6 (3\rho^2 - 2) \rho \cos \theta \\
+ Z_7 (3\rho^2 - 2) \rho \sin \theta + Z_8 (6\rho^4 - 6\rho^2 + 1) \]  

The \( Z_0 \) term describes “piston,” which represents the mean value of the wavefront. An ideal system without aberrations would be described by this term alone. “Tilt” is described by the \( Z_1 \) and \( Z_2 \) terms (tilt in the \( x \) and \( y \) directions, respectively), and describes a shift in the location of an image in the transverse direction. Piston and tilt are not actually aberrations, but only shift the location at which an ideal image will be created.

The \( Z_3 \) term describes “defocus,” which represents a shift in the location of an image in the longitudinal direction. The \( Z_4 \) and \( Z_5 \) terms represent “astigmatism,” which occurs when rays propagating in the horizontal direction and the vertical direction have different focal points. The \( Z_4 \) term represents astigmatism in the \( x-y \) plane and the \( Z_5 \) term represents astigmatism in a plane rotated 45° relative to the \( x-y \) plane.

“Coma” is described by the \( Z_6 \) and \( Z_7 \) (coma in the \( x \) and \( y \) directions, respectively), and describes a difference in magnification for points in the image not on the optical axis. Coma increases at further distances from the optical axis. “Spherical aberration” is described by the \( Z_8 \) term, which is a change in the longitudinal focal point for rays at different locations relative to the optical axis. Figure 3 shows the Zernike polynomials for these nine terms.
Optical aberrations can also be represented by Seidel aberrations, which are an approximation to the Zernike polynomials.

Defects in optical systems can also arise due to manufacturing effects. Issues including tooling marks on optical surfaces, inhomogeneous material properties, and imperfect alignment of components after fabrication can all produce deviations from the ideal designed system. These manufacturing effects can not be captured by Zernike polynomials, but can be included through the use of other nonlinear transformation models.

1.1.6 Image Registration

Image registration is the process of mapping one image to another image through a transformation. There are several types of transformations that can be applied:
• Rigid transformations consist of translations and/or rotations. With this type of transformation, the size and shape of the original image is preserved. A rigid transformation consists of up to three parameters (one rotation, \( \theta \), and two translations, \( t_x \) and \( t_y \)) for a 2D image. This equation can be used to transform from an image with coordinates \( x \) and \( y \) to an image with coordinates \( x' \) and \( y' \) for a rigid transformation.

\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix}
= \begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  x \\
  y
\end{bmatrix}
+ \begin{bmatrix}
  t_x \\
  t_y
\end{bmatrix}
\]  

(6)

• Affine transformations include the rigid transformations listed above, as well as scaling or shearing of the image. The size and shape of the image can be changed with affine transformations. An affine transformation preserves the parallelism of lines in an image. Both rigid and affine transformations act globally on the entire image. An affine transformation consists of up to six parameters:

\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix}
= \begin{bmatrix}
  c_{11} & c_{12} \\
  c_{21} & c_{22}
\end{bmatrix}
\begin{bmatrix}
  x \\
  y
\end{bmatrix}
+ \begin{bmatrix}
  t_x \\
  t_y
\end{bmatrix}
\]  

(7)

• Perspective transformations also act on the image globally, but do not necessarily preserve the parallelism of lines in the image. The keystone effect would fit into this case of transformation. A general transformation matrix can be used to carry out a perspective transformation:
\[
\begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix} = \begin{bmatrix}
    a_{11} & a_{12} & a_{13} \\
    a_{21} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{bmatrix} \begin{bmatrix}
    x \\
    y \\
    1
\end{bmatrix}
\]

(8)

\[
x' = \frac{u}{w}
\]

(9)

\[
y' = \frac{v}{w}
\]

(10)

- Nonlinear transformations can act locally on different parts of the image. This enables more complex deformation of the image. Nonlinear transformations can be carried out using numerous methods, including polynomials, b-spline grids, radial basis functions, and others. Nonlinear transformations may require an optimization process to compute the mapping from one image to another.

Figure 4 shows an example of an affine transformation and a nonlinear transformation.

**Figure 4:** Affine transformation (left) and nonlinear transformation (right)

### 1.2 Motivation

The level to which misalignment in HMDs can be tolerated is not well understood, as evidenced by the wide disagreement in tolerable levels of convergence, divergence,
and dipvergence. Understanding the effects of misalignment on human performance also requires understanding the level of misalignment present in HMDs themselves. Previous methods for characterizing HMDs do not adequately account for various sources of misalignment, including manufacturing tolerances, off-axis viewing of HMDs, and relative differences between images seen by the left and right eyes. In this effort, a misalignment characterization system was developed to accurately characterize the misalignment present in HMDs.

1.3 Thesis Outline

Chapter 2 describes the hardware setup used to align HMDs and capture images of the distortion present. Chapter 3 describes image registration methods for mapping the measured distorted images to undistorted reference images. Chapter 4 discusses the misalignment characterized for two distinct HMDs. Chapter 5 describes a method for generating composite misalignment correction for both on- and off-axis viewing of HMDs. Chapter 6 describes the characterization of luminance of HMDs.
CHAPTER 2
HMD ALIGNMENT MEASUREMENTS

2.1 HMD Alignment Characterization System

The HMD alignment characterization system, as shown in Figure 5, was designed to mimic the ocular alignment of most human observers. The system consists of an HMD mounting bracket, two cameras, and numerous optical translation and rotation stages to adjust the orientation of the cameras relative to the HMD. The cameras can move independently, enabling accurate measurement of viewing angles with varying degrees of vergence and of human observers with varying or asymmetric interpupillary distances (IPD). The apparatus enables measurement of both on- and off-axis distortions. Overall, the system has 10 degrees of freedom:

- Yaw of both cameras simultaneously
- Roll of both cameras simultaneously
- Longitudinal translation of both cameras towards or away from HMD
- Lateral translation of both cameras
- Vertical translation of both cameras
- Yaw of each camera individually
- Lateral translation of each camera individually
• Pitch of HMD

Figure 5: HMD alignment characterization system

The cameras utilized were PixelINK PL-B781U monochrome cameras. The monochrome cameras provide a higher spatial resolution than color cameras with the same number of pixels due to the absence of interpolation on red-, green-, and blue-filtered images being used to produce a full-resolution image. The specifications for these cameras are listed in Table 1. The effect of the camera distortion is characterized and removed prior to characterizing the distortion of the HMDs.
Table 1: PixeLINK PL-B781U camera specifications [15]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>2208 × 3000 pixels</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>3.5 × 3.5 μm</td>
</tr>
<tr>
<td>Responsivity</td>
<td>4.4 DN/(nJ/cm²)</td>
</tr>
<tr>
<td>Fixed-Pattern Noise</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Photo Response Non-Uniformity</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>60 dB</td>
</tr>
<tr>
<td>Exposure Range</td>
<td>63 μs to 2 s</td>
</tr>
<tr>
<td>Color Filter</td>
<td>-</td>
</tr>
<tr>
<td>Power</td>
<td>3.2 W (USB)</td>
</tr>
</tbody>
</table>

The lenses used with the cameras were Fujifilm DV3.8x4sR4A-1 lenses. These lenses have adjustable focus, zoom, and iris settings. The specifications of the lens are listed in Table 2.
<table>
<thead>
<tr>
<th><strong>Table 2: Lens specifications [16]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Focal Length</strong></td>
</tr>
<tr>
<td><strong>Iris Range</strong></td>
</tr>
<tr>
<td><strong>Horizontal Field of View</strong></td>
</tr>
<tr>
<td><strong>Vertical Field of View</strong></td>
</tr>
<tr>
<td><strong>Focus Range</strong></td>
</tr>
<tr>
<td><strong>Back Focal Distance</strong></td>
</tr>
<tr>
<td><strong>Exit Pupil Location (from image plane)</strong></td>
</tr>
<tr>
<td><strong>Entrance Pupil Location (from back of flange)</strong></td>
</tr>
</tbody>
</table>

The spatial resolution of the cameras and lens system was measured using the USAF 1951 resolution test chart, as shown in Figure 6. The measured modulation transfer function of each camera is shown in Figure 7. A contrast ratio of 50% is produced with a spatial resolution of 0.17 line pairs/pixel, indicating approximately 6 pixels are required to resolve a line pair with a 50% contrast ratio.
Figure 6: Image of USAF 1951 resolution test chart recorded using monochrome camera
2.2 Head-Mounted Displays

Two HMDs were evaluated here: the SA-Photonics SA-62/S and the SA Photonics SA-65. The SA-62/S is a semi-transparent HMD (i.e. "see-through") intended for augmented reality or mixed reality applications. The SA-65 is opaque. The specifications of the two systems are listed in Table 3. The field of view was verified experimentally by overlaying the HMD imagery on an external pattern of known size and distance from the cameras. The SA-62/S HMD is shown in Figure 8.
### Table 3: HMD specifications

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td><strong>Horizontal Field of View</strong></td>
<td>53°</td>
<td>55°</td>
</tr>
<tr>
<td><strong>Vertical Field of View</strong></td>
<td>33°</td>
<td>34.4°</td>
</tr>
<tr>
<td><strong>Eye Box</strong></td>
<td>10 mm</td>
<td>-</td>
</tr>
<tr>
<td><strong>Eye Relief</strong></td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td><strong>Display Resolution</strong></td>
<td>1920 × 1200 pixels</td>
<td>1920 × 1200 pixels</td>
</tr>
<tr>
<td><strong>IPD Adjustment Range</strong></td>
<td>55 – 75 mm</td>
<td>55 – 85 mm</td>
</tr>
</tbody>
</table>

![SA-62/S HMD](image)

**Figure 8: SA-62/S HMD**
2.3 Camera Calibration

The cameras are calibrated by recording an image of an external pattern and registering that image to an undistorted digital reference pattern. The alignment apparatus is carefully aligned with respect to the external pattern. A laser level is used to ensure that the alignment apparatus is not rotated relative to the external pattern. Distance measurements to either side of the apparatus are used to ensure that the external pattern is normal to the apparatus. The experimental setup is shown in Figure 9. The pattern used is a 96 x 71 cm black and white checkerboard with 14 x 10 checkers. A small gray checker is placed on the pattern to easily locate its center. This system was designed to be highly portable, therefore the pattern is kept vertical and normal to the characterization system through the use of several optical posts rather than a permanent mount.
Figure 9: Measurement of external pattern using alignment characterization system

For the HMDs under test, the expected focal distance is greater than 2 meters, although the external pattern is placed between 0.5 to 1 meters from the entrance pupil of the cameras. The pattern is placed at a closer distance than the HMD virtual image due to field of view limitations. The test pattern must cover a larger field of view than the HMD image for adequate characterization. Only the area of the HMD image that falls within the area of the checkerboard will be properly characterized, thus the HMD image must appear within this boundary. To cover a larger field of view, the external test pattern would need to be larger while maintaining its rigid shape, and would reduce the portability of the system. The location of both the external pattern and the HMD virtual image are beyond the hyperfocal distance of the cameras, so both patterns are in sharp focus despite their relative difference in
location. The image metrics and image registration process do provide subpixel-level accuracy on the scale of the camera pixels, so recording the images beyond the hyperfocal distance is not strictly necessary.

When recording the external pattern for camera calibration, the left and right cameras are kept parallel and equidistant from the center of the test pattern, and the HMD is removed from the apparatus. A recorded image of the test pattern is shown in Figure 10. The exposure time for the cameras is adjusted such that the black checkers appear black (no significant reflection from ambient lights) and the white checkers appear white (sufficient exposure to be near, but not exceeding, saturation). The pattern appears slightly off-center in Figure 10 because the cameras are slightly offset on either side from the center of the pattern. Because the initial photographs are intended to characterize only the distortion present in the camera, the spacing between the cameras need not precisely match the IPD of the HMD.
Figure 10: Recorded image of external pattern
The degree of misalignment in the HMD is calculated by performing image registration of a distorted pattern displayed on the HMD to an undistorted reference pattern. The cameras are first characterized using an external pattern to measure and remove any distortion effects introduced by the cameras themselves. After applying the camera correction, the distorted pattern displayed on the HMD is captured and matched to the undistorted reference pattern. A warp map is created for the left and right oculars specifying the amount of X and Y displacement for each pixel in the distorted reference pattern to match the undistorted pattern. The relative difference between these warp maps indicates the misalignment between the left and right oculars.

The image registration process is carried out in two steps. First, the corners of the checkers are identified and matched to the same corners in the reference pattern. The checkerboard corner detection is a fast method that provides an initial estimate of the warp required to produce the reference pattern. This is followed by an optimization of b-spline parameters to provide the final warp map. This is a slower method but provides more accurate results. The checkerboard corner detection
provides a starting point for the b-spline registration to improve computational efficiency and robustness.

3.1 Checkerboard Corner Detection

The checkerboard corner detection process is carried out in four steps:

- Detect corners in image
- Identify which corners are on the checkerboard pattern
- Sort the checkerboard corners in a specified order
- Map the checkerboard corners from the original image to the reference image

The Harris corner detection method is used to find corners in the image [19]. Large variations in intensity in the local neighborhood of a pixel signify a higher likelihood that that pixel corresponds to a corner. A corner should have large variations in all directions while an edge will not have large variations along one direction. The corner likelihood metric can be specified mathematically by (11) through (13). The sensitivity parameter, $k$, controls how closely corners can be located relative to each other. The threshold parameter, $R$, controls the amount of intensity variation necessary to define a pixel as a corner. The values used for these parameters were 0.04 for $k$ and $10^{-8}$ for $R$. Figure 11 shows corners detected using the Harris method in an image.
\[ M = \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \]  

(11)

\[ R = \det(M) - k \cdot (\text{trace}(M))^2 \]  

(12)

\[ R = I_x^2 I_y^2 - (I_x I_y)^2 - k(I_x^2 + I_y^2)^2 \]  

(13)

Figure 11: Corners detected using Harris method

In the recorded images of the external patterns, there is additional clutter outside the area of interest in which corners can be detected. This clutter must be removed.
so that only the corners of the checkerboard pattern remain. In the local neighborhood of corners that are located on the checkerboard, there should be four quadrants of pixels, two of which are predominantly black and two of which are predominantly white. The black quadrants should be located opposite of each other relative to the corner point, as should the white quadrants. These features can be used to discriminate checkerboard corners from non-checkerboard corners.

Mathematically, this process is implemented by first extracting a local image, $C$, around each corner. This local image is then split into four regions corresponding to the upper left of the selected corner, $C_{UL}$, the upper right, $C_{UR}$, bottom left, $C_{BL}$, and bottom right, $C_{BR}$. The similarity metrics, $q$, of these four images to a checkerboard corner is defined in (14), (15), (16), and (17).

$$q_1 = \sum_x \sum_y 1 \cdot C_{UL}$$  \hspace{1cm} (14)

$$q_2 = \sum_x \sum_y 1 \cdot (1 - C_{UR})$$  \hspace{1cm} (15)

$$q_3 = \sum_x \sum_y 1 \cdot (1 - C_{BL})$$  \hspace{1cm} (16)

$$q_4 = \sum_x \sum_y 1 \cdot C_{BR}$$  \hspace{1cm} (17)
To also handle the case where the black regions occur in the upper left and bottom right, similarity metrics are also created for these cases. The similarity metrics, \( r \), are similar to those shown in (14), (15), (16), and (17) except with the upper left and bottom right images subtracted from 1 rather than the upper right and bottom left.

A corner located on the checkerboard should have high values for \( q \) while a corner not located on the checkerboard should have low values. The values for \( q_1 \) should be similar to \( q_4 \) and the values for \( q_2 \) should be similar to \( q_3 \). A corner is defined as being located on a checkerboard if the metric in (18) is satisfied, where \( t_a \) and \( t_b \) are thresholds for the similarity metrics. The value for \( t_a \) is set to 300 and the value for \( t_b \) is set to 0.1.

\[
\left[ (q_1 \land q_2 \land q_3 \land q_4 > t_a) \lor (r_1 \land r_2 \land r_3 \land r_4 > t_a) \right] \land \\
\left( \frac{|q_1 - q_4|}{q_1 + q_4} \land \frac{|q_2 - q_3|}{q_2 + q_3} < t_b \right) \\
\lor \left( \frac{|r_1 - r_4|}{r_1 + r_4} \land \frac{|r_2 - r_3|}{r_2 + r_3} < t_b \right)
\]  

(18)

Where \( \land \) is the Boolean operator AND, and \( \lor \) is the Boolean operator OR.

Figure 12 shows the corner similarity metrics identified for two corners in an image, one of which is located on the checkerboard, and one of which is not. The diagonal similarity metrics are much smaller for the corner on the checkerboard, and the four local similarity metrics are higher as well.
This method does have several limitations, but they do not have a large effect on this current application. The four local images (upper left, upper right, lower left, and lower right) are selected using a global rectilinear Cartesian coordinate system. Checkerboards that are significantly rotated (>45°) or that have extreme levels of barrel or pincushion distortion may have checkerboard corners that have an equal number of black and white pixels in these four quadrants. However, during the alignment process the checkerboard is always placed as close to normal and unrotated as possible. It is highly unlikely that significant rotations would be seen. The camera system also does not distort the image significantly enough for this to be an issue.

Figure 12: Corner metrics for two corners in image, one located on checkerboard and one not located on checkerboard

\[
\begin{align*}
    r &= [711.3, 309.6, 274.7, 479.8] \\
    \frac{|r_1-r_4|}{r_1+r_4} &= 0.1944 \\
    \frac{|r_2-r_3|}{r_2+r_3} &= 0.0596 \\
    r &= [739.3, 729.5, 715.5, 751.8] \\
    \frac{|r_1-r_4|}{r_1+r_4} &= 0.0084 \\
    \frac{|r_2-r_3|}{r_2+r_3} &= 0.0096
\end{align*}
\]
Somewhat uniform illumination of the checkerboard pattern is required for this method. This is not a very strict limitation, and only becomes an issue when black checkers are illuminated enough to produce significant reflections, or when white checkers are not illuminated enough and appear very dark. On a normalized scale from 0 (black) to 1 (white), this method can handle black pixels ranging from 0 to 0.4 and white pixels ranging from 0.6 to 1. The illumination of the checkerboard pattern should be kept as uniform as possible, but this is not so critical of a limitation to require special equipment to illuminate the pattern.

Additional checks are used to eliminate spurious corners detected. The checkerboard corners are all located relatively close to each other. If a corner is found that is significantly larger than the average distance between corners, then this is eliminated as it is likely not located on the checkerboard pattern. Corners that are extremely close are merged into a single corner. This step enables detection of corners on checkerboard patterns that have grey lines separating white and black checkers from each other. Figure 13 shows the checkerboard corners identified in red.
To transform the detected checkerboard corners to the reference image, the corners must be sorted consistently between the captured image and the reference pattern. The corners are sorted so that the upper left corner is labeled as corner #1. The next corners are labeled going from left to right across the first row. After the first row is complete, the next corner is the first left corner of the second row, and so on.

The sorting process is carried out by finding the perimeter of the checkerboard pattern using the convex hull around the detected corners [20]. For checkerboard patterns that show barrel distortion, this may be sufficient to detect the outer perimeter of the checkerboard pattern. However, for patterns with pincushion distortion or other non-convex distortions, not all perimeter corners will be detected. To find these, the convex hull is "squeezed" to find the next closest corners.
to the original convex hull. Corners are said to be located on the perimeter if they are sufficiently close to the previous perimeter and they do not induce extra notches in the perimeter. By ensuring that only four corners have a large angle between the previous corner and the next corner, an approximately rectangular checkerboard pattern will be found. The convex hull squeezing process is carried out recursively until no corners are added to the perimeter. Figure 14 shows the perimeter of the checkerboard corners identified in green. Figure 15 shows the process of squeezing the convex hull to capture all corners along the perimeter for a checkerboard pattern with pincushion distortion.

![Checkerboard with convex hull](image)

**Figure 14: Identifying perimeter of checkerboard with a convex hull**
The convexity between consecutive points is used to determine whether the squeezed hull is approximately rectangular. The convexity is defined as the angle between the line segment immediately preceding the current point and the line segment immediately following the current point. An approximately rectangular hull should have only four sections where the convexity is close to 90°. If adding a point to the squeezed hull would create a fifth or sixth section with convexity close to 90°, then the point should not be included in the squeezed hull. This metric, along with the distance to the current hull, are the two metrics used to determine whether a point should be added to the squeezed hull.

Figure 16 shows the distribution of convexity for points in the outermost squeezed hull of the checkerboard pattern shown in Figure 11, Figure 12, Figure 13, and Figure 14. Most sections have a convexity near 0° while only four sections have a convexity greater than 80°. This indicates that this metric is a very good discriminator for identifying points that should be included in the squeezed hull.
Figure 16: Convexity of perimeter points

Using the total number of corners, $N$, and the number of corners on the perimeter, $P$, the number of rows and columns of the checkerboard may be determined using the quadratic equation:

$$a = -1$$  \hspace{1cm} (19)

$$b = \frac{P + 3}{2}$$  \hspace{1cm} (20)
The first row of sorted corners is then found by following the first row of the perimeter corners from the upper left corner of the checkerboard. The second row is found by finding the squeezed hull of the unsorted checkers and then following the perimeter corners again. This process is repeated for all rows of the checkerboard pattern.

The sorted checkerboard corners can then be used to create a transformation field from the original image to the reference image. The pixels in the original image corresponding to checkerboard corners are matched to the corresponding checkerboard corners in the reference image. The displacements of pixels not at these corners are interpolated to calculate an approximate transformation. This method transforms the distorted image to be very similar to the reference image, with displacement errors under 2 pixels in the interior of the checkerboard and up to 20 pixels on the edges of the checkerboard. The checkerboard corners on the edges of the checkerboard are not detected because they do not have two quadrants of predominantly white pixels and two quadrants of predominantly black pixels surrounding them. The image mapping is then less accurate in this region.
3.2 B-Spline Registration

The transformed image after performing checkerboard matching is close to the reference image but not completely registered. To completely match the original image to the reference, B-spline registration is used to calculate the remaining pixel displacement. B-splines are used to fit curves through a set of control points.

B-splines are locally controlled, meaning that changing the parameters of the B-spline only affects a small region of the full curve. For the image registration task carried out here, this can be either a benefit or a drawback. Local control enables small-scale distortions to be accurately represented by B-splines. However, the B-spline can also overfit pixels within a single checker by adjusting local parameters. Several white pixels in the distorted image could be mapped to a single white pixel in the reference image. To avoid cases like this, a smoothing penalization factor, $\lambda$, is introduced [21]. The cost function, $C$, for the optimization is then:

$$
C = C_{\text{similarity}}(I_{\text{reference}}, T(I_{\text{distorted}})) + \lambda C_{\text{smooth}}(T) \tag{23}
$$

Where $C_{\text{similarity}}$ is the metric of similarity between the reference image, $I_{\text{reference}}$, and the distorted image, $I_{\text{distorted}}$, after undergoing a transformation, $T$, and $C_{\text{smooth}}$ is the metric of smoothness of the B-spline grid. The similarity metric used here was the residual complexity metric [22], although other metrics were also evaluated and performed well (cross-correlation and sum of squared differences). The parameters being optimized here were the locations of the B-spline grid control points. A gradient descent algorithm was used to optimize the B-spline parameters [22].
Figure 17 shows the registered image of the external pattern after checkerboard registration and after B-spline registration.

Figure 17: Image of external pattern after checkerboard registration (left) and after B-spline registration (right)

The convergence of the B-spline optimization process was analyzed. Stricter tolerances will provide more optimized B-spline grid. However, after a certain limit, the increase in accuracy is offset by the increase in computational time. To find an acceptable balance between these parameters, the optimization performance was analyzed with varying levels of tolerance, as shown in Figure 18.
The accuracy corresponding to a tolerance of $10^{-6}$ is taken to be the truth value, with an RMS error of 0 pixels. The error of other tolerance values was then calculated relative to this truth value. The total RMS error is under 1 pixel for all regions of the display at tolerances under $10^{-4}$. As this is the maximum level of accuracy expected to be achieved by this system, improvements beyond this point are not necessary. A tolerance of $10^{-5}$ was used to provide some leeway if other images require tighter tolerancing to produce <1 pixel accuracy.
It should be noted that other parameters can affect the convergence rate of the optimization, such as annealing rate, smoothing penalization factor, and the step size. Only tolerance was investigated here.

3.3 HMD Image Registration

Once the cameras are calibrated, the HMD misalignment may then be characterized. The HMD was mounted to the alignment characterization system with the exit pupils of the HMD oculars located close to the entrance pupils of the lenses. An opaque black curtain was placed over the system to block any imagery other than that of the HMD. The cameras and lenses were positioned to provide the desired orientation corresponding to a human observer’s ocular alignment with an IPD of 70 mm. Once the HMD and cameras were aligned to the desired orientation, a checkerboard reference pattern was displayed on the HMD. The exposure of the cameras was adjusted and images of the pattern were recorded for each eye.

The inverse transformation corresponding to the camera calibration warp map was applied to the recorded image to remove distortion due to the camera itself. To ensure accuracy, the image of the distorted pattern on the HMD must be located within the field of view over which the cameras were calibrated, as shown in Figure 19. In this image, the HMD image underfills the calibrated region. The pixels of the HMD imagery are recorded by the pixels on the camera with a ratio of 1:1.9 (1 camera pixel per 1.9 HMD pixels). Figure 20 shows a recorded HMD image before and after camera calibration is applied. Reflections of the pattern can be seen in the image prior to calibration. The image is also magnified because the external pattern
is stretched to match the reference pattern during camera calibration. Therefore, when the camera calibration is applied to the distorted HMD image, the resultant image is stretched as well.

Figure 19: Overlay of external pattern for camera calibration (green) and HMD image (magenta)
The images of the external checkerboard pattern captured for camera calibration are always recorded on-axis. However, the HMD may be measured at large off-axis angles that can introduce a keystone effect into the image. This effect occurs when an image is projected onto a surface at an angle. This effect is removed with the use of a transformation matrix. The keystoned image is transformed according to these equations [23]:

\[
x' = \frac{x \cos \alpha}{\cos \alpha - \frac{y}{D} \sin \alpha}
\]

\[
y' = \frac{y}{\cos \alpha - \frac{y}{D} \sin \alpha}
\]

Where \(x\) and \(y\) are the image coordinates in the keystoned image, \(x'\) and \(y'\) are the images in the transformed image, \(\alpha\) is the camera rotation angle, and \(D\) is the distance to the external pattern used in the camera calibration process. Because the distance to the external pattern and the camera rotation angle are known, the
transformed image can be computed. Keystone correction is only necessary for pitch or yaw rotations, as roll rotations do not induce a larger distance to the camera from different regions of the image. These equations apply to keystone due to a rotation in one direction, but this method can be extended to simultaneous rotation in two directions. Figure 21 shows an image with keystone and with the keystone effect removed.

![Figure 21: Image with keystone due to 10° rotation (left) and image with keystone effect removed](image)

Block matching was used to center the left and right images prior to calculating HMD misalignment. The right image was translated in integer pixel increments until it was brought into the closest alignment with the left image. This process was kept computationally efficient by only checking translations of the right image near where the centers of each distorted pattern align. Figure 22 shows the left and right images overlaid before and after block matching. After block matching, some misalignment is still visible, most notably in the lower right corner, as indicated by pink and green fringes. This misalignment will be characterized next.
Figure 22: Overlay of left (green) and right (magenta) images prior to block matching (left) and after block matching (right)

The left and right HMD images are then registered to the undistorted reference pattern using the same checkerboard detection and B-spline registration process used for the camera calibration. The relative misalignment between left and right images is calculated by evaluating the difference between the warp maps calculated for the left and right images.
4.1 Repeatability

Three images of the external pattern were captured in quick succession using exactly the same focus, zoom, iris, and position settings. The external pattern also remained stationary. Three images were also captured of the pattern on the HMD-displayed pattern using these same camera settings. These images provide data to analyze the repeatability of the optimization process and camera measurement. The standard deviation of the average total RMS misalignment between these three successive runs was 0.7 HMD pixels (0.34 mrad). This is an expected level of error, as the HMD image is undersampled over the cameras’ calibrated field of view.

The repeatability of the measurement process was also analyzed in the presence of user alignment error. Due to the portable design of the apparatus, the alignment of the external pattern relative to the cameras may not be constant between successive measurements. Various minor errors in pattern rotation and translation relative to the cameras could introduce errors in the camera calibration process. To analyze this effect, the external pattern was removed and repositioned three times with images recorded at each successive aligned position. The standard deviation of the
average total RMS misalignment between successive runs was 0.8 HMD pixels (0.39 mrad), which is comparable to the error inherent in the software characterization alone, without pattern realignment. Therefore, it can be concluded that the pattern alignment method is highly repeatable, with small differences in pattern alignment introducing very little additional error. These results also imply that the inherent accuracy of the apparatus (and the remaining results described herein) is on the order of ±0.8 HMD pixels (0.39 mrad).

4.2 SA-62/S

4.2.1 On-Axis

The relative misalignment between the left and right HMD oculars was determined by subtracting the pixel displacement of one ocular from the pixel displacement of the other. Figure 23 shows the misalignment of the SA-62/S HMD under on-axis viewing conditions (i.e. cameras parallel and pointing straight ahead). The heatmap shows the total misalignment (combined horizontal and vertical displacement) in pixels. The average RMS error in several concentric regions of the HMD was also calculated: the center 15° field of view, the intermediate region between 15-30° field of view, and the outer region of the HMD beyond 30° field of view. The RMS error in the horizontal direction varied from 3.6-5.5 pixels (1.7-2.7 mrad) over the three regions. The RMS error in the vertical direction increased from 2.5 pixels (1.2 mrad) in the center of the display to 3.9 pixels (1.9 mrad) in the outer region.
Figure 23: Relative misalignment between left and right oculars of SA-62/S for on-axis viewing

Horizontal misalignment, although present in the HMD, may not be readily apparent to human observers. The vergence of the human ocular system readily accommodates for some degree of horizontal misalignment by perceiving the misalignment as a horizontal disparity between the two images. The result is a false stereo depth cue, which may cause difficulties in perceptually reconciling HMD imagery with see-through real world imagery. Vertical misalignment is much more difficult to accommodate and may be visible to human observers. To visualize this effect, an image of typical heads-up display (HUD) symbology has been warped using the warp map from the left ocular and overlaid with the same image warped using the warp map from the right ocular. This warped image is shown with both horizontal and vertical warping applied in Figure 24 and only vertical warping...
applied in Figure 25. The horizontal misalignment is visible in Figure 24 but very little misalignment is visible in Figure 25, which is representative of the false stereo image a human observer would see in the absence of any external real world “see-through” content (i.e. the eyes verge to align, or fuse, the left and right images).

Figure 24: Warped image of HUD symbology with both horizontal and vertical warping applied
The largest vertical misalignment occurs in the outer region of the HMD, so it is not readily visible in the image of HUD symbology, which is located near the center of the display. Figure 26 shows an image of text warped in the vertical direction only, in a manner similar to Figure 25. In this image, double lines of text can be seen in the bottom right corner.
4.2.2 Off-Axis

The relative misalignment between left and right eyes was also characterized for off-axis ocular alignments. The cameras were rotated 1° in either yaw, pitch, or roll to emulate a helmet slipping from its ideal position. The relative misalignment is shown in Figure 27. For the SA-62/S under test, there was not a dramatic difference in misalignment when viewing on-axis or off-axis by 1°. The maximum deviation in average RMS misalignment from the on-axis condition in the horizontal direction was 1.2 pixels (0.58 mrad) in the central region of the HMD, 1.1 (0.53 mrad) pixels in the intermediate region, and 2.2 pixels (1.07 mrad) in the outer region. The maximum deviation in average RMS misalignment from the on-axis condition in the vertical direction was 0.9 pixels (0.44 mrad) in the central region, 0.6 pixels (0.29
mrad) in the intermediate region, and 0.7 pixels (0.34 mrad) in the outer region. The average RMS misalignment in the three HMD regions is shown in Table 4.
Figure 27: Relative misalignment with no rotation (top), pitch 1° up (2nd row, left), pitch 1° down (2nd row, right), yaw 1° left (3rd row, left), yaw 1° right (3rd row, right), roll 1° left (bottom, left), roll 1° right (bottom, right)
Table 4: Average RMS misalignment, by concentric measurement region, between left and right oculars in mrad (pixels) for off-axis conditions

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<th>Rotation</th>
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4.2.3 Vergence

The relative misalignment between left and right eyes was characterized for additional convergence conditions. The cameras were rotated inwards 1° each or 2° each to emulate convergence. These convergence rotations correspond to viewing distances of 1.9 and 0.9m respectively. The relative misalignment is shown in Figure 28. Unlike simultaneous rotation of the cameras in a certain direction, converging or diverging rotation did have a large effect on misalignment. This was most noticeable along the left and right edges of the images. The average RMS misalignment in the outer region increases from 3.9 pixels (1.9 mrad) in the vertical direction for the parallel case to 7.6 pixels (3.7 mrad) for the 1° converging case and 15.3 pixels (7.4
mrad) for the 2° converging case, roughly doubling for each degree of convergence. The average RMS misalignment in the central region in the horizontal direction increased from 5.5 pixels (2.7 mrad) for the parallel case to 8.3 pixels (4.0 mrad) for the 1° converging case and 20.6 pixels (9.9 mrad) for the 2° converging case. The average RMS misalignment in the three HMD regions is shown in Table 5.

Figure 28: Relative misalignment with parallel cameras (top), converged 1° (bottom left), converged 2° (bottom right)
Table 5: Average RMS misalignment between left and right oculars in mrad (pixels) for vergence conditions

<table>
<thead>
<tr>
<th>Vergence</th>
<th>Center X</th>
<th>Center Y</th>
<th>Intermediate X</th>
<th>Intermediate Y</th>
<th>Outer X</th>
<th>Outer Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>1.7 (3.6)</td>
<td>1.2 (2.5)</td>
<td>1.5 (3.1)</td>
<td>1.3 (2.7)</td>
<td>2.7 (5.5)</td>
<td>1.9 (3.9)</td>
</tr>
<tr>
<td>Converge 1°</td>
<td>1.9 (4.0)</td>
<td>1.3 (2.6)</td>
<td>1.6 (3.3)</td>
<td>1.6 (3.3)</td>
<td>4.0 (8.3)</td>
<td>3.7 (7.6)</td>
</tr>
<tr>
<td>Converge 2°</td>
<td>4.5 (9.3)</td>
<td>0.9 (2.0)</td>
<td>3.6 (7.4)</td>
<td>2.5 (5.1)</td>
<td>9.9 (20.6)</td>
<td>7.4 (15.3)</td>
</tr>
</tbody>
</table>

4.2.4 Misalignment Correction

Distortion in the HMD images can be corrected through the use of a warp map. The pixels in the original distorted image are redrawn at a different location according to the warp map. Two different sets of warp maps were tested to counteract the effects of the distortion. A manufacturer-supplied warp map based upon HMD design calculations was applied, as well as left/right warp maps calculated using the alignment toolset described here. It should be noted that because the manufacturer supplied warp map was calculated from the ideal design for identical left/right eyepieces, it is the same warp map for both the left and right HMD channels and cannot account for manufacturing variations in the as-built HMD. Figure 29 shows the captured image after camera calibration for these two cases. With the manufacturer-supplied warp map, the difference in the size and shape of checkers was more noticeable. The checkers near the center are larger than those near the edges, and the left edge also had a noticeable curvature effect.
The relative misalignment for each of the warp maps was characterized, and is shown in Figure 30. The manufacturer-supplied warp map is identical for the left and the right eyes, and therefore shows little to no improvement in correcting misalignment between the left and right eyes. The warp maps created using the alignment toolset are different for each eye resulting in significantly less left/right misalignment than using either no warp map or the manufacturer-supplied warp map. The average RMS errors in the three regions of the HMD are shown in Table 6. Subjectively, observers also report that the alignment toolset distortion corrections described here appear superior to the manufacturer-supplied warp maps when carefully viewing various geometric test patterns.
Figure 30: Relative misalignment with no warp map applied (top), manufacturer-supplied warp map (bottom left), and alignment toolset warp map (bottom right)

Table 6: Average RMS misalignment between left and right oculars in mrad (pixels) for various warp maps

<table>
<thead>
<tr>
<th>Warp Map</th>
<th>Center</th>
<th></th>
<th>Intermediate</th>
<th></th>
<th>Outer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>X</td>
<td>Y</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>None</td>
<td>1.7 (3.6)</td>
<td>1.2 (2.5)</td>
<td>1.5 (3.1)</td>
<td>1.3 (2.7)</td>
<td>2.7 (5.5)</td>
<td>1.9 (3.9)</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>2.2 (4.0)</td>
<td>0.9 (1.7)</td>
<td>2.0 (3.6)</td>
<td>1.3 (2.6)</td>
<td>2.6 (4.8)</td>
<td>1.6 (3.0)</td>
</tr>
<tr>
<td>Alignment Toolset</td>
<td>0.7 (1.3)</td>
<td>0.7 (1.3)</td>
<td>0.6 (1.2)</td>
<td>0.7 (1.4)</td>
<td>1.1 (2.0)</td>
<td>0.7 (1.4)</td>
</tr>
</tbody>
</table>
4.3 SA-65

4.3.1 On-Axis

The same process was carried out for the SA-65 HMD. The relative misalignment between the left and right HMD oculars was determined by subtracting the pixel displacement of one ocular from the pixel displacement of the other. This HMD is more difficult to align, likely due to having a smaller eyebox. This is true for both wearing the HMD or for using it with the alignment toolset. For this reason, the outer edges of the HMD are not focused well, and are thus excluded from the misalignment calculations. Figure 31 shows a captured image of the pattern displayed on the SA-65 HMD in which the corners are not visible.
Figure 31: Captured image of pattern displayed on SA-65 HMD

Figure 32 shows the misalignment of the SA-65 HMD under on-axis viewing conditions (i.e. cameras parallel and pointing straight ahead). The heatmap shows the total misalignment (combined horizontal and vertical displacement) in pixels. The average RMS error in several concentric regions of the HMD was also calculated: the center 15° field of view, the intermediate region between 15-30° field of view, and the outer region of the HMD beyond 30° field of view. The RMS error in the horizontal direction varied from 1.9-2.8 pixels (0.9-1.4 mrad) over the three regions. The RMS error in the vertical direction increased from 1.7 pixels (0.9 mrad) in the center of the display to 2.9 pixels (1.5 mrad) in the outer region.
Figure 32: Relative misalignment between left and right oculars of SA-65 for on-axis viewing

The measured warp maps for the SA-65 HMD were applied to an image of typical HUD symbology. The warp map from the left ocular was applied to the image and overlaid with the same image warped using the warp map from the right ocular. This warped image is shown with both horizontal and vertical warping applied in Figure 33 and only vertical warping applied in Figure 34. Because the levels of misalignment are small, the effects of this misalignment are not very noticeable in these figures.
Figure 33: Warped image of HUD symbology with both horizontal and vertical warping applied
The largest vertical misalignment occurs in the corners of the HMD, so it is not readily visible in the image of HUD symbology, which is located near the center of the display. Figure 35 shows an image of text warped in the vertical direction only, in a manner similar to Figure 34. In this image, double lines of text can be seen in the bottom left corner.
4.3.2 Off-Axis

The relative misalignment between left and right eyes was also characterized for off-axis ocular alignments. The cameras were rotated 1° in either yaw, pitch, or roll to emulate a helmet slipping from its ideal position. The relative misalignment is shown in Figure 36. For the SA-65 under test, there was not a dramatic difference in misalignment when viewing on-axis or off-axis by 1°. The most significant deviation occurs for the yaw 1° right scenario. The maximum deviation in average RMS misalignment from the on-axis condition in the horizontal direction was 0.7 pixels (0.34 mrad) in the central region of the HMD, 0.6 pixels (0.28 mrad) in the intermediate region, and 1.0 pixels (0.48 mrad) in the outer region. The maximum
deviation in average RMS misalignment from the on-axis condition in the vertical direction was 0.8 pixels (0.42 mrad) in the central region, 0.5 pixels (0.25 mrad) in the intermediate region, and 1.1 pixels (0.51 mrad) in the outer region. The average RMS misalignment in the three HMD regions is shown in Table 7.
Figure 36: Relative misalignment with no rotation (top), pitch 1° up (2nd row, left), pitch 1° down (2nd row, right), yaw 1° left (3rd row, left), yaw 1° right (3rd row, right), roll 1° left (bottom, left), roll 1° right (bottom, right)
Table 7: Average RMS misalignment, by concentric measurement region, between left and right oculars in mrad (pixels) for off-axis conditions

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Center</th>
<th>Intermediate</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>X</td>
</tr>
<tr>
<td>None</td>
<td>0.9 (1.9)</td>
<td>0.9 (1.7)</td>
<td>1.0 (3.1)</td>
</tr>
<tr>
<td>Pitch 1° Up</td>
<td>0.6 (1.2)</td>
<td>0.7 (1.4)</td>
<td>0.8 (1.5)</td>
</tr>
<tr>
<td>Pitch 1° Down</td>
<td>0.8 (1.5)</td>
<td>0.9 (1.8)</td>
<td>0.8 (1.5)</td>
</tr>
<tr>
<td>Yaw 1° Left</td>
<td>1.1 (2.3)</td>
<td>1.1 (2.2)</td>
<td>0.9 (1.8)</td>
</tr>
<tr>
<td>Yaw 1° Right</td>
<td>0.9 (1.8)</td>
<td>0.5 (0.9)</td>
<td>1.1 (2.2)</td>
</tr>
<tr>
<td>Roll 1° Left</td>
<td>1.0 (2.0)</td>
<td>1.3 (2.5)</td>
<td>1.0 (2.0)</td>
</tr>
<tr>
<td>Roll 1° Right</td>
<td>1.0 (1.9)</td>
<td>0.6 (1.3)</td>
<td>1.0 (2.1)</td>
</tr>
</tbody>
</table>

4.3.3 Vergence

The relative misalignment between left and right eyes was characterized for additional convergence conditions. The cameras were rotated inwards 1° each to emulate convergence. This convergence rotation corresponds to a viewing distances of 1.9 m. The relative misalignment is shown in Figure 28. Unlike simultaneous rotation of the cameras in a certain direction, converging rotation did have a large effect on misalignment. This was most noticeable along the left and right edges of the images. The average RMS misalignment in the outer region increases from 3.9 pixels (1.9 mrad) in the vertical direction for the parallel case to 7.6 pixels (3.7 mrad) for the 1° converging case and 15.3 pixels (7.4 mrad) for the 2° converging
case, roughly doubling for each degree of convergence. The average RMS misalignment in the central region in the horizontal direction increased from 5.5 pixels (2.7 mrad) for the parallel case to 8.3 pixels (4.0 mrad) for the 1° converging case and 20.6 pixels (9.9 mrad) for the 2° converging case. The average RMS misalignment in the three HMD regions is shown in Table 5.

Figure 37: Relative misalignment with parallel cameras (left), converged 1° (right)

Table 8: Average RMS misalignment between left and right oculars in mrad (pixels) for vergence conditions

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Intermediate</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vergence</strong></td>
<td><strong>X</strong></td>
<td><strong>Y</strong></td>
<td><strong>X</strong></td>
</tr>
<tr>
<td>Parallel</td>
<td>0.9 (1.9)</td>
<td>0.9 (1.7)</td>
<td>1.0 (2.1)</td>
</tr>
<tr>
<td>Converge 1°</td>
<td>2.5 (5.0)</td>
<td>0.7 (1.3)</td>
<td>2.2 (4.5)</td>
</tr>
</tbody>
</table>
CHAPTER 5

COMPOSITE CORRECTION OF HMD MISALIGNMENT

With an HMD, the operator may not always focus on the center of the displayed image. Most human eye movements are under ±15°. Viewing objects at a greater angle than this is usually accomplished with a combination of head and eye movements [24]. Even within this range, the misalignment in the HMD is not necessarily constant. When viewing objects at large angles, a different part of the optical system of the HMD is being viewed by the operator. The misalignment in these regions can be characterized with the alignment characterization system by rotating and translating the cameras to match eye pupil locations.

However, after characterization, the issue of correcting this off-axis misalignment is present. The operator may view objects with a large eye rotation, but also may view objects in the center of the display. Correcting the entire image for only one of these scenarios will degrade the alignment quality in other scenarios. Eye tracking could be utilized to track the region of the display the operator is viewing, and to dynamically adjust the misalignment correction currently implemented. This is computationally expensive, and eye tracking is not widely available for most HMDs.
Alternatively, correction maps could be selectively applied to the image in regions corresponding to the orientation in which they were measured. A correction map measured with a camera rotation of $0^\circ$ would be applied to the center of the image, and a correction map measured with a camera rotation of $10^\circ$ would be applied to the image at a location $10^\circ$ from the center. The image would not be simultaneously corrected for misalignment over the entire image, but would be corrected for the region of the image the operator was focused on. This method was used here to selectively correct HMD misalignment.

5.1 HMD Characterization

The HMD was first characterized using similar methods described previously in Chapters 2 and 3. The HMD used was the SA Photonics SA-62/S. The HMD was measured with the cameras in three configurations:

- No rotation (on-axis)
- $10^\circ$ yaw to the left
- $10^\circ$ yaw to the right

The HMD image moves laterally when undergoing a yaw rotation. Because of this effect, the external pattern must be placed much closer to the cameras to ensure that the captured HMD images are within the calibration area. The external pattern is no longer beyond the hyperfocal distance of the cameras. This is not a large issue due to the subpixel accuracy provided by the image registration algorithms.
The HMD image was captured in each of these three configurations. An overlay of the three captured HMD images after correcting for camera distortions and the keystone effect is shown in Figure 38.

![Image](image.png)

**Figure 38: Captured HMD image after camera calibration for 10° yaw to the left (red), 0° rotation (green), and 10° yaw to the right (blue)**

The misalignment was then characterized using the image registration methods described in Chapter 3. The correction maps for each of these three configurations is shown in Figure 39 for the horizontal direction and Figure 40 for the vertical direction.
Figure 39: Correction map in the horizontal direction for 10° yaw to the left (left), 0° rotation (center), and 10° yaw to the right (right)

Figure 40: Correction map in the vertical direction for 10° yaw to the left (left), 0° rotation (center), and 10° yaw to the right (right)

5.2 Composite Correction Map Generation

The composite correction map was created by combining the individual correction maps from each configuration into a single composite map. Each individual correction map was applied in the region in which it was captured (the 10° yaw correction map is applied to the region of the image 10° from the center). A filter was used to smoothly transition from one correction map to the other. The filter used was a logistic function:

\[
f = \frac{1}{1 + e^{-k(x-x_0)}}
\]  

(26)
Where \( f \) is the value of the filter at the current location, \( k \) is the slope of the filter, \( x \) is the horizontal pixel location, and \( x_0 \) is the central location of the correction map. The slope was set to 0.01 and the central location depends on the specific configuration. Various values for the slope were attempted, and 0.01 was utilized because it produced the most accurate composite correction map. Figure 41 shows the filters used for each individual correction map. The total value of all three filters sums to 1 across all locations.

![Filter values for left, center, and right correction maps](image)

**Figure 41: Filter values for left, center, and right correction maps**

The filter was applied to the three individual correction maps and they were added together to produce a composite correction map. Figure 42 and Figure 43 show a
comparison of the correction maps generated by measuring the HMD using only a 0° rotation configuration, and the correction maps generated using the compositing process. The magnitudes of the pixel displacement are much greater in the composite maps, indicating that the image must be warped more severely to correct aberrations when viewing off-axis.

Figure 42: Correction map in the horizontal direction for 0° rotation (left) and composite correction map (right)

Figure 43: Correction map in the vertical direction for 0° rotation (left) and composite correction map (right)
The composite correction map was applied to the SA-62/S HMD and evaluated subjectively. The checkerboard reference pattern used to characterize the HMD was displayed with the composite correction map applied. Operators reported that the shape of the checkers appeared very square across the field of view, and the size of the checkers appeared very uniform. When focused on a small region of the display, the checkerboard appeared very consistent and uniform across the entire field of view. When viewing large regions of the display, global variations in the checkerboard were noticeable, likely as the composite correction map transitioned from one individual map to another.

These subjective evaluations indicate that the composite correction map may be applicable and provide additional benefit in certain applications but not in others. When focused on small symbols in various regions of the HMD, as would be the case for HUD symbology, the composite correction process could provide uniform imagery display across the entire field of view. When viewing large imagery, the effects of compositing individual correction maps is noticeable and distracting. The use of this method can provide improved spatial misalignment correction for an HMD, but is only feasible for certain applications which do not require simultaneous visualization of large field of view imagery.
Imagery displayed on an augmented reality HMD must show sufficient contrast to the background of the outside world to be visible. If the luminance of the HMD is sufficiently brighter than the background, then the imagery will be visible. However, if the HMD is too bright relative to the background, then information in the outside world may not be visible. To evaluate these effects, the luminance of the HMD was calibrated. All of these measurements were carried out using the SA-62 HMD.

6.1 Calibration

The luminance of the HMD can vary over time due to temperature or humidity variations in the environment in which it is being used. To account for these effects, an apparatus was constructed to measure the luminance of the HMD. A spectrometer is used to measure the light output of the HMD versus wavelength, and the luminance is calculated from these measurements. The HMD slots into the apparatus, and is locked in space vertically, laterally, and longitudinally. This ensures that the location of the HMD relative to the spectrometer is fixed for all measurements. The spectrometer can be moved to measure either the left or the right oculars.
The spectrometer used was an Ocean Optics Maya2000 Pro. Its specifications are listed in Table 9. The image from the HMD is imaged onto the spectrometer slit using a 25 mm lens. An opaque barrel is used to set the lens at the correct standoff distance from the spectrometer slit.

Table 9: Ocean Optics Maya2000 Pro specifications [25]

<table>
<thead>
<tr>
<th>Spectral Range</th>
<th>165 – 1100 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>0.32 counts/e-</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>8000:1</td>
</tr>
<tr>
<td>Signal-to-Noise Ratio</td>
<td>450:1</td>
</tr>
<tr>
<td>Dark Noise</td>
<td>8.2 RMS counts</td>
</tr>
</tbody>
</table>

The spectrometer is not a true luminance meter, but is simple to align with the HMD and record measurements. To ensure that the correct luminance values are reported from this process, the spectrometer was calibrated against a Konica Minolta CS-200 chroma meter (specifications shown in Table 10), an instrument widely used for measuring luminance.
Table 10: Konica Minolta CS-200 chroma meter specifications [26]

<table>
<thead>
<tr>
<th>Measuring Angle</th>
<th>0.1, 0.2, or 1°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance Range (Measuring Angle of 1°)</td>
<td>0.01 – 200,000 cd/m²</td>
</tr>
<tr>
<td>Luminance Range (Measuring Angle of 0.2°)</td>
<td>0.01 – 5,000,000 cd/m²</td>
</tr>
<tr>
<td>Luminance Range (Measuring Angle of 0.1°)</td>
<td>0.01 – 20,000,000 cd/m²</td>
</tr>
<tr>
<td>Luminance Accuracy (0.01 – 1 cd/m²)</td>
<td>±0.02 cd/m² ± 1 digit</td>
</tr>
<tr>
<td>Luminance Accuracy (1 – 200,000 cd/m²)</td>
<td>±2% ± 1 digit</td>
</tr>
<tr>
<td>Luminance Repeatability (0.01 – 1 cd/m²)</td>
<td>±0.01 cd/m² ± 1 digit</td>
</tr>
<tr>
<td>Luminance Repeatability (1 – 8 cd/m²)</td>
<td>±0.5% ± 1 digit</td>
</tr>
<tr>
<td>Luminance Repeatability (8 – 200,000 cd/m²)</td>
<td>±0.1% ± 1 digit</td>
</tr>
</tbody>
</table>

The Konica Minolta CS-200 was aligned with the HMD and the luminance of the HMD was recorded at several different brightness settings. These values were compared to the spectrometer results to produce a calibration curve, as shown in Figure 44. The relationship between the spectrometer and chroma meter is linear, resulting in a simple calibration.
The stability of the spectrometer was also compared against a calibrated halogen light source (Ocean Optics HL-2000-CAL). A 1.25 neutral density filter was used to attenuate the light source and avoid saturation of the spectrometer. The results were very consistent across multiple days and across multiple measurements, as shown in Figure 45.
The calibrated spectrometer was then used to analyze the luminance of the HMD. The HMD luminance was measured to be fairly constant over a single day as shown in, but varies significantly with measurements between days as shown in Figure 46. For these measurements, the spectrometer was not moved between days to avoid introducing any alignment error, even if this effect would be small.

**Figure 45: Spectra of calibrated halogen light source measured across multiple days**

![Spectra of calibrated halogen light source measured across multiple days](image)

Counts

Wavelength (nm)
The luminance of the HMD was calibrated by recording the luminance of the HMD at several brightness (video level) settings. Independent calibrations are recorded for the left and right oculars, as they do not produce the same luminance levels. A calibration for a given day is shown in Figure 47. The calibration is produced using a polynomial fit. The shape of this curve is consistent across measurements from different days, but the absolute magnitude of the values changes. At the low and high ends of the display brightness settings, the curve flattens out, indicating that most of the luminance change occurs in the intermediate brightness settings.
The luminance of the HMD display is not necessarily constant over the full field of view of the display. To assess this effect, an instrument was needed that could characterize the spatial distribution of luminance. The PixeLINK cameras used previously in the alignment toolset were used for this purpose. The PixeLINK cameras were calibrated to measure luminance by recording measurements of a reflectance standard (Photo Research Model SRS-3), as shown in Figure 48. These values were then compared to those values to those recorded by the Konica Minolta CS-200. The target was recorded with varying levels of illumination and camera exposure time.
The resulting calibration is a function of source luminance and exposure time, and is shown in Figure 49. The use of these cameras as luminance meters is not extremely accurate, but provides a rough measurement of spatial distribution of luminance.
The HMD was then recorded using the PixeLINK cameras, and the luminance distribution was calculated. Figure 50 shows the raw image recorded of the HMD, and Figure 51 shows the resulting luminance calculation. Moire patterns are clearly visible due to the interaction between the HMD pixels and the camera pixels. The luminance is highest in the center of the display and is much lower at the edges. The maximum luminance is approximately 3 times higher than the minimum luminance.
Figure 50: Raw image of HMD
6.3 Projector Screen Luminance

The transparent HMD was utilized with background imagery displayed on a projector screen. The projector was a Christie Matrix StIM LED DLP projector (specifications shown in Table 11). The luminance of the screen was also calibrated to assess a contrast between the HMD and the screen.
Table 11: Christie Matrix StIM specifications [27]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>600 lumens</td>
</tr>
<tr>
<td>Uniformity</td>
<td>95% brightness and color uniformity</td>
</tr>
<tr>
<td>Resolution</td>
<td>1920 x 1200</td>
</tr>
<tr>
<td>Illumination</td>
<td>RGB + IR LEDs</td>
</tr>
</tbody>
</table>

A small target was displayed on the screen, covering between 1 and 21 pixels depending on the distance to the target. When the target was far away (covering between 1 and 5 pixels), the luminance of each individual pixel was measured using the 0.1° measuring angle of the Konica Minolta CS-200. For larger targets, the luminance of the entire target was measured using the 0.2° measuring angle.

The luminance of the target at the various distances was averaged over an area of 21 pixels (the largest target size evaluated), and is shown in Figure 52. The pixel fill factor (0.95) was incorporated for measurements involving individual pixels. The hitch in the curve at a target distance of 600 m occurs where the measuring process was switched from measuring individual pixels to measuring the full target. The brightest measurement for an individual pixel increases when multiple pixels are illuminated on the target. With a 1-pixel target, the brightest individual pixel is 16.2 cd/m² but this increases to 38.6 cd/m² with a 5-pixel target. The effect of luminance sensitivity to spatial pixel interaction has been previously documented [28].
Using these methods, both an HMD and a background source can be calibrated for precise luminance values. This enables accurate calculations of contrast between these two sources.
CHAPTER 7
CONCLUSIONS

7.1 Current Effort

A toolset was developed to measure and correct spatial misalignment in HMDs. This toolset consists of a hardware system with two cameras mounted to various rotation and translation stages. The system emulates the ocular position of most human observers through ten degrees of freedom (yaw and roll rotations of both cameras; pitch of the HMD; lateral, longitudinal, and vertical translation of both cameras; and yaw and lateral translation of each camera individually). Two HMDs were evaluated: the SA Photonics SA-62/S and SA-65.

The distortion present in the cameras was characterized first by recording a physical checkerboard pattern. The image of this pattern was matched to a reference image through an image registration process. The corners of the measured checkerboard pattern were identified and matched to the corners of the reference checkerboard pattern. A B-spline registration process was used to further refine the image registration. Once the camera distortion was characterized, it was removed from the HMD images so that only the misalignment present in the HMDs themselves was characterized.
Images captured on the HMD of a checkerboard pattern were matched to a reference image. The HMD images were undersampled at a value of 1 camera pixel for every 1.9 HMD pixels. Block matching was used to remove large horizontal translations between left and right HMD images, as these offsets can easily be removed by the vergence of the human ocular system. The keystone effect was removed from images captured with yaw or pitch rotations. The relative misalignment between the left and right images was calculated using the difference between the warp map used to match the left image to the reference and the right image to the reference. The measurements were repeatable to a standard deviation of 0.8 HMD pixels.

For both HMDs measured, very little misalignment was present in the HMDs near the center of the display. The misalignment was higher near the edges and corners of the display. Small off-axis rotations of 1° in yaw, pitch, or roll did not have a large effect on the relative misalignment. However, introducing a vergence angle did have a significant effect on the relative misalignment. This effect was especially pronounced at the edges of the display. The relative misalignment present in the SA-62/S was corrected by applying a warp map corresponding to the measured misalignment. Recharacterizing the HMD after correction produced much lower relative misalignment when compared to no correction or to the manufacturer-supplied correction. This result was expected as only the warp map created here accounts for differences in the left and right images.
The misalignment present in the HMDs is not constant, but rather changes depending on which part of the display the operator is viewing. A method was developed here to correct the misalignment in different regions of the display by blending warp maps together to create a composite correction for the HMDs. This method did improve the uniformity of the display in local regions, as the composite warp map is tailored to several regions of the display rather than only one. This improvement in local regions does come at the cost of noticeable variations in the global image. Whether or not this tradeoff is acceptable depends on the application and operator preference.

The luminance variation in HMDs was also characterized using a spectrometer and a camera. Both of these devices were first calibrated using a Konica Minolta CS-200 chroma meter. The luminance of the HMD varies from day to day, and the approach used here enables rapid calibration of the HMD luminance for each day. The luminance of the display is also not constant across the field of view. The luminance in the center of the display is approximately three times higher in the center of the display versus the corners.

7.2 Future Work

The methods developed here are generally applicable to any HMD, not to a specific HMD platform. This toolset can be used to characterize new HMD platforms and introduce correction methods for these HMDs, not only for viewing directly on-axis but also for cases in which the HMD is not perfectly aligned with the operator, or for when the operator is viewing the HMD off-axis.
With the relative misalignment in HMDs characterized, the effects of this misalignment on human operators could now be characterized. There may be limits of misalignment that are not tolerable for most human observers, and there may be types of misalignment that do not cause significant issues for operators. The answers to these questions are currently unknown or have widely varying results [2, 4].
REFERENCES


[22] A. Myronenko, Non-rigid image registration, regularization, algorithms and applications, Oregon Health & Science University, 2010.


