Automatic Geometry Calibration for Multi-Projector Display Systems with Arbitrary Continuous Curved Surfaces

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Abstract: A large-scale multi-projector display system offers high resolution, high brightness and immersive visualization for realistic experience to end users. It has been demonstrated to be effective tackling the conflict between the increasing demands of super-resolution display and the resolution limitation of a single display system. However, there is still no standardization method for curved surface projection screen. In this paper, we propose a novel approach for calibrating multi-projector display systems which have curved surfaces. Firstly, based on a detailed analysis on arbitrarily curved surfaces, we present a 3D reconstruction algorithm based on Bezier surface models. Then, for fully utilizing the projection area of each projector, we propose a novel curved-surface stitching algorithm to achieve geometry seamlessness of multi-projector display systems. Experimental results show that by constructing local Bessel models for the curved screen, the proposed method performs better than traditional approaches, i.e., the new method achieves geometric calibration with higher accuracy. The proposed method of modelling projection screen and the corresponding automatic geometric correction scheme effectively increase the utilization ratio of the original projection area of each projector and improve the calibration accuracy of multi-projector system with continuous curved surface.

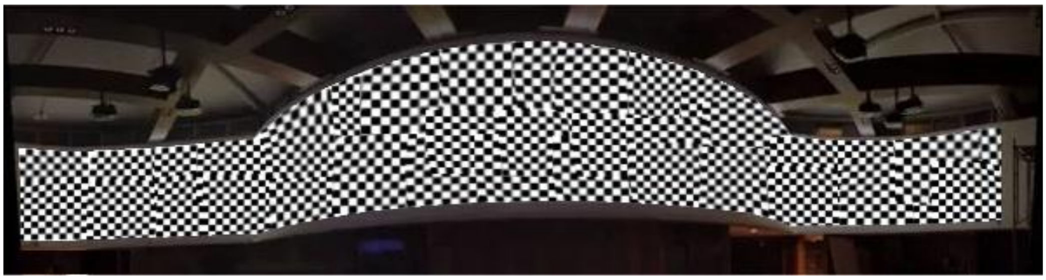
1. Introduction

With the widespread demands of ultra-high-resolution display platform, multi-projector display walls have attracted attentions from various fields, such as multimedia digital display system design, immersive visualization and entertainment, scientific dynamics applications, etc. Traditional large screen display systems are mostly constructed by several CRT (Cathode Ray Tube) or LCD (Liquid Crystal Display) panels, which cannot realize real seamless effect, but can satisfy some practical requirement and still occupy a larger market share [1]. In recent years, through integrating the projection capabilities of multiple projectors, multi-projector display wall technologies are used for high-resolution large screen display systems. The two key problems of multi-projector display wall are geometry calibration and colour correction of the output images [2-3]; and this paper focuses on the former. Geometry calibration refers to the process of evaluating and correcting the geometric distortion of the output images on the display wall [4], which usually requires image capture using cameras as well as a feedback loop.

In this paper, we present a general automatic geometry calibration method for multi-projector display walls with arbitrary continuous curved surfaces. Based on the binocular vision principle, the proposed method firstly used two calibrated cameras to reconstruct the display wall and obtained the local model of the projection surface. Then, we computed the mapping relationship from the image space to the 3D projection surface. Finally, according to the principle of making full use of projectors' original projection areas, we calculate the pre-distortion matrices to geometrically calibrate their output images. Compared with existing methods, the proposed method can be applied to arbitrary continuous curved display surfaces by 3D reconstruction using only two ordinary cameras. Fig. 1 depicts the two main steps of the proposed method displaying China's famous painting 'Riverside Scene at Qingming Festival'. Fig. 1 (a) shows the 3D reconstruction of the display wall (Section 3); and Fig. 1 (b) shows the result of geometry calibration and edge fusion (Section 4).

2. Related work

Early researches on geometry calibration of multi-projector display wall mainly focused on planar multi-projector display walls [2-5]. Yang et al. [2] presented a spatially reconfigurable multi-projector display system, named PixelFlex, which provided a new level of automatic configurability to form large format displays, but instead of a commercial PC-cluster, it generally required a single SGI host. Huang et al. [3] proposed an improved geometry calibration method that considered the non-linear lens distortions through an image sampling process. But this method mainly focused on correcting the distortion brought by cameras. By building and refining a camera homography tree to automatically address uncalibrated camera images, Chen et al. [4] presented vision-based geometry calibration system for aligning the projections on an arbitrarily large display wall. Wang et al. [5] designed a robust calibration pattern and presented a related geometry calibration algorithm for planar multi-projector display wall. However, this method can output a regular display area, but the irregular part of the original projection area is wasted. Lai et al. [6] viewed the multi-projector system as a cluster of storage-compute-display (SCD) nodes. The navigation and modification problems with multi-projector system are then converted into problems of SCD nodes storage, management and coordination. Zhong et al. [7] presented a weighted average optimization approach for image synthesis process of multi-projector display systems, but it only improves the display results by evaluating the lost angular information and reallocating them in the rendering stage. Siegl et al. [8] proposed a novel multi-projector system for dynamic projection mapping by handling various physical stray-light effects, which mainly focused on dynamic scenes. Wang et



a

b

Fig.1. *The two main steps of the proposed method displaying China's famous painting 'Riverside Scene at Qingming Festival'* ***(a)*** 3D reconstruction of the display wall using black and white calibration matrix, ***(b)*** Result of geometry calibration and edge fusion

al. [9] proposed a hierarchical colour correction framework for automatic multi-projector calibration. However, the proposed approach only focused on the back-projection multi-projector display system.

In recent years, geometry calibration for non-planar multi-projector display walls became of interested in scientists from various related fields [10], but most of their studies focused on special shape display wall, such as spherical surface and circular surface displays. Harville et al. [11] described a practical method to create large scale, immersive displays by tiling multiple projectors on a curved surface. The key advantage of this method is its use of a single calibration camera, which enabled by reliance on a fiducial border to define the projection window on the screen. Sajadi et al. [12, 13] presented a novel method to calibrate multiple casually aligned projectors on fiducial-free piecewise smooth vertically extruded surfaces using a single camera. But these methods only focused on special shaped curved screen, such as cylinder. Zhang et al. [14] proposed a practical geometry calibration method based on self-adapting subdivision mesh, which mainly focused on establishing the one-to-one correspondence of pixels between the frame buffer of projectors and image of camera. Park et al. [15] presented a novel approach that utilized a simple handheld camera to automatically calibrate multi-projector displays. However, the proposed method may inaccurately calculate the correspondence during the decoding procedure if the input images are blurry. Majumder et al. [16] presented a demo which demonstrated integration of general content delivery from a window desktop to a multi-projector display of arbitrary, shape, size. But there are no details on how to generalize this method on commercial PCs or PC-clusters. Gaur et al. [17] provided a budget approach for large screen display using a single high-resolution monitor or projector, which mainly aims to recover the artificial feature points at the boundary of each projector's projection region. Chen et al [18] proposed an algorithm for automatic geometric correction based on camera feedbacks from multi-projector display system to address the problems existing in interactive manual geometric correction. Babar et al. [19] proposed a scalable hardware architecture design for geometric correction of projected content, which allows addition of projector channels. The proposed scheme provided real-time correction of HD quality video streams and thus enabled the use of this technology for both embedded and standalone devices. Li et al. [20] presented a new method for automatically calibrating a multi-projector system in a non-planar environment without using 3D reconstruction. The main limitation of this method does not work for non-parameterised screens because it cannot obtain the camera's position. Zhou et al. [21] presented an automatic multi-projector calibration approach for spherical Fish Tank Virtual Reality (FTVR) display. But this method also aims to some special shaped display conditions. Tehrani et al. [22] presented a distributed geometric calibration technique to coordinate multiple casually aligned projectors on a fiducial free arbitrary surface with multiple casually aligned cameras. However, only four projectors are used in the experiment with arbitrary shape display surfaces using a sandpit. Nagata et al. [23] proposed a curved surface fitting method using a raster-scanning window. The proposed method focused on calibrating the original organized point cloud data (PCD) and extracting the original features in the presence of noise.

Willi et al. [24] proposed a fully automated self-calibration method for arbitrarily complex multi-projector system, which enabled reliable and accurate calibration without any manual parameter tuning. But the proposed method assumes that all the devices use lenses with perspective projections.

3. 3D reconstruction of the display wall

At the setup stage, the two calibrating cameras (Camera One and Camera Two, as shown in Fig. 2) have to be adjusted to make their internal parameters (f, k, Sx, Sy, Cx, Cy) and external parameters (α, β, γ, Tx, Ty, Tz) consistent [26], where f is the focal length; k is the radial distortion level, when k is negative, the distortion is barrel shaped, or the distortion is pillow shaped; Sx, Sy are zoom ratio factors, which are used to represent the distance between adjacent pixels in the horizontal and vertical directions on the image sensor; (Cx, Cy) is the principal point, which is the vertical projection point in the image plane of the projection centre, and also the centre of radial distortion; T= (Tx, Ty, Tz) is the translation vector; R = R(α, β, γ) is the rotation vector, α,β,γ are the rotation angles relative to the X axis of the camera's coordinate system.

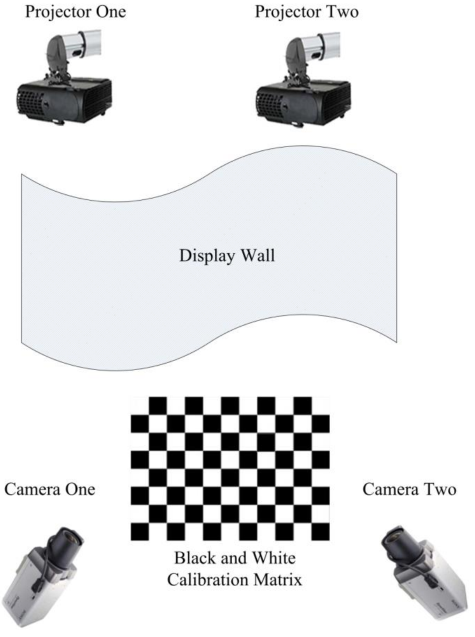


Fig.2. *3D reconstruction of the display wall*

The 3D reconstruction process of the display wall includes three steps: firstly, we use two calibrated cameras to capture the black and white calibration matrix before the display wall (as shown in Fig. 2) as well as the special pattern images that are projected on the display surface; secondly, we recognize the feature points on the captured images and reconstruct the display wall; finally, we use an optimized algorithm to create the 3D mesh model of the display wall. The black and white calibration matrix is used as a bridge between the two cameras to establish the common world coordinated system. In addition, in actual operations, we only require reconstructing part of the display surface that is coved by the original projection area and get the local model of the display wall. The detailed algorithm of 3D reconstruction for arbitrary continuous curved display wall is shown in Algorithm 1.

Algorithm 1. 3D reconstruction for arbitrary continuous curved display wall.

Input: six internal parameters {f, k, Sx, Sy, Cx, Cy} and six external parameters {α, β, γ, Tx, Ty, Tz} of the two cameras.

Output: Local Bessel surface model of each projector.

Step 1: Synchronously sample the black and white calibration matrix by two cameras to obtain images P1 and P2. According to our experimental experience, to ensure the stability of the reconstruction process, both the images P1 and P2 should cover no less than two thirds of the black and white calibration matrix.

Step 2: Establish the Common World Coordinate System (CWCS) according to the images P1 and P2. To simplify the computation, we set the camera one's coordinate system as the CWCS and re-adjust the external parameters of the two cameras. After adjustment, camera one's rotation vector becomes a unit matrix, and camera one's translation vector becomes a zero matrix.

Step 3: Let each projector project the preset black and white pattern image (as shown in Fig. 3) onto the display wall, then use two cameras to synchronously capture the images on the display wall to obtain images P3 and P4.

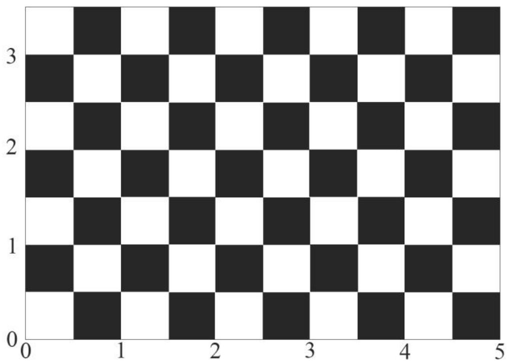


Fig.3. *Black and white calibration matrix with preset specification*

Step 4: Recognize the black and white grid corners in images P3 and P4, and get a series of corresponding points' 3-tuple S1: {P_I(x, y), P_{C1}(u1,v1), P_{C2}(u2,v2)}, where P_I is the set of points in the image coordinate system before projection, P_{C1} is the set of points in the Camera One's coordinate system, and P_{C2} is the set of points in the Camera Two's coordinate system.

Step 5: Use the two cameras' internal and external parameters to reconstruct the set of points P_{C1} and P_{C2}, and get a series of corresponding points' 2-tuple S2: {P_I(x, y), P_{CWCS}(x, y, z)}, where P_{CWCS} is the set of points in the CWCS.

Step 6: Create local Bessel surface model for each projector. Firstly, we let each projector to project black and white calibration matrix to the display wall. The two cameras are used to capture pictures of the projecting area for each project. Then, the grid corner points are extracted, calculated and used to reconstruct the P_{CWCS} points. Lastly, we use the P_{CWCS} points as data points to create local Bessel surface

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model by De Casteljau's Algorithm, as shown in Fig. 4. In Fig. 4, we select some critical P_{CWCS} points as control points (shown as red dots in Fig. 4) to construct the local Bessel surface model. These control points were selected according to the local curvature of the display wall. The purpose of down-sampling the P_{CWCS} points is to reduce the computational complexity, since the local Bessel surface model can be generated with enough points. The accuracy of the construction depends on the default specification of the black and white pattern used in Step 3, such as black and white grid density, relative dimension. The tensor product form of local Bessel surface model in the De Casteljau's Algorithm is defined as:

$$P(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} P_{ij}B_{i,m}(u)B_{j,n}(v), \quad (1)$$

where u, $v\in$ [0,1], P_{ij} (i=0,1,...,m; j=0,1,…,n) is the position of the (m+1)×(n+1)-th control points inversely solved by De Casteljau's Algorithm, $B_{i,m}(u)$ and $B_{j,n}(v)$ are the m and n times Bernstein basis functions respectively.

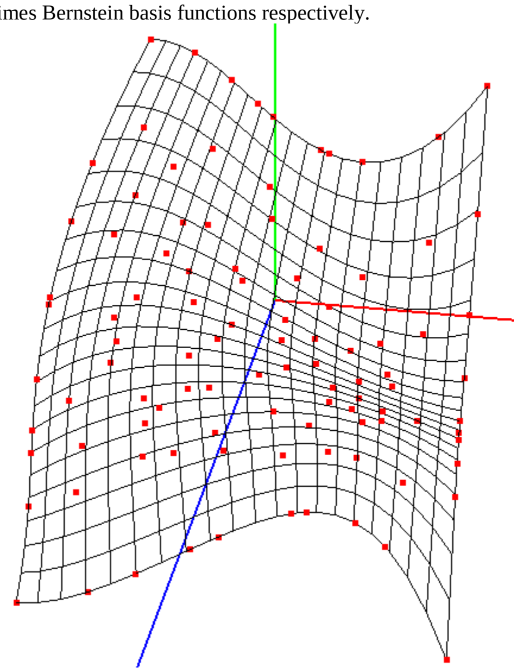


Fig.4. *Local Bessel surface model of the display wall created by P_{CWCS} points (red points). All red points are positioned on the surface mesh*

4. Geometry calibration

Based on the local Bessel surface model of the display wall (Fig. 5) and the principle of making full use of each projector's original projection area, this section proposed a novel geometry calibration method. This method discarded the defect of traditional geometry calibration methods which averagely distributed the projection task and allocated the projection task according to each projector's projection ability.

4.1. Generalized geometric transformation function

The generalized geometric transformation function of a projector is the mapping from its image space (U, V) before projection to a specific three-dimensional projection space (x, y, z) determined by the display wall. The generalized geometric transformation function is defined as:

$$f(x,y,z) = F(u,v). \quad (2)$$

Typically, because of the nonlinear distortion of projector lens and the complexity of the display wall, Formula (2) is nonlinear and cannot be described by affine transformation. But when the 3D mesh model of the display wall is fine enough, the generalized geometric transformation in each grid element can be piecewise approximated by an affine transformation, as shown in Formula (3), where $\boldsymbol{M}$ is a 4x3 matrix. We use the 4 vertices of each grid unit and the corresponding data of the 8 neighbour nodes to solve the $\boldsymbol{M}$ and obtain a set of affine transformation matrix corresponding to each projector.

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \boldsymbol{M}\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \quad (3)$$

4.2. Automatic geometry calibration algorithm

Based on the generalized geometric transformation function of each projector, we presented an automatic geometry calibration algorithm. The proposed algorithm includes three parts: 3D curved surface stitching of the ideal output images, the allocation of projection tasks and the calculation of the pre-distortion matrix set of each projector.

The detailed algorithm of automatic geometry calibration is shown in Algorithm 2.

Algorithm 2 Automatic geometry calibration for arbitrary continuous curved display wall

Input: generalized geometric transformation function of each projector.

Output: pre-distortion matrix set for each projector.

Step 1: Construct an ideal display surface R with first-order geometric continuity. Set the combined projection area of two adjacent projectors which can be represented by a four sided Bessel surface:

$$P(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} P_{i,j}B_{i,m}(u)B_{j,n}(v), \quad (4)$$

$$Q(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} Q_{i,j}B_{i,m}(u)B_{j,n}(v), \quad (5)$$

where u, $v\in$[0,1]; $P_{i,j}$ ($0\le i\le m$, $0\le j\le n$) and $Q_{i,j}$ ($0\le i\le m$, $0\le j\le n$) are the control points for the corresponding surface; $B_{i,m}(u)$ is m times Bernstein basis function which is defined as formula (6); $B_{j,n}(v)$ is defined similar to $B_{i,m}(u)$.

$$B_{i,m}(u) = \frac{m!}{i!(m-i)!}u^i \cdot (1-u)^{m-i} \quad (6)$$

In order to ensure the smooth continuity of the ideal display surface in U and V direction, $P_{i,j}$ and $Q_{i,j}$ have to satisfy two conditions: common boundaries and common tangent planes, as defined:

$$\begin{cases} P(1,1) = Q(0,1) \\ P(1,0) = Q(0,0) \end{cases}, \quad (7)$$

$$Q_u(0,v) = \alpha(v)P_u(1,v) + \beta(v)P_v(1,v), \quad (8)$$

where α(v) is a positive constant, and β(v) is the linear function of v.

Step 2: Based on the principle of making full usage of each projector's original projection area, we allocate the projection tasks of the ideal display surface R based on the original projection area created by multiple projectors (Fig.

4

6). For planar surface multi-projector display problems, traditional geometry calibration methods looked for maximized rectangular size in the public projection area [3, 5]. However, for arbitrary continuous curved surface, it is difficult to achieve geometry calibration using methods like planar multi-projector display methods. It is also one of the important contributions of this study, which fills the gap for geometry calibration on curved surfaces. Based on 3D curved surfaces stitching, we used De Casteljau algorithm and point by point recursively calculate the projection area for each projector. Taking a multi-projector display wall with two projectors as an example, set the parametric model for each projector as:

$$P(u,v) = \sum_{i=0}^{m-a} \sum_{j=0}^{n-b} P_{i,j} B_{i,m}(u) B_{j,n}(v), \qquad (9)$$

where $P_{i,j}$ ($0 \le i \le m$, $0 \le j \le n$) are control points, u, $v \in [0,1]$, $a \in [0,m]$, $b \in [0,n]$.

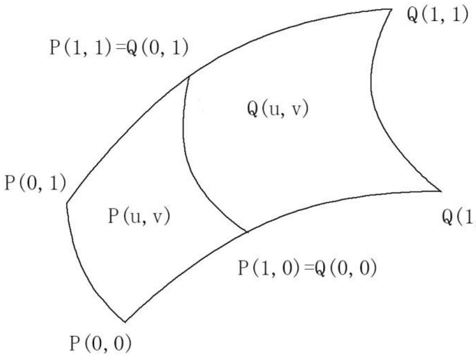
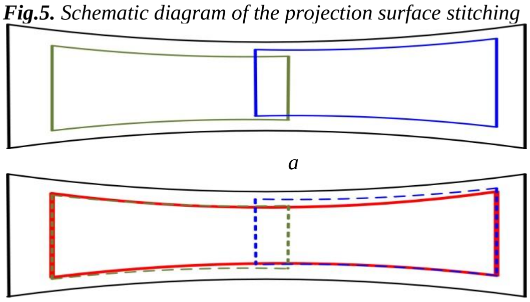


Fig.5. *Schematic diagram of the projection surface stitching*



a

b

Fig.6. *The ideal display surface R maximally utilizes the existing projection area created by multiple projectors* ***(a)*** An example of two overlapped projection areas, ***(b)*** The red bounding box shows the ideal display surface R

In the process of calculating the projection area of each projector, based on the centre point of the original projection area of each projector, a recursive method is used to obtain all the surface points, shown in Formula (10). To explain the whole process in detail, the De Casteljau's algorithm is first applied to the polygon sequence constructed by n+1 control points, taking the parameter u into consideration. After m recursions, a polygon M is constructed by n+1 vertices $P_{0,j}^{m,0}$ (j=1, 2, …, n) in the v axis direction. Again, applying De Casteljau's algorithm to the polygon M, taking the parameter v into consideration and after n recursions, we obtain a new point for the desired projection area. In this way, the ideal projection area $\tilde{R}_i$ (i=1, 2, …, k) for each projector can be computed, where k is the number of projectors to form a multi-projector display wall.

$$P_{i,j}^{a,b} = \begin{cases} P_{i,j} (a = 0, b = 0) \\ (1-u)P_{i,j}^{a-1,0} + uP_{i+1,j}^{a-1,0} \ (a = 1,2,\cdots,m; b = 0) \\ (1-v)P_{0,j}^{m,b-1} + vP_{0,j+1}^{m,b-1} (a = 0; b = 1,2,\cdots,n) \end{cases} \qquad (10)$$

Step 3: Subdivide the curved display surface of each projector into meshes. Based on the ideal projection area $\tilde{R}$ from Step 2, more vertices are added by the Loop subdivision ideas [27]. The bending degree of each vertex on the projection area can be expressed by the discrete curvature K:

$$K = \frac{2<n_v, v_j - v>}{||v_j - v||^2}, \qquad (11)$$

Finally, we get the refined ideal projection area $\hat{R}_i$ (i=1, 2, …, k), where k is the number of projectors to form a multi-projector display wall.

Step 4: Solve the pre-distortion matrix set corresponding to each projector. The pre-distortion matrix M is calculated by the least square method; we use its three vertices of ach triangle mesh and select at least 2 adjacent nodes on the refined ideal projection area $\hat{R}$. Similar to the methods for planar multi-projector display wall [5], the pre-distortion matrix set is applied to the corresponding region in the image buffer before the projections are applied.

5. Results

Two experiments are conducted to test and compare the performance of the proposed method with other existing methods. All tested methods were implemented under the same hardware configuration and using the same programming language, i.e. Visual Studio 2012 and OpenGL. The experimental platform includes 1 PC (Intel Core i7 6700K CPU, 8G RAM, Quadro K2000 graphics card), 1 six screen expansion instrument (MVD206), 6 LCD projectors (EPSON) with resolution 1024x768, 2 1080P network cameras (HIKVISION), 1 HD curved grey soft curtain and 1 black-and-white lattice calibration matrix. The experimental result comparison was performed using three technical indicators: average local error (ALE), average global error (AGE) and average time-consuming [4]. ALE quantifies the calibration error between adjacent projectors; and AGE is a metric for measuring the overall registration of a display wall:

$$ALE = \frac{1}{M \cdot N} \sum_{\forall p \in \Omega} \sum_{\forall (i,j) \in \Phi \times \Phi} I(i,p) \cdot I(j,p) \cdot \|p_i - p_j\|^2, \quad (12)$$

$$AGE = \frac{1}{M \cdot N} \sum_{\forall p \in \Omega} \sum_{\forall k \in \Phi} I(k,p) \cdot \|p - p_k\|^2, \quad (13)$$

where p refers to the control points in the overlapping region (red point in Fig. 4); Ω is the set of all feature points; Φ is the set of all projectors; and $I(i,p)$ is an indicator variable. If p resides within the display area of projector i, then $I(i,p) = 1$, otherwise $I(i,p) = 0$.

5.1. Geometry calibration with circular surface

This experiment uses six projectors to create 2x3 projector array, and the multi-projector display wall is a 2 meters high circular surface with 3 meters diameter. In order to quantitatively analyse the proposed geometry calibration method, we perform geometry calibration by our method and other three methods presented in literatures [11, 15, 19] respectively, and the results are shown as Table 1.

From Table 1, the average local error and average global error of our methods are significantly lower than the other three methods. The main reason is that after the 3D surface stitching and projection task allocation, the ideal projection area is subdivided further. It also can be seen from Table 1, the average time consumed by our method is higher than the other three methods. This is due to the implementation of our method involves automatic 3D surface stitching, which is relatively complex. However, in practical applications, because of the geometry calibration process is completed off-line, the relatively high average time consumption does not have a negative impact on the normal work of the multi-projector display wall.

Table 1 Performance comparison of several geometry calibration methods

Evaluation Criteria	Method [11]	Method [15]	Method [19]	Our Method
Average local error	2.17	1.95	1.73	1.13
Average global error	2.53	2.11	2.25	1.19
Average time(ms)	1.65	2.44	2.19	4.08

5.2. Geometry calibration with general continuous curved surface

In order to further evaluate the proposed method, this part of the experiment constructs a multi-projector display wall with general continuous curved surface and tests our method by five different projector arrays. The results are shown as Table 2.

Table 2 Performance comparison of our method in different environments

Number of projectors	Average local error	Average global error	Average time (ms)
1X2	1.27	1.43	2.07
1X3	1.41	1.82	2.91
2X2	2.01	2.29	3.66
2X3	2.33	2.69	4.95

In Table 2, with the increment of the projectors' number, the average global error and average local error are increased. This is mainly because of the limited resolution of the network cameras used in the experiment. With the increasing total projection area, the feature pattern images' resolution will be reduced, since the images need to include the entire display wall. The solution to this problem is to improve the resolution of the network cameras or use similar methods as in [4].

Furthermore, to verify the scalability of the proposed method, Table 2 shows the computational complexity and the number of projectors. We can see that, from Table 2, with the increment of projectors' number, the average time consumption increases, due to 1) hardware bottlenecks and 2) algorithm complexity. On the hardware aspect, with the increment of projectors' number, the PC requires more resources to generate and display the output images. Therefore, the speed of the geometry calibration algorithm will be affected. On the other hand, with the increasing of projectors' number, the time used in both obtaining all the surface points, as shown in Eq. (10), and subdividing the curved display surface of each projector into meshes will increase accordingly, which therefore requires more time for 3D surface stitching. PC clusters with more computing power can be used to relieve the above problem and balance the display images [27].

In addition, compared with Table 1, when the number of projectors composing the projection system is the same, the average local error, average global error and average time are increased, since Table 2 utilizes a more general continuous curved surface compared to the display wall used in Table 1.

6. Conclusion

This paper presents a general geometry calibration method for multi-projector display wall with arbitrary continuous curved surfaces. Based on the principle of binocular vision and the theory of projective geometry, a novel 3D reconstruction algorithm for arbitrary continuous curved projection surfaces is designed. To fully use all functions of the projectors, we propose an automatic geometry calibration algorithm for multi-projector display wall with arbitrary continuous curved surfaces. The pre-distortion matrices are calculated to geometrically calibrate the output images. Experimental results demonstrate that the proposed modelling method of the projection screen together with the corresponding automatic geometric correction scheme effectively increase the utilization ratio of the projection area of each projector and improve the calibration accuracy of the overall multi-projector system. It is worthwhile to mention that, instead of using gray-coded stripe pattern, the proposed method uses black and white patterns to infer the intrinsic relationship between the projectors. Gray-coded strip patterns, like horizontal and vertical lines [4], or strip of light [5], are acceptable for flat screen or special curve screen models. However, for curved surfaces models, the parameter estimation process is difficult to obtain enough feature points.

As one limitation, this paper mainly focuses on the geometry calibration for multi-projector display walls with continuous curved surface. The proposed method is suitable for projection screens with continuous curved surface. While for projection screens with non-continuous curved surfaces or corners surfaces, the proposed method does not work, since it is difficult to effectively match the continuity of the display surface. Further study of multi-projector display walls with non-continuous curved surface or cornered surface is one of our future research directions.

7. Acknowledgments

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