Active Calibration of Camera-Projector Systems based on Planar Homography

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Abstract—This paper presents a simple and active calibration technique of camera-projector systems based on planar homography. From the camera image of a planar calibration pattern, we generate a projector image of the pattern through the homography between the camera and the projector. To determine the coordinates of the pattern corners from the view of the projector, we actively project a corner marker from the projector to align the marker with the printed pattern corners. Calibration is done in two steps. First, four outer corners of the pattern are identified. Second, all other inner corners are identified. The pattern image from the projector is then used to calibrate the projector. Experimental results of two types of camera-projector systems show that the projection errors of both camera and projector are less than 1 pixel.

Keywords—Calibration; Projector; Camera; Homography

I. INTRODUCTION

Structured-light 3D reconstruction is one of the 3D reconstruction techniques which measure a 3D shape of an object using projected light patterns and a vision sensor. The technique is widely used in many applications such as archaeology, precision shape measurement, and industrial inspection [1,3]. In contrast to stereo vision, the structured-light technique does not require any complicated correspondence search. Instead, it can reconstruct a 3D shape of an object accurately and fast without an additional process. However, the technique requires the geometric relationship between a projector and a camera [1,7].

Calibration of camera-projector systems is widely investigated. Since a projector can be regarded as an inverse camera, there is planar homography between the projector and the camera if the projection is done on a planar object [6]. Since the projector is considered as an inverse camera, we can use this property to calibrate a camera-projector system. Similar to regular camera calibration, we can calibrate a projector if pictures of a calibration pattern from the view of the projector are available. If the pictures can be generated.

Two types of camera-projector systems are used in the experiments. Calibration results show that the projection errors of both the camera and the projector are less than 1 pixel.

II. CAMERA-PROJECTOR CALIBRATION

A. Related work

Calibration of camera-projector systems fall into two main categories. One is calibration of the 2D homography between the camera and the projector. The other is calibration of the stereo geometry between them.

Zhang and Huang used a pattern board for the calibration of a phase-shift structured light system. They calculate unique codes of structured light for accurate depth range computation. For this calculation, they use additional structured light, centroid line images, and phase line images [12].

Cui calibrated a camera first. Then he calibrated a projector using a white flat surface by projecting a pattern of known position [4]. Chen used similar method with Cui’s [3]. Zhou and Zhang proposed a calibration method of using 1D lines instead of 2D structured light. They tried to find the normal vector between a projected line and the projector’s central plane. It is similar to the line laser calibration [13]. Ashdown, Raskar, and Song apply 2D homography of camera-projector systems to games applications [2,8,9]. Gao et. al. use both printed and projected checkerboard patterns to calibrate a camera-projector system. They match the corners of the projected and printed patterns. However, their technique does not consider the lens distortion of a projector [5].

B. Proposed method

The planar homography of a camera-projector system is valid only when an image is projected on a planar screen. This is because there is always a 2D homography between image planes of any two projective imaging devices, if the devices take pictures of a planar object [6]. Since the projector is considered as an inverse camera, we can use this property to calibrate a camera-projector system.

In this paper, a simple and active calibration technique is proposed. The proposed method generates a projector image of a calibration pattern and it is used for calibration. To identify the pattern coordinates in the projector image, a corner marker is projected and it is captured by a camera. To align the marker with the corners of a printed pattern, we measure the alignment error and move the marker iteratively until the error reduces close to zero.
other pictures obtained from a camera, we can calibrate both camera and projector with respect to a reference coordinate system, which is the same as the stereo camera calibration \[10\].

Here, a problem arises because there is no picture of the pattern from the view of the projector. To generate the pattern pictures, it needs to know the homography parameters between the camera and the projector. Assuming there is a perspective homography between the devices, at least four known image point pairs are needed, which are represented in 2D coordinates of each image plane.

To derive the homography parameters, four corners of the pattern are used. In the camera image of the pattern, coordinates of four corners are detected. To know the coordinates of the same corners in the view of the projector, we propose an active method.

Suppose the coordinates of pattern corners in the camera and projector images are \((x, y)\) and \((x', y')\), respectively as shown in Figure 1. At the beginning, we generate a projector pattern in the center of the projector image. Now, the center of the marker is the current marker position. Let \((x'_0, y'_0)\) be the initial position of the projector marker in the projector image coordinates. By capturing an image of the pattern board, we find the coordinates of the marker in the camera image. Let \((x_0, y_0)\) be the initial position of the marker in the camera image coordinates. Because the coordinates \((x, y)\) is already known, we need to reduce the alignment error, \(\varepsilon = (x, y) - (x_0, y_0)\). We call this as iterative corner tracking (ICT).

As shown in Figure 1, the 2D coordinates of four outer corners of the pattern are determined by ICT. Then, we can derive a perspective matrix of the camera-projector system. Using the matrix, a projector image of the pattern is generated and the image is used for projector calibration.

By the way, the transformation matrix cannot represent the lens distortion of the projector. Even though the projected image of the 4 outer corners are exactly matched with that on the printed pattern, there are still alignment errors in other inner corners.

To solve these problems, we perform another active method. All inner corners of the projector image are projected to the pattern. At each corner, we again measure the displacement error between the coordinates of the printed corner and the projected corner. Since the perspective matrix already transforms all inner corners close enough to printed corners, there are only small errors in the corners. By using a similar ICT method at each corner, we align all corners. Finally, using the Zhang’s \[11\] camera calibration method, we calibrate the camera-projector system very accurately.

### III. Active Projector Calibration

#### A. ICT to outer corners

This section describes actual implementation of the proposed calibration technique. We use calibration patterns which has total 64 corners, 8 in the x-axis direction and 6 in the y-axis direction of the world coordinates. In the camera images, we find all corners using the Harris corner detection algorithm. Among the corner points, we select 4 outer corners which coordinates are \((0,0,0)\), \((8\times d_x,0,0)\), \((0,6\times d_y,0)\), and \((8\times d_x, 6\times d_y,0)\), respectively. Here, \(d_x\) and \(d_y\) are the x and y distance between corners.

Suppose the image coordinates of one of these outer corners are \((x, y)\). We find the corresponding coordinates \((x', y')\) in the projector image using ICT as described in the previous section. As shown in Figure 2, the shape of the corner marker is designed to make it easy to compute the center of the marker. The marker image is separated using a simple background subtraction method as shown in Figure 2.
To determine the position of the current marker, we need to find the centroid of the marker. Using the Sobel edge detection, we first get the x-edge and y-edge images of the marker as shown in Figure 3. Then x and y directional histograms of the edge images are acquired. As shown in the figure, histograms are acquired in very narrow rectangular regions in the edge images. Figure 4 shows the x and y directional histograms of the marker edge image. The center of the marker is determined from the histograms.

\[
C_x = \frac{\sum x \cdot h(x)}{\sum h(x)} \\
C_y = \frac{\sum y \cdot h(y)}{\sum h(y)}
\]

(2)

(3)

The first centroid is \((x'_0, y'_0)\). Then, we move the marker iteratively toward a corner point as shown in Figure 5. The same processing is done repeatedly to determine the coordinates of the four outer corners.

After the coordinates of four outer corner points are determined in the project image, eight parameters of a perspective homography are solved. We solved the parameters using the least square method. The homography transforms the camera image to the projector image. After generating the project image, we calibrate the projector using the same algorithm used in camera calibration.

B. ICT to inner corners

Once we determine the coordinates of the outer corners in the project image, we can generate all other inner corners by uniformly interpolating the outer corners. In an ideal case, the projected inner corners should match with those of the pattern board. However, it doesn’t because the lens distortion of the project is different than that of the camera. To solve this problem, the coordinates of all inner corners are adjusted by a similar method to ICT. Figure 6 shows an example of inner corner tracking. Initial positions are very close to printed pattern corners. Therefore, each corner position is adjusted in very short time.

IV. EXPERIMENTAL RESULTS

As shown in Figure 7, two types of camera-projector systems are used. CamPro1, a compact size system, consists of a 1024x768 resolution color camera and a projector. CamPro2, a micro size system, consists of 1024x768 resolution black and white camera and a projector.

We use a red-blue pattern board and a green-colored marker in CamPro1. Projection error of world points \(X_w\) to an image point \(x'\) is used as calibration error measurement such that

\[
x' = PX_w \\
e = |x - x'|,
\]

(4)

(5)

where \(x\) is the original image point used in calibration and \(P\) is PPM. We acquire PPMs of all devices. The result of projection error is shown in the following tables. By determining coordinates of all corners, we can calibrate the systems very accurately. Figure 8 shows plots of projection errors.

<table>
<thead>
<tr>
<th>Error (pixel)</th>
<th>Camera</th>
<th>Projector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer corners</td>
<td>outer+inner</td>
</tr>
<tr>
<td>Max.</td>
<td>0.41</td>
<td>3.45</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.15</td>
<td>0.52</td>
</tr>
<tr>
<td>RMS</td>
<td>0.17</td>
<td>0.64</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.08</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 1: CamPro1 projection error.

<table>
<thead>
<tr>
<th>Error (pixel)</th>
<th>Camera</th>
<th>Projector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer corners</td>
<td>outer+inner</td>
</tr>
<tr>
<td>Max.</td>
<td>2.13</td>
<td>11.4</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.61</td>
<td>1.14</td>
</tr>
<tr>
<td>RMS</td>
<td>0.71</td>
<td>1.72</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.37</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Table 2: CamPro2 projection error.
Figure 8: Plots of projection error. From top, error of camera, projector with outer corners, and all corners. (a) Campro1 (b) Campro2.

V. CONCLUSIONS

We propose a new active calibration technique of camera-projector systems. Conventional methods require expensive equipments or complex processing. However, the proposed technique is very simple and doesn’t require additional equipments. We determine the coordinates of projector corners by actively projecting and moving a corner marker from the projector. By iteratively aligning the marker to all corners, we reconstruct the pattern image from the view of the projector. Error analysis shows that the accuracy of the proposed technique.

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