

Automatic Registration of Multi-Projector on Parameterized Surface in Two-Dimensionality

Shuaihe Zhao* and Shuling Dai

The State Key Laboratory of VR Technology & Systems, Beihang University, Beijing 100191, China

*Corresponding author

Abstract—Multi-projector, large scale displays are used in scientific visualization, virtual reality, and other visually intensive applications. A number of camera based techniques have been proposed to register the geometry of planar displays in two-dimensionality and non-planar displays in one-dimensionality. This paper put forward a method of geometric registration for curved display in two-dimensionality. Gray code structured light images projected are used as feature of the curved screen. Two pairs of binocular-camera are used to capture feature points which need to be reconstructed in three-dimensional. Projection transformation between each projector and curved screen is calculated to gain pre-warp template. By projecting the pre-warp template, a geometrical seamless projection can be made.

Keywords—multi-projector; seamless display; geometric registration; Gray code; calibration

I. INTRODUCTION

Tiling multiple projectors on non-planar displays is a common way to build high resolution, wide field of view and large-scale vision system in virtual reality. In this vision system, viewer can receive immersive visual experience with their eyes not from equipment on the head which will make them uncomfortable. Multi-projector system is achieved by overlapping projections with each other and can form a seamless rendering view. To calibrate the geometric distortions of projection on curved surface and to align and blend the overlapped parts of the projections are the challenges. In this paper, we propose a camera-based technique to deal with seamless display on curved surface in two-dimensionality.

Some work on multi-projector tiled displays uses planar surfaces, which can simplify geometric correction and alignment. In commercially available planar displays, alignment is typically performed manually. However, many research groups have exploited camera-based approaches to automate this process [1-3]. Recent high resolution projector developments ease the use of multi-projector in planar display, but in curved screens multi-projector alignment has the significance of research.

To solve the geometric correction and alignment, camera is brought into the projector system to observe the screen. Homography is used to model the camera perspective and transfer points on the screen surface to the projector's frame buffer [4-7]. For tackling non-planar surfaces, especially quadric surfaces such as domes, cylindrical screens, ellipsoids, or paraboloids, Raskar et al. proposed conformal mapping and quadric transfer to minimize stretching of projected image

pixels on the surfaces. Harville et al. attempted to eliminate the geometric correction and alignment by attaching physical fiducial points to part of the screen with camera [8-9]. But the physical fiducial is excrescent on the screen. Then structured light for the camera-projector system is used to achieve the registration. In this method, calibration of the camera-projector system and 3D reconstruction of the display surfaces can be achieved without physical fiducial [10-12]. These work, however, projected on curved surface tackle the problem in one-dimensionality, like tiling multiple projections in horizontal on the curved screen.

The work presented in this paper adopts binocular vision to achieve the registration of multi-projectors on parameterized surface in two-dimensionality. It proposes a novel geometric calibration approach based on Gray code structured light, with two major advantages. First, the cameras of binocular vision only need to capture part of each projection on the screen not the whole, which can be suitable for capturing the pictures on large screens. Secondly, the new method enables the geometric correction and alignment of multi-projector in two-dimensionality, like three projections in one row meanwhile two rows in vertical.

II. GEOMETRIC REGISTRATION

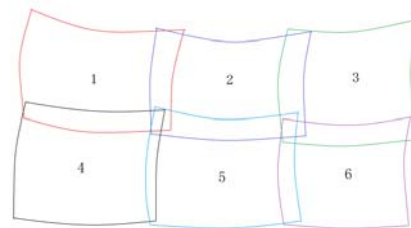


FIGURE I. MULTI-PROJECTOR IN TWO-DIMENSIONALITY.

When using multi-projector in two-dimensionality as shown in figure 1, the curved screen is always large enough to load all the projections that the camera generally cannot capture the whole projections. Each texture projected on the curved screen is warped and the overlapping between projectors is diverged. The issue is how to generate images projected on curved screen that appear correctly to the viewer. The principle of our algorithm is as shown in figure 2.

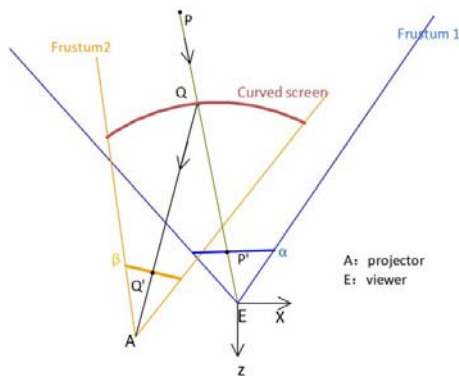


FIGURE II. PRINCIPLE OF THE ALGORITHM.

Point E represents the location of the viewer and point A represents the location of the projector. The models of view and projector are established as frustum 1 and frustum 2 respectively. A point P in space, which can be seen at point E , images at point P' on the plane α in frustum 1 and passes point Q on the curved screen. Point Q images at point Q' on plane β in frustum 2. Then reverse the process, the projector projects point Q' to the curved screen at point Q , which can be seen by the viewer at point E , indicated the image of point P . The work in this paper is to create the projected texture which is customized to the shape of the curved screen and consistent with our viewing experience. We create a 3D mesh M of the curved screen surface in frustum 1, then compute texture coordinates U of M in frustum 2, thereby find a mapping M^Π of M on β plane.

This section describes how to display an image that has minimum distortion over the curved screen. First consider a plane surface projection, the solution is to project images as if the audience is viewing the projection in a fronto-parallel fashion, and this is achieved by keystone correction when the projector is skewed. Then consider a curved surface projection. Intuitively, we wish to 'wallpaper' the image onto the curved surface, so that locally each point on the curved surface is undistorted when viewed along the surface normal. The normal may vary, so a map that minimizes the distortion needs to be compute. In our research conformality is used as a measure of distortion. The input image is a 2D texture on α plane, the pre-warp image is the 2D texture in β plane, and meanwhile their corresponding area on the curved screen is a 3D mesh. The conformal map between the 2D texture and the corresponding 3D mesh on the display surface is angle preserving. Our research minimizes angle deformation and non-uniform scaling between the 2D textures and their corresponding regions on the 3D surface. The steps of our algorithm are as follows:

- Project structured light from the projectors, capture images with two pairs of calibrated cameras.
- Compute the parameterization model of the curved screen from the feature points captured.
- Resolve parameters of the projectors.

- Create a 3D mesh M of the curved surface from the viewpoint, compute texture coordinates U of M , thereby finding a mapping M^Π of M on β plane.
- Render M from the viewpoint of the projector using U as the texture coordinates.

III. FEATURE POINTS CAPTURE

Multi-projector system in the case of two-dimensionality projection is hard to capture and reconstruct the feature points. Since the overlapping parts of adjacent projections distribute in vertical and horizontal direction, a two pairs of calibrated cameras method is employed to capture the overlap. This two pairs of cameras are located in the horizontal direction as shown in figure 3. Binocular-camera 1 captures four projections on the left meanwhile binocular-camera 2 captures four projections on the right. Thereby each projection on the curved screen has a portion of image to be observed by the cameras.

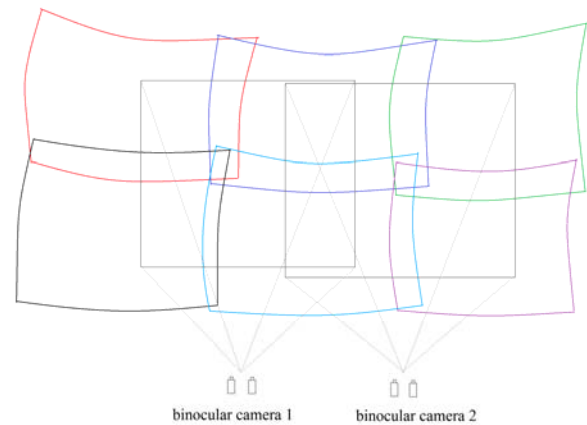


FIGURE III. BINOCULAR CAMERA.

In the multi-projector system, the curved screen needs to be clean without physical markers. Hence we employ the structured light images as the feature to be captured by the cameras.

Gray code is used to code the structured light images. The Gray code is an ordering of the binary numeral system such that two successive values differ in only one bit. A set of Gray code image is decoded as a gray grading image which has different gray stripes. An example of 4 bits Gray code image decoding to a gray grading image is shown in figure 4.



FIGURE IV. GRAY CODE IMAGE DECODE TO GRAY GRADING IMAGE.

The black and white grids represent 0 and 1 respectively in the binary picture of Gray code. The Gray code for decimal 0

rolls over to decimal 15 with only one switch change, so the coding has excellent anti-interference performance.

The processes of the feature capturing are as follows and shown in figure 5.

- Design a sequence of images coded in the Gray code.
- Project the sequence of Gray code images from the projectors to the curved screen.
- Capture images by the calibrated camera.
- Gain a gray grading image by decoding the Gray code images.

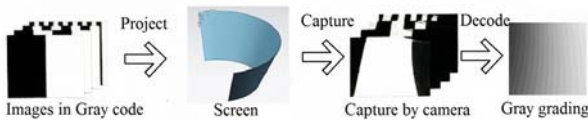


FIGURE V. PROCESSES OF FEATURE CAPTURING.

The Gray code images correspond to the gray grading images respectively in landscape and portrait orientation for each projector. The crossover points of the gray grading edges are the feature points to be captured. For each gray grading image, the number of the gray grades is 2^R , where R is the bit of the Gray code. The gray value of the n th gray grade is $n \cdot 2^{8-R}$, if the value was decoded as G , n can be obtained,

$$n = \frac{G}{2^{8-R}} \quad (n \in \{0, 1, 2, \dots, 2^R - 1\}) \quad (1)$$

The frame buffer coordinate of the n th gray grade's edge which neighbors the lower gray grade is

$$c_i = n \cdot 2^{-R}, \quad 0 \leq c_i < 1 \quad (2)$$

Put (1) into (2), the value of c_i can be gained:

$$c_i = G / 256 \quad (3)$$

It thus appears that, for the same projector the feature points captured by the binocular cameras can be matched simply because the corresponding points have the same value of the gray grade.

IV. CALIBRATION

In this multi-projector system, two pairs of cameras are used to capture the feature points projected on the curved screen. With these feature points, three components can be calculated: 1) the coordinates of the feature points in space, 2) unified coordinate frame of different binocular cameras, and 3) the projectors' parameters.

A. Three-Dimensional Reconstruction

The model of binocular camera can be regarded as two arbitrary perspective views. Mapping between two arbitrary perspective views of an opaque quadric surface in 3D can be expressed using a quadric transfer function, ψ . While a planar transfer can be computed from 4 or more pixel correspondences, quadric transfer requires 9 or more correspondences. If a homogeneous point in 3D, X (expressed as a 4×1 vector) lies on the quadric surface Q (expressed as a symmetric 4×4 matrix), then $X^T Q X = 0$ and the homogeneous coordinates of the corresponding pixels x in the first camera and x' in the second camera are related by

$$x' \cong Bx - \left(q^T x \pm \sqrt{(q^T x)^2 - x^T Q_{33} x} \right) e \quad (4)$$

Given pixel correspondences (x, x') , this equation is traditionally used to compute the 21 unknowns: the unknown 3D quadric $Q = [Q_{33} \quad q; q^T \quad 1]$, a 3×3 homography matrix B and the epipole in homogeneous coordinates, e . The epipole is the image of the center of projection of the first camera in second camera. Then remove part of this ambiguity by defining

$$A = B - eq^T \quad E = qq^T - Q_{33} \quad (5)$$

and obtain the form,

$$x' = Ax \pm e\sqrt{x^T Ex} \quad (6)$$

Here $x^T Ex = 0$ defines the outline conic of the quadric in the first camera and A is the homography via the polar plane between the second and the first camera. Note that this equation contains (apart from the overall scale) only one ambiguous degree of freedom resulting from relative scaling of E and e . This can be removed by introducing an additional normalization constraint, such as $E(3,3) = 1$ [6]. Further, the sign in front of the square root is fixed within the outline conic in the image. As the internal parameters of the two cameras are known, a triangulation of corresponding pixels and a linear method are used to calculate parameters of quadric transfer $\{A, E, e\}$. Involve estimating the quadric Q directly from point correspondences.

B. Coordinate Frame Unifying

In this system, two binocular-camera pairs are used to observe the projected imagery. Typically, each binocular-camera pair is established for specific projectors and has its own coordinate frame. Note that the different portions of the screen surface observed by different binocular-camera pairs have overlapping area. The different coordinate frames can be unified using the feature points in the overlapping area.

We define the coordinate frame of binocular-camera pair C_1 as the global coordinate frame. The overlapped area of two binocular-camera pairs lies in the same projectors, thus both binocular-camera pairs C_1 and C_2 can see the feature points of the projector P_i . Then using the feature point correspondences (X, X') acquired in the overlapping region between C_1 and C_2 , an ideal transformation consisting of a rotation R_{jf} , a translation T_{jf} and a scale S_{jf} can be computed to bring C_1 and C_2 into alignment.

$$S_{jf} X' = R_{jf} X + T_{jf} \quad (7)$$

Matching the feature points correspondences by the gray grade value, construct the following objective cost function

$$\varepsilon = \sum_i \|X_i' - \tilde{X}_i\|^2 \quad (8)$$

Here $\tilde{X}_i' = (R_{jf} X_i + T_{jf}) / S_{jf}$. So R_{jf} , T_{jf} and S_{jf} can be estimated by iterative optimization algorithm, that C_2 can be computed in the same coordinate frame with C_1 .

C. Projector Modeling

In this multi-projector system, each projector has its own matrix H_{pj} which reflects the transformation between reconstruction points X_i in space and correspondences points x_i on the projection plane as follows:

$$x_i = H_{pj} X_i \quad (9)$$

According to projection geometry, for the projector P_j , a transformation consisting of a rotation R_{pj} , a translation T_{pj} and a projection matrix K_{pj} can be obtained by QR decomposition of matrix H_{pj} .

$$H_{pj} = K_{pj} [R_{pj} | T_{pj}] \quad (10)$$

The projection matrix K_{pj} is an upper triangular matrix and the rotation matrix R_{pj} is an orthogonal matrix.

V. GEOMETRIC DISTORTION REGISTRATION

To register geometric distortion, three components have been known: 1) a 3D model of the display surface, 2) the projectors' perspective (in the form of a view frustum with respect to the curved surface), and 3) the viewer's perspective (with respect to the curved surface). The method of mosaic a

seamless multi-projector system in two-dimensionality is shown as follows:

First step, since the 3D model of the display surface is known from the reconstruction points, render a 3D mesh M of the curved screen using the viewer's perspective specified.

Second step, for each projector, map the correspondences portion M_{pj} of the 3D mesh to the projection plane by the transformation H_{pj} , then the pre-warp template m_j in 2D is obtained.

Third step, through projecting the pre-warp template m_j , a geometric seamless image can be seen at the location of the viewer. An example is shown in figure 6.



FIGURE VI. EXAMPLE OF MOSAIC.

Note that these calculations are registered to a common coordinate frame.

VI. CONCLUSION

Multi-projector is showing the potential to create a high resolution and wide view field vision system applied to virtual reality or entertainment. The capability of automatic geometric alignment of multiple projected images eases the setup and reduces the cost of large scale vision system. This paper has investigated how to register geometric distortion of multi-projector in two-dimensionality on curved screen with two binocular cameras. From this method, it can create a seamless display that adapts to the surfaces.

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