9.3-5

Correcting Luminance for Obliquely-Projected Displays

Robert ULICHNEY[1], *Senior Member IEEE*, and Rahul SUKTHANKAR[2], *Member IEEE*
[1]Hewlett-Packard Co, Cambridge, MA [2]Intel Research Pittsburgh, PA

Abstract-- **Oblique projection geometry is a major factor in display luminance non-uniformity. Feedback from an arbitrarily-positioned camera is used to find homography transformations between projector and screen. From this we determine the ratio of pixel areas to flatten the illumination field.**

I. INTRODUCTION

Projection-based products are becoming a competitive alternative for HDTV display. In most home environments, it is impractical to orient a projector perpendicularly to the screen. Oblique projection affords less awkward placement of the product, and can drastically reduce inadvertent shadows by viewers. Two important problems need to be solved before oblique front projection becomes practical: (1) correcting the image distortion, and (2) eliminating the display luminance non-uniformity caused by the oblique geometry -- since points on the screen that are closer to the projector will be brighter than points farther away. Earlier research [1, 2] has addressed the first problem, however very little has been reported on approaches for the second. A recent study [3] measures a single sample screen of the projector assuming a calibrated camera; with a single measurement, the response of the projector across all image levels cannot be known nor properly accounted for.

The method proposed in this paper does not require a photometrically-calibrated camera, as we only use the camera to measure geometry. In the case of display walls, one approach, [4] accounts for the luminance error caused by areas of overlap but ignores the problem of oblique projection. For the oblique projection scenario, the geometric distortion alone can be the largest contributor to non-uniformity. This paper describes an efficient method for eliminating this type of non-uniformity without requiring any measurement of projector output. The solution presented here can be implemented in commodity projectors display products.

II. METHOD FOR CORRECTING OBLIQUE PROJECTION

This section describes the system for generating an attenuation array to account for the differences in pixel brightness due to oblique projection by using a video camera to sense the geometry of the display and screen. To do this we first need to determine the transform relating projector coordinates to screen coordinates. Knowing this transform, we then find the relative area of a projected pixel. From this we can generate the attenuation array used to modify all projected pixels so that they have the same value as the dimmest pixel.

Fig. 1 shows an arbitrary placement of both camera and projector. Since the camera does not see an undistorted view of the projection screen, ${}_p\mathbf{H}_s$, the 3x3 homography transformation from projector to screen coordinates, cannot be computed in a single step. We assume that the camera is able to view a rectangle of known aspect ratio, for instance, the boundaries of a

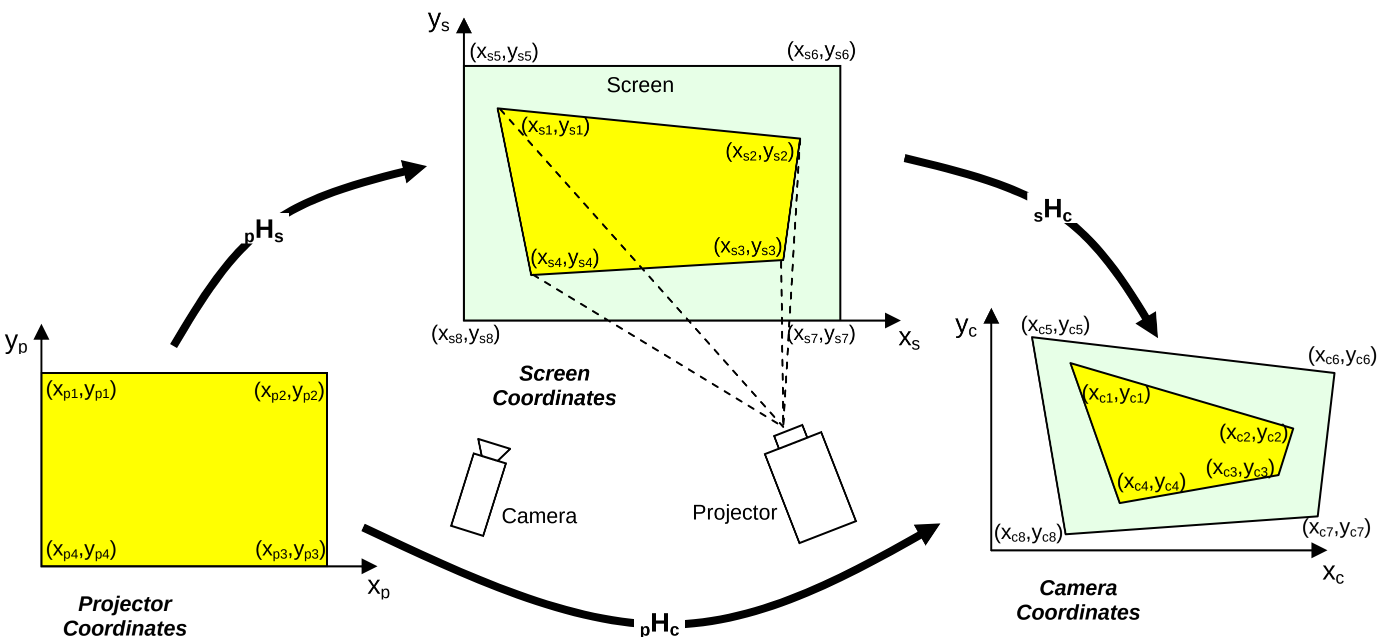

Fig. 1. Oblique display due to an off-axis projector with an off-axis camera. ${}_p\mathbf{H}_s = {}_s\mathbf{H}_c^{-1}\,{}_p\mathbf{H}_c$

physical screen. Although the positions of the camera, projector and screen are all unknown, we can recover ${}_p\mathbf{H}_s$ by composing sequences of homographies, as described below.

First, we observe that the mapping from projector to camera coordinates (${}_p\mathbf{H}_c$) can be decomposed into a mapping from projector to screen (${}_p\mathbf{H}_s$) followed by a mapping from screen to camera (${}_s\mathbf{H}_c$). This gives us the relationship: ${}_p\mathbf{H}_s = {}_s\mathbf{H}_c^{-1}\ {}_p\mathbf{H}_c$. Both of the homographies on the right hand side of this equation can be determined from known point correspondences. The ${}_p\mathbf{H}_c$ computation uses the four points defined by the projection area, where (x_c, y_c) refer to camera coordinates:

$$(x_{p1}, y_{p1}) \leftrightarrow (x_{c1}, y_{c1})\ ;\ (x_{p2}, y_{p2}) \leftrightarrow (x_{c2}, y_{c2})$$
$$(x_{p3}, y_{p3}) \leftrightarrow (x_{c3}, y_{c3})\ ;\ (x_{p4}, y_{p4}) \leftrightarrow (x_{c4}, y_{c4})$$

The ${}_s\mathbf{H}_c$ computation uses the four points defined by the physical projection screen:

$$(x_{s5}, y_{s5}) \leftrightarrow (x_{c5}, y_{c5})\ ;\ (x_{s6}, y_{s6}) \leftrightarrow (x_{c6}, y_{c6})$$
$$(x_{s7}, y_{s7}) \leftrightarrow (x_{c7}, y_{c7})\ ;\ (x_{s8}, y_{s8}) \leftrightarrow (x_{c8}, y_{c8})$$

Note that we do not need to know the actual dimensions of the projection screen -- simply its aspect ratio. This is because the units of measurement for screen coordinates are arbitrary, enabling us to use:

$$(x_{s5}, y_{s5}) = (0, \alpha)\ ;\ (x_{s6}, y_{s6}) = (1, \alpha)$$
$$(x_{s7}, y_{s7}) = (1, 0)\ ;\ (x_{s8}, y_{s8}) = (0, 0)$$

where α is the screen's aspect ratio, expressed as the X dimension over the Y dimension.

Once ${}_p\mathbf{H}_c$ and ${}_s\mathbf{H}_c$ have been determined (by solving the linear equations), computing ${}_p\mathbf{H}_s$ requires only a few matrix operations.

If we assume that each pixel is equally illuminated inside the projector, then the non-uniformity in luminance due to oblique projection is precisely related to the relative area of the projected pixel. In other words, pixels that subtend a large area are dim, while pixels that project onto a small area are bright. This section describes how we can determine the relative area of a projected pixel, provided that the homography between projector and screen (${}_p\mathbf{H}_s$) is known.

First, we observe that we are only interested in the ratios of areas between different pixels. This allows us to express the area of a pixel in any arbitrary units. The ratio of the areas between two projected pixels is given by the ratio of the Jacobean of the mapping. For homographies, this reduces to:

$$\frac{S(x_{pi}, y_{pi})}{S(x_{pj}, y_{pj})} = \frac{\left|h_7 x_{pj} + h_8 y_{pj} + h_9\right|^3}{\left|h_7 x_{pi} + h_8 y_{pi} + h_9\right|^3}$$

where $S(x_{pi}, y_{pi})$ is the area of a projected pixel at location (x_{pi}, y_{pi}), $S(x_{pj}, y_{pj})$ is the area of a projected pixel at location (x_{pj}, y_{pj}), and h_7, h_8, h_9 are the elements in the third row of the projector-screen homography matrix, ${}_p\mathbf{H}_s$.

The goal is to arrive at an attenuation value at each pixel location so that all pixels will have the value of the dimmest pixel. (We can only take light away, as opposed to creating more light.) The dimmest pixel is that with the largest pixel area. If the largest pixel were positioned at (x_{pj}, y_{pj}), then the above ratio would be the attenuation value for a pixel at location (x_{pi}, y_{pi}). So the problem reduces to finding the location of the largest pixel.

For each pixel in projector space (x_p, y_p), we define a value

$$w(x_p, y_p) = |h_7\, x_p + h_8\, y_p + h_9|.$$

From the above ratio, it follows that the largest $S(x_p, y_p)$ will have the smallest $w(x_p, y_p)$. We record the smallest $w(x_p, y_p)$ as w_d, which corresponds to the dimmest projected pixel. The entries in the attenuation array to correct for oblique geometry are thus given by:

$$a_o(x_p, y_p) = [\, w_d / w(x_p, y_p)\,]^3$$

The attenuation, a_o, will have a value of 1 at the location of the dimmest pixel, and a value less than one everywhere else.

III. RESULTS

The run time system incorporating this attenuation array would simply multiply input pixels to the projector by the attenuation value corresponding to the pixel address. The result of this operation is shown in Fig. 2. In this figure, the relative luminance is indicated by the closeness of the grid lines. Because of the nonrectangular shape, appropriate source pixels in the corrected projection are blanked so that the regions as indicated are not displayed resulting in a projection that has both uniform luminance and a rectangular active region.

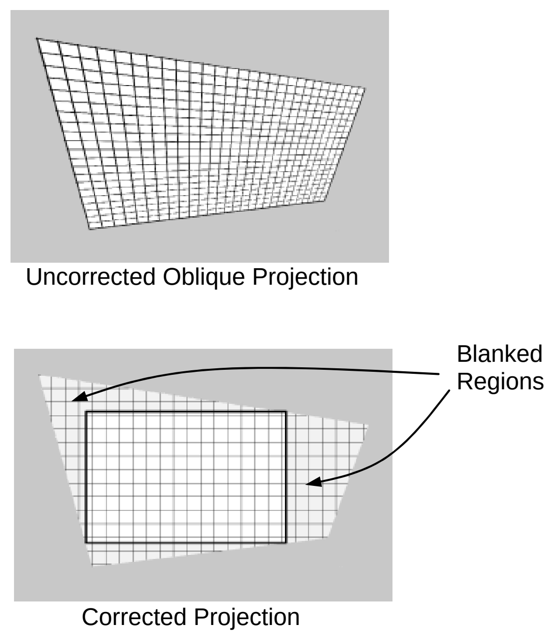

Fig. 2. Original uncorrected projection, and the resulting projection with uniform luminance.

REFERENCES

[1] Sukthankar, R., R. Stockton, M. Mullin. "Smarter Presentations: Exploiting Homography in Camera-Projector Systems", *Proceedings of International Conference on Computer Vision*, 2001.

[2] Raskar, R. "Immersive Planar Display Using Roughly Aligned Projectors", Proceedings of IEEE Virtual Reality, 2000.

[3] Majumder, A., R. Stevens, "LAM: Luminance Attenuation Map for Photometric Uniformity in Projection Based Displays", *ACM Symposium on Virtual Reality Software and Technology* (VRST), Nov. 11-13, 2002.

[4] Majumder, A., R. Stevens, "Color Non-Uniformity for Projection Based Displays: Analysis and Solutions", *IEEE Transactions on Visualization and Computer Graphics*, 10(2), 2004.