A unified calibration method with a parametric approach for wide-field-of-view multiprojector displays

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A Unified Calibration Method with a Parametric Approach for Wide-Field-of-View Multiprojector Displays

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Abstract

In this paper, we describe techniques for supporting a wide-field-of-view multiprojector curved screen display system. Our main contribution is in achieving automatic geometric calibration and efficient rendering for seamless displays, which is effective even in the presence of panormic surround screens with the multiview calibration method without polygonal representation of the display surface. We show several prototype systems that use a stereo camera for capturing and a new rendering method for quadric curved screens. Previous approaches have required a calibration camera at the sweet spot. Due to parameterized representation, however, our unified calibration method is independent of the orientation and field of view of the calibration camera. This method can simplify the tedious and complicated installation process as well as the maintenance of large multiprojector displays in planetariums, virtual reality systems, and other visualization venues.


1 Introduction

A display system should fulfill at least two requirements in order to obtain a vivid immersive sensation: first, the displayed imagery should occupy as much as possible of the user’s view at high resolution; and second, the imagery should appear seamless.

Over the past several years there have been various reports on the use of projectors for scalable display systems [1, 4, 5]. To create seamless display systems using multiple projectors, the projectors need to be aligned geometrically and to provide uniformity of both intensity and color across the entire display. In the case of immersive applications, it is important to present perspectively correct imagery at the users’ eye position, or sweet spot.

In this paper we present a multiprojector display system capable of creating seamless, high resolution imagery on quadric, wide-field-of-view display surfaces using a proposed unified automatic projector-alignment method.

2 Concept of Correcting Image

The principal concept of correcting image distortion is to apply the inverse of the distortion caused by projection on the curved screen [2, 3]. The calculation of inverse distortion is equivalent to finding a mapping function \( \Psi_{vs} \) from a pixel position \( x \) in the camera to a corresponding pixel position \( x' \) in the projector. Suffix \( i \) indicates the projector index, and suffix \( \hat{c} \) indicates the camera coordinate system. The direction of mapping is from camera \( \hat{c} \) to projector \( i \). In addition, \( e \) or \( v \) indicates the eye position, also referred to as a virtual camera [2], and \( r \) denotes the reference coordinate system.

3 Calibration Using Multiple Images Captured From Different Locations

In the case of wide-field-of-view or spherical screens, it is difficult, if not impossible, to fit the entire screen within a single camera view.

We extend the calibration method to one using multiple images from different camera locations, so that the entire screen is covered. The camera images have an overlapping area that includes part of the projectors’ overlapping area. The captured images with the overlapping area can then be used to unify differently reconstructed 3D points into a unified 3D coordinate system. We refer to this approach, which requires several camera images at different locations, as the multiview calibration method.

Given \( I \) projectors and \( S \) cameras, the goal is to calculate the mapping functions \( \Psi_{vs} \) to align the projectors and correct for image distortion. Our method consists of three steps. The first step is to determine the screen geometry \( Q \) for the entire display surface. The next step is the derivation of the mapping functions \( \Psi_{vs} : (s = 1 \cdots S, i = 1 \cdots I) \). Finally, in the third step, \( \Psi_{vs} \) is transformed into \( \Psi_{cp} \) using virtual camera method.

The calculated mapping function has a variety of errors and cannot be applied directly to image distortion. Using \( A_{vs}, E_{vs}, e_v \) computed in the previous step as the initial values [2, 3], we can improve the precision of the parameters by minimizing the following cost function \( C_v \):

\[
C_v = \sum_k \left| \hat{x}_{vs}^k - \hat{x}_{vs}^k \right|^2,
\]

where \( \hat{x}_{vs}^k = P_v X_{vs}^k \) and

\[
\hat{x}_{vs}^k = A_{vs} X_{vs}^k \pm \left( \frac{k}{(x_p^k)^2 E_{vs}(x_p^k)} \right) e_v.
\]

That is, \( A_{vs}, E_{vs}, \) and \( e_v \) that minimize Eq. (1) are found using known \( \hat{x}_{vs}^k \) and \( x_p^k \).

The projective matrix \( P_v = K_v I / 0 \) is a virtual one so that it can
be defined mathematically with zero error. In addition, we reconstructed $X_{pi}^{D,k}$ using the stereo camera so that the virtually projected point $x_k^i$ has higher accuracy than the estimated point $\tilde{x}_k^i$. We believe that using $x_k^i$ as a reference is reasonable.

In the final step, the mapping function $\Psi_{ep}$ from projector $p_i (i = 1 \cdots I)$ to the actual eye ‘e’ (i.e., $v_0$) is calculated. Each mapping function $\Psi_{ev_i} (s = 1 \cdots S, i = 1 \cdots I)$ has already been calculated, so that if we can find mapping function $\Psi_{ep}$, we can calculate the actual mapping function $\Psi_{ep}$ using Eq. (2):

$$\Psi_{ep} = \Psi_{ev_i} \Psi_{ev_i} (s = 1 \cdots S, i = 1 \cdots I).$$

The relative position and orientation of the reference virtual camera and eye can be geometrically calculated using the virtual camera method so that mapping function $\Psi_{ev_i}$ from the reference virtual camera to the eye ‘e’, i.e., reference virtual camera $v_0$, is calculated.

4 Prototyping of display system and evaluation

4.1 Display system

Figure 2(a), (b), and (c) shows a wide-field-of-view cylindrical display system to which the unified calibration method has been applied. Image generation is carried out in the PC cluster, and real-time distortion correction is carried out on the GPU of the commodity graphics boards, implemented as a two-pass rendering approach.

4.2 Evaluation

As shown in Table 1. The current worst-case ratio of error between projectors is about 0.20% (12 mm) on screen, which is equivalent to 2 pixels. Although the worst geometric misregistration error of 12 mm might give a negative impression of our method, in reality this is not the case for the following reasons:

1. The worst-case error in the overlapping area occurs in a very small region and is located near the edge of the screen.
2. This error can be further reduced by increasing the projector’s resolution and decreasing the projection distance of the projector with respect to the surface.
3. These geometric discrepancies between projectors are reduced with intensity blending.

Figure 2(d), (e), and (f) shows several other applications of this unified calibration method to different types of quadric screens. This method allows various types of screens to be calibrated, regardless of the size, field of view, and projection type.

Table 1: Performance of calibration for each projector with line pattern (Projecting image of 6 meters length)

<table>
<thead>
<tr>
<th>Projector No.</th>
<th>Mean error in pixels (Number of measured points)</th>
<th>Maximum ratio of error to projecting length [%] in overlapping area (Measurement error [mm])</th>
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<tbody>
<tr>
<td>1</td>
<td>0.243 (178)</td>
<td>0.07 (4.0)</td>
</tr>
<tr>
<td>2</td>
<td>0.223 (121)</td>
<td>0.13 (8.0)</td>
</tr>
<tr>
<td>3</td>
<td>0.260 (218)</td>
<td>0.20 (12.0)</td>
</tr>
<tr>
<td>4</td>
<td>0.223 (231)</td>
<td>0.05 (3.0)</td>
</tr>
<tr>
<td>5</td>
<td>0.292 (232)</td>
<td>–</td>
</tr>
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5 Conclusion and future work

In this paper, we describe a unified automatic geometric calibration approach for displays on parametric screens. In particular, we show that even for wide-field-of-view display systems, we can use a simple pair of cameras and compute geometric and photometric parameters for quadric curved screens. We believe that this is the first auto-calibration system for a wide-field-of-view system, and that it eliminates the camera-at-sweet-spot problem. We have successfully built several prototypes with the proposed approach.

In the future, we would like to modify the quadric assumption to support a wider variety of curved screens. We can also apply a maximum likelihood method for optimization of the mapping function so that it is more robust to screen deviations and image noise.

We hope that by reducing the complexity of installing and maintaining curved display systems, virtual reality and visualization can be used in more casual settings.

References