Geometrical Compensation for Multi-view Video in Multiple Camera Array

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Abstract – *In this paper, we present a geometrical compensation method for a calibrated multi-view video that is captured by the one-dimensional (1-D) parallel or arc camera array. Since the multi-view video may include geometical errors, we define a compensating transformation based on a two-dimensional (2-D) homography. After we apply the compensating transformation, we obtain all the image planes which are aligned vertically and rotated to be suitable for the camera array. Experimental results show that the proposed method correctly compensates the geometrical errors of the multi-view video. We can provide not only a clear viewpoint change in the multi-view video but also the simplicity and accuracy in matching between adjacent views.*

Keywords - *Multi-view Video, Multiple Camera Array, Geometrical Image Compensation*

1. INTRODUCTION

Multi-view video is a collection of videos that captures a three-dimensional (3-D) scene using two or more cameras. Unlike the single-view video, we can generate 3-D dynamic scenes from multiple viewpoints, which means that viewers can choose viewpoints within the available range. It is also possible to extract depth maps and implement 3-D videos from multi-view video. Recently, various multi-view video applications, such as free viewpoint TV (FTV), 3-D TV, surveillance, and immersive teleconference have been discussed [1][2].

To capture multi-view video, we construct a multiple camera array and arrange cameras on that. There are several types of multiple camera array. The multiple camera arrays in Stanford University have more than 100 cameras in the two-dimensional (2-D) parallel array and the 2-D arc array, respectively [3]. In Nagoya University, 100 cameras are employed and set up the one-dimensional (1-D) parallel array, the 1-D arc array, and the 2-D parallel array [4]. Each camera array has its own regular distance and angle between neighboring cameras. We can also make camera arrays by considering the number of cameras, scenes, purposes, and so on.

However, multi-view video has unavoidable geometrical errors which are due to an image mismatch in the vertical direction and an irregular camera rotation. These errors can occur since we construct camera arrays by human hands. Therefore, we have serious obstacles to time and accuracy in matching between views. In addition, we cannot expect a clear and smooth viewpoint change in multi-view video. Therefore, we need to compensate these errors in multi-view video.

In the case of stereo camera system, rectification can be one solution for those problems. Rectification is a classical topic in stereo vision. It makes all the epipolar lines of two images parallel and aligns the vertical mismatch [5]. After rectification, the two image planes become coplanar and the corresponding points in both images have the same vertical coordinates. There are numerous algorithms for stereo rectification. However, there are few methods to compensate the geometrical errors of multi-view video.

In this paper, we present a geometrical compensation method for calibrated multi-view video in 1-D parallel array and 1-D arc array. We introduce a pinhole camera model and features of multiple camera array. We then explain the proposed method and show our experimental results.

2. GEOMETRICAL CHARACTERISTICS OF MUILTIPLE CAMERA ARRAY

2.1. Camera model

A pinhole camera is modeled by the optical center **C** and the image plane R. A 3-D point **M** in space is projected onto R as an image point **m**. Since **C** plays a role of the center of the projection, **m** is the intersection of R and the line through **C** and **M**.

The line containing **C** and orthogonal to R is called the optical axis. The distance between **C** and R is the focal length. The intersecting point of the optical axis and R is the principal point. The image plane R has its own 2-D orthogonal coordinate system. Figure 1 shows a pinhole camera model.

In order to describe the camera operation, which means the relationship between **M** and **m**, we can define the camera projection matrix **P**.

$$\tilde{\mathbf{m}} = \mathbf{P}\tilde{\mathbf{M}} = \mathbf{A}[\mathbf{R}|\mathbf{t}]\tilde{\mathbf{M}}, \qquad (1)$$

where tilde means that the point is represented in homogeneous coordinates. As indicated in Eq. (1), the camera projection matrix consists of matrices **A** and **R**, and the vector **t**.

The 3×3 matrix **A** is composed of the intrinsic camera parameters that characterize the physical features of the camera. The 3×3 matrix **R** and the vector **t** are the extrinsic camera parameters that indicate the orientation and the position of the camera, respectively. The world coordinate system can be transformed to the camera coordinate system through **R** and **t**.

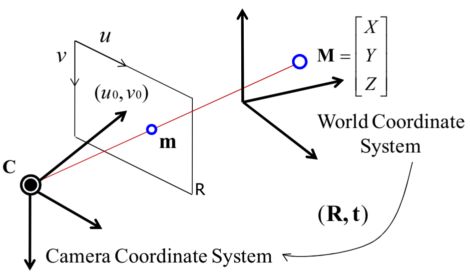


Fig. 1. Pinhole camera model

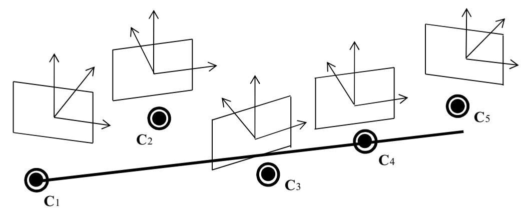
2.2. Multiple camera array

In general, there are two main types of multiple camera array, which are parallel camera array and arc camera array. Ideal parallel camera array has cameras which are located on a line called the baseline. Each camera has an equal distance to the neighboring cameras. Every optical axis is orthogonal to the baseline.

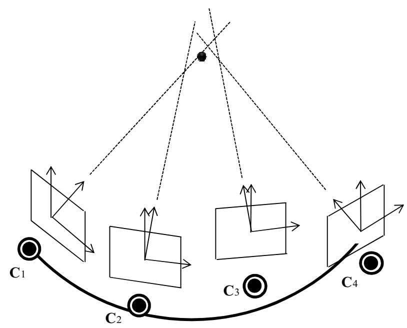
Ideal arc camera array can be constructed based on an ideal arc in space. Cameras are placed on the arc with the same distance to the adjacent cameras and the same angle between the neighboring optical axes. Then, the distance from the arc origin to each optical center becomes identical.

However, practical multiple camera array does not satisfy the ideal conditions since it is constructed by human hands without any mechanical aligning instruments. Therefore, cameras have the errors in the camera rotation and translation. In addition, each camera has different physical characteristics, which means that the intrinsic parameters of all the cameras are not equal. This problem also becomes a reason that yields the errors in multiple camera array.

Figure 2 shows that all the cameras in practical multiple camera array are not perfectly arranged. They have different distances to the adjacent cameras, different focal lengths, and unsuitable camera rotations. Therefore, we obtain the crucial mismatch between views in vertical coordinates, and camera angles. This mismatch can be significant obstructions to time and accuracy in view matching since they deteriorate the correlation between views. In addition, we cannot avoid an uneven viewpoint change when we watch a scene from multiple views.



(a) 1-D parallel camera array



(b) 1-D arc camera array

Fig. 2. Practical multiple camera array

3. GEOMETRICAL COMPENSATION IN MULTIPLE CAMERA ARRAY

In order to solve those problems, we propose the geometrical compensation method for multi-view video in multiple camera array, especially in 1-D parallel camera array and 1-D arc camera array.

We compensate all the image planes by applying the compensating transformation that is calculated by the 2-D homography between the original view and the compensated view of each camera.

In this section, we explain the algorithm to compute the compensated projection matrices, which mean the camera parameters of the cameras in ideally arranged camera array.

3.1. Compensation for 1-D parallel camera array

To compute the compensated camera parameters, we consider both camera intrinsic parameters and camera extrinsic parameters. We can find new optical centers, which are collinear and located with an equal distance to the adjacent cameras.

For the first step, we obtain the initial line by the iterative midpoint connecting algorithm. As shown in Fig. 3, the line through two cross-marked points becomes the initial line as the result of this algorithm.

Let m be an odd number. For m cameras, the midpoint of the initial line becomes the new optical center $\mathbf{C}'_{(m+1)/2}$ of $\mathbf{C}_{(m+1)/2}$. We then set a proper 3-D search range around the two adjacent original optical centers $\mathbf{C}_{(m+1)/2-1}$ and $\mathbf{C}_{(m+1)/2+1}$. We can find the new optical centers $\mathbf{C}'_{(m+1)/2-1}$ and $\mathbf{C}'_{(m+1)/2+1}$ in each search range that have the same distance to $\mathbf{C}'_{(m+1)/2}$ as the length of the initial line. Note that they have to be collinear with the initial line.

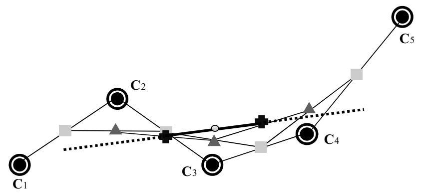


Fig. 3. Iterative midpoint connecting algorithm

After obtaining the two new optical centers, we can obtain all the other new optical centers by sequentially performing this procedure.

For even number of cameras, or m is even, two cross-marked points become $\mathbf{C}'_{m/2}$ and $\mathbf{C}'_{(m/2)+1}$, which are the new optical centers of $\mathbf{C}_{m/2}$ and $\mathbf{C}_{(m/2)+1}$, respectively. We then follow the same procedure.

After finding all the new optical centers, we consider the camera rotation and the intrinsic parameters. We adjust each camera rotation first so that the horizontal axis of every image plane becomes parallel to the initial line. All vertical axes have to be orthogonal to the adjusted horizontal axes and the direction of the new optical axes. We use the average of all the original optical axes as the direction of the new optical axes.

Finally, we regulate the intrinsic parameters. To make all image planes coplanar, we replace the focal length of all the cameras by the average of the focal lengths of all the cameras. We also substitute each principal point by the average value of all the original principal points to align the horizontal mismatch and the vertical mismatch.

Thus, we acquire the compensated camera parameters of all the cameras by the whole process. We can calculate the compensating transformation for each camera. Figure 4 shows a geometrically compensated 1-D parallel camera array by applying the compensating transformation.

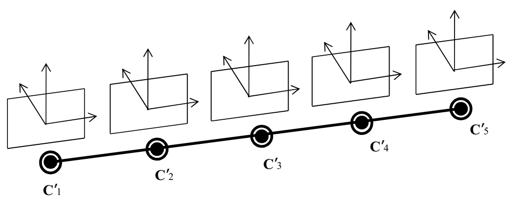


Fig. 4. Compensated 1-D parallel camera array

3.2 Compensation for 1-D arc camera array

In the case of 1-D arc array, we also follow the same procedure. The line through the two adjacent optical centers which are located in the middle of the arc becomes the initial line. We measure two values first. Let d be the length of the initial line and θ be the average angle between the two adjacent optical axes of all the cameras.

Let n be an even number. For n cameras, the initial line passes $\mathbf{C}_{n/2}$ and $\mathbf{C}_{(n/2)+1}$, and we consider these two points as the new optical centers $\mathbf{C}'_{n/2}$ and $\mathbf{C}'_{(n/2)+1}$. To find $\mathbf{C}'_{(n/2)-1}$, we set a 3-D search range around $\mathbf{C}_{(n/2)-1}$ and look for a point that satisfies three conditions. As shown in Fig. 5, the line from the found point to $\mathbf{C}'_{(n/2)}$ must have the length of d and the angle of θ between the direction of the initial line. The line also has to be coplanar with the plane made by the initial line and the average of all the original optical axes. In this way, we can find all the new optical centers $\mathbf{C}'_k$ in the search range around $\mathbf{C}_k$.

For odd number of cameras, which means odd n, we use the line that passes $\mathbf{C}_{(n-1)/2}$ and $\mathbf{C}_{(n-1)/2+1}$ as the initial line, and we follow the same procedure.

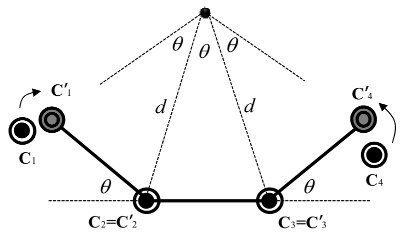


Fig. 5. Calculation of new optical centers

After obtaining all the new optical centers, we need another two points $\mathbf{C}'_0$ and $\mathbf{C}'_{n+1}$, which are the relocated points of the virtual optical centers $\mathbf{C}_0$ and $\mathbf{C}_{n+1}$. We extrapolate the positions of $\mathbf{C}_0$ and $\mathbf{C}_{n+1}$, firstly. Then, we set a 3-D search range in each side and find $\mathbf{C}'_0$ and $\mathbf{C}'_{n+1}$.

For the next step, we consider the camera rotation and the intrinsic parameters. To regulate the camera rotation, we make n chords by connecting the two optical centers as shown in Fig. 6. We then adjust each camera rotation so that the horizontal axis of k-th image plane becomes parallel to the corresponding chord that passes $\mathbf{C}'_{k-1}$ and $\mathbf{C}'_{k+1}$. The optical axis of each image plane has to be coplanar with the plane made by the initial line and the average direction of all the original optical axes.

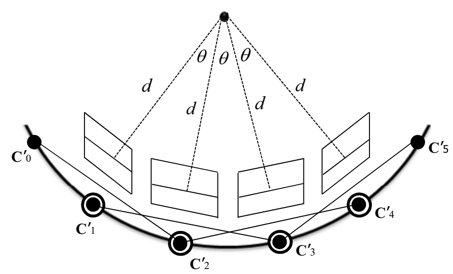


Fig. 6. Compensated 1-D arc camera array

Finally, we replace each focal length and each coordinate of the principal point by the average of their original values, respectively. Thus, we can calculate the compensating transformation and obtain compensated 1-D arc camera array like Fig. 6. All the image planes have an equal distance to the arc origin and an equal angle between the neighboring cameras.

(a) Test sequences in the 1-D parallel camera array (b) Test sequences in the 1-D arc camera array

(c) Compensated test sequences in the 1-D parallel camera array (d) Compensated test sequences in the 1-D arc camera array

Fig. 7. Test sequences before and after compensation in the 1-D parallel array and the 1-D arc array

4. EXPERIMENTAL RESULTS

We apply the proposed method to multi-view test sequences. We captured two types of test sequences. One is captured by the 1-D parallel camera array with six cameras and the distance of about 4 cm. The other is captured by the 1-D arc camera array with six cameras, which has the distance of 6.5 cm and the angle of 4 degrees between the adjacent cameras, approximately. The resolution is 1024×768 in pixels.

We define that the amount of the error, which is occurred in searching of the new optical center, cannot exceed 10^{-3}. Despite the tiny error, we acquired accurately compensated results.

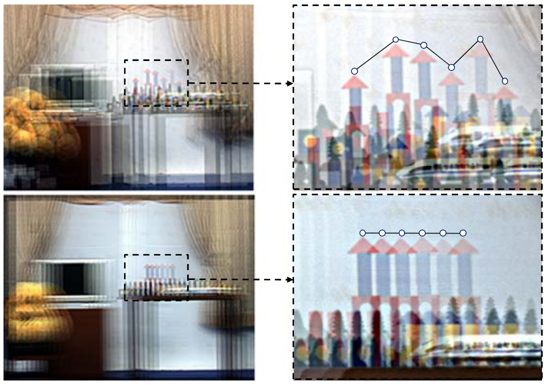


Fig. 8. Results in the 1-D parallel camera array

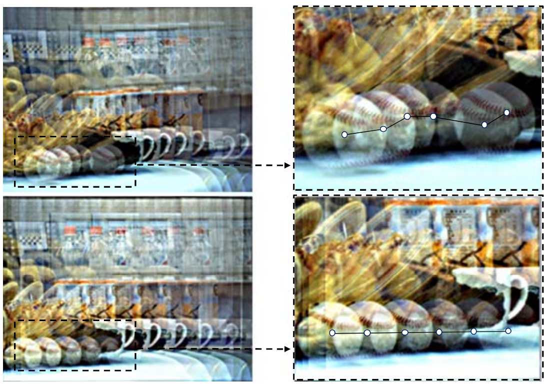


Fig. 9. Results in the 1-D arc camera array

Figure 7 shows the test sequences before and after compensation. In the sequences, there are the vertical mismatch and the uneven camera rotation between views. Although holes are generated around the image boundaries due to the compensating transformation; they are correctly aligned. Figures 8 and 9 are the synthetic images of the two test sequences before and after compensation. We can notice that there is no serious mismatch in the vertical direction among views but the uniform displacement in the horizontal direction according to camera positions.

5. CONCLUSION

In this paper, we have presented the geometrical compensation method for multi-view video captured by multiple camera array. From our experiments, we obtained the compensated results in 1-D parallel type and 1-D arc type of multiple camera arrays. Those results can be considered as multi-view video captured by ideally aligned camera array. With the compensated videos, we can provide not only advantages of simplicity and accuracy in matching process between views but also a clear and smooth viewpoint change in multi-view video.

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