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Geometric Image Compensation Method for a Portable Projector Based on Prewarping Using 2D Homography

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Abstract

As portable multimedia devices become more popular and smaller, the use of portable projectors is also rapidly increasing. However, when portable projectors are used in mobile environments in which a dedicated planar screen is not available, the problem of geometric distortion of the projected image often arises. In this paper, we present a geometric image compensation method for portable projectors to compensate for geometric distortions of images projected on various types of planar or nonplanar projection surfaces. The proposed method is based on extraction of the two-dimensional (2D) geometric information of a projection area, setting of the compensation area, and prewarping using 2D homography. The experimental results show that the proposed method allows effective compensation for waved and arbitrarily shaped projection areas, as well as tilted and bent surfaces that are often found in the mobile environment. Furthermore, the proposed method is more computationally efficient than conventional image compensation methods that use 3D geometric information.

Keywords: Geometric image compensation, prewarping, 2D homography

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1. Introduction

As multimedia devices become more popular and smaller, the use of portable projectors in mobile environments is also rapidly increasing. However, portable projectors are often used in small rooms, where a dedicated screen or an appropriate planar projection surface is not available for the projection of large images. Thus, several types of geometric distortions of the projected images can be generated from the planar or nonplanar projection surfaces, which may include tilted, bent, curved, or arbitrarily shaped walls.

In this paper, we present a geometric image compensation method for portable projectors to compensate for geometric distortions of images projected on various types of planar or nonplanar projection surfaces. The proposed method, required projector-camera system, is based on extraction of the 2D geometric information of a projection area, optimal compensation area generation, and prewarping using 2D homography between the original input image and the distorted image captured by a camera. The advantages of the proposed method are as follows. First, the proposed method enables image compensation for nonplanar projection surfaces such as bent, waved or arbitrarily shaped, as well as tilted surfaces. Secondly, the proposed method performs more computationally efficient image compensation in comparison with conventional methods.

2. Related Work

Various studies based on projector-camera systems have been carried out to compensate for geometric distortions of images projected on various types of planar or nonplanar projection surfaces. In general, a projector-camera system is defined as a system consisting of a projector (or multiple projectors) and a camera (or multiple cameras) in which the projector projects images on a surface, and the camera takes the projected images. This system controls the projected images using the camera images taken so that observers see properly aligned rectangular images on the projection surface. Raskar et al. proposed a method based on a projector-camera system for correctly displaying rectangular images on an arbitrarily tilted (inclined) planar surface (keystoned position)[1]. This method applies techniques for the epipolar geometry of a pair of cameras to a projector-camera system, and then prewarps the projected image using two-dimensional (2D) homography so that it is correctly shown on the tilted planar surface. However, it requires a full calibration for the projector-camera system and deals only with the geometric compensation of the image projected on the tilted planar surfaces. Sukthankar et al. also proposed a method for correcting keystone error on a planar surface [2]. However, it does not also cope with image distortions caused by arbitrarily shaped surfaces. Lee et al. suggested a compensation method for images projected on bent surfaces as well as on tilted planes[3]. However, their method is based on corner detection in the projection area, which poses limitations on compensating for geometric distortions inside the projected images. Therefore, it cannot compensate for image distortions occurring on waved or arbitrarily shaped surfaces. Park et al.[4][5]used Zhang's calibration method[6] to perform camera and projector calibration and define 2D-3D geometric relationships between the camera and the projection surface, and between the projector and the projection surface. However, this method requires complex camera and projector calibration and 3D modeling of the projection surface, making it computationally extensive.

3. Geometric Image Compensation Method

The general principles of the proposed geometric image compensation method are as follows. As shown in **Fig. 1**, A that indicates the relationship between the original input image(2D) and the distorted image(2D), homography $H_{o\text{-}s}$ between the original input image to be fed into the projector and the projected image(3D) on the screen, and homography $H_{s\text{-}d}$ between the projected image on the screen and the distorted image captured by a camera, are defined as a single homography $H_{o\text{-}d}$. Using $H_{o\text{-}d}$, geometric distortions of the image are compensated from the camera's perspective, which is assumed to be from the user's point of view. Homography $H_{o\text{-}d}$ and its inverse homography $H_{d\text{-}o}$ are defined as follows:

$$d = H_{o-d}o\ ,\quad \mathrm{o} = H_{d-o}\mathrm{d} \tag{1}$$

where d and o are the homogeneous coordinates of the distorted and original input images. We can obtain $H_{d\text{-}o}$ by using four corresponding dots of the distorted and original input images and perform inverse transform of the original input image to compensate for the image distortions caused by the shape of the projection surface. However, adequate compensation of the image cannot be achieved without the consideration of the projector's projection range. In other words, when the image is transformed for geometric compensation, some pixels may be present that cannot be projected, and therefore cannot be transformed. Therefore, we need to extract the effective projection range for the projection surface, properly scale the original input image, and generate the prewarped image(2D) by applying $H_{d\text{-}o}$ to compensate for the geometric distortions of the projection surface, as shown in **Fig. 1**, B that indicates the relationships among the scaled original input image, the prewarped image, and the compensated image(2D). The homogeneous coordinates of the prewarped image are defined as follows:

$$p = H_{d-o}s \tag{2}$$

where p represents the homogeneous coordinates of the prewarped image, and s represents the homogeneous coordinates of the scaled original input image. Once the prewarped image is projected from the projector, the homogeneous coordinates of the compensated image observed from the user's point of view can be defined with $H_{o\text{-}d}$ as follows:

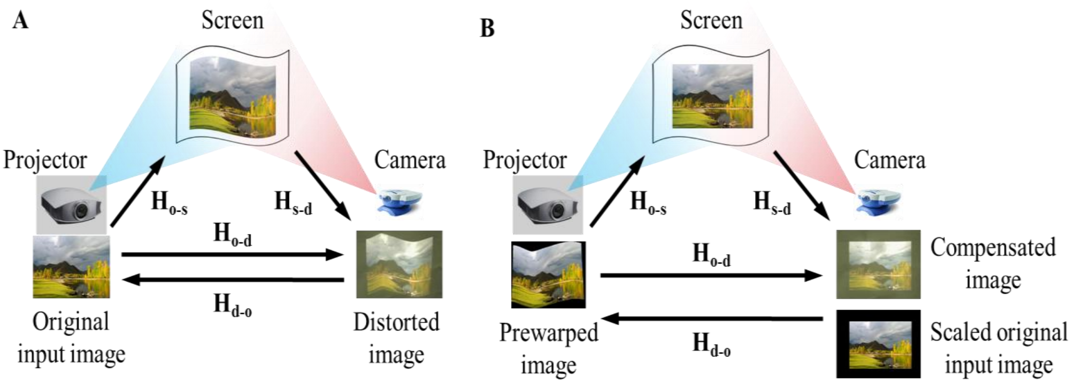

Fig. 1. The principles of the proposed geometric image compensation method: (A) The relationship between the original input image and the distorted image; (B) The relationships among the scaled original input image, the prewarped image, and the compensated image.

$$c = H_{o-d}\, p \qquad (3)$$

where c represents the homogeneous coordinates of the compensated image. From (2) and (3), the relationship between the homogeneous coordinates of the scaled original input image and the compensated image from the user's view point can be written as

$$c = H_{o-d} H_{d-o} s = s \qquad (4)$$

Equation (4) indicates that the compensated image has a form identical to that of the scaled original input image, which is the original input image scaled by setting of the compensation area. Therefore, the proposed method involves a step for setting of the compensation area, taking into account the size and range of the effective projection area. After calculating homography $H_{d\text{-}o}$, the prewarped image is generated and finally projected, enabling a user to see the compensated rectangular image on a nonplanar projection surface.

The proposed method consists of the following three steps: extraction of the 2D geometric information of a projection surface using predefined pattern images, setting of the compensation area, and prewarping using 2D homography. The following subsections describe these three steps in detail.

3.1 Extraction of the 2D Geometric Information of a Projection Surface

For high-quality geometric image compensation, accurate geometric information of the projection surface is essential. For this, an appropriate pattern image containing a large number of feature points (called "dots" in this paper) is generally required. However, an excessively high number of dots decreases the distance between the dots, causing a problem with detection of the dots due to the shape and complexity of the projection surface, the focal points of the projector and the camera, and the ambient light conditions. To cope with this problem, we use several slightly different artificial pattern images in which the dots are equally spaced in an individual pattern image and the positions of the dots do not overlap across the entirety of the pattern images. These individual pattern images are sequentially projected to the projection surface, and the dots in each distorted individual pattern image captured by a camera from the user's point of view are automatically detected. Then, all the detected dots are combined into a single combined pattern image, allowing the 2D geometric data of the projection surface to be acquired with high accuracy and precision. This process can cause the pattern image to have a high dot resolution, and also allows correct detection of all of the dots in the pattern image. Finally, the dots in the combined pattern image are labeled to acquire the 2D geometric information of the projection surface.

3.2 Setting of the Compensation Area

If homography $H_{d\text{-}o}$ is applied to the original input image without taking into account the effective projection range of the projector, the correspondence relationship between some pixels of the undistorted original input pattern image and the distorted pattern image projected on a nonplanar projection cannot be fully defined (**Fig. 2**, C). The size of the compensated image may also become excessively reduced according to the geometric shape of the projection surface(**Fig. 2**, D). **Fig. 2** shows this problem and the need for setting of the compensation area. The original input image to be projected to a bent surface (i.e., the center of the surface is folded in a 90-degree angle) is shown in **Fig. 2**, A. The projection range of the projector is indicated by bright gray regions in **Fig. 2**, B. The compensated images, which are produced by applying the different compensation areas, are shown in **Fig. 2**, C, D, and E. **Fig. 2**, C displays the problem in which some pixels of the original input image are lost when the compensation area is set outside the projection range. In **Fig. 2**, D, although the compensation area is set within the projection range, the size of the compensated image is excessively reduced. **Fig. 2**, E displays the compensated area and the corresponding compensated image when the effective projection range is taken into account to select the most adequate compensation area. The process of setting the optimal compensation area can be divided into three steps: 1) assigning a range for searching the compensation area, 2) determining a rectangle to search the compensation area, 3) searching the compensation area. **Fig. 3** shows a pseudo-code for the process of setting the optimal compensation area

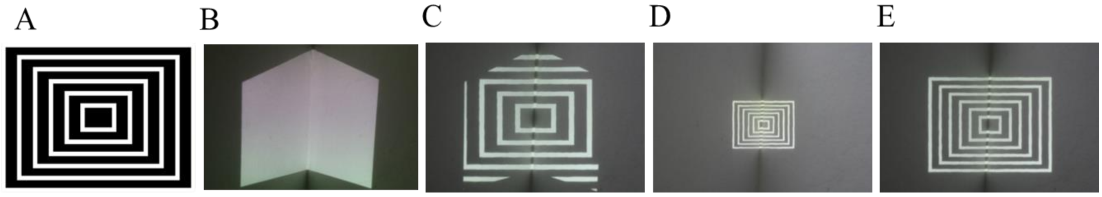

Fig. 2. Different compensation results according to setting of the compensation area: (A) Original input image to be projected to a bent surface; (B) Projection range of the project indicated by the gray regions; (C) A compensated image when the compensation area is set outside the projection range; (D) A compensated image when the compensation area is set very small inside the projection range; (E) A compensated image of the proposed method.

```
// Assigning a range for searching the compensation area
s_range = get_scan_range(Idistorted);

// Determining a rectangle to search the compensation area
p_range = get_projection_range(Idistorted);
oi_ratio = original_image_width/original_image_height;
s_width = square_root(p_range* oi_ratio);

// Searching the compensation area
while (0 < s_width) {
            s_height = s_width/oi_ratio;
            for(y = s_range_y_min to s_range_y_max – s_height) {
                        for(x = s_range_x_min to s_range_x_max – s_width) {
                                    start_point = [x, y];
                                    end_point = [x + s_width, y + s_height];
                                    rect = get_rect(start_point, end_point);
                                    if (rect in p_range) {
               // Setting of the image scaling factor
                                              s = s_width/original_image_width;
                                              scaled_image = scaling (original_image, s);
                                              s·Ioriginal = insert_image_to_area (scaled_image, rect);
                   return;
            }
         }
    }
    s_width = s_width–1;
}
```

Fig. 3. A pseudo-code for the process of setting the optimal compensation area

3.3 Prewarping

Prewarping involves configuring the projection surface through a mesh divided into rectangles consisting of 4 dots in the pattern image. Correspondence relationships among the meshes in the original pattern and the distorted pattern on a projection surface are elicited by extracting the 2D geometric information of the projection surface as described in Section 3.1. Then, after setting the compensation area as described in Section 3.2, homography $H_{d\text{-}o}$ is derived from these correspondence relationships. Using this $H_{d\text{-}o}$, the prewarped image for finally compensating geometric distortions of the projected image from the user's point of view is generated.

Correspondence relationships are defined by mapping four corresponding corner dots of the meshes in the original pattern and distorted pattern, and the coordinates of the pixels inside a mesh are determined with homography $H_{d\text{-}o}$ using the following equation [7][8]:

$$\begin{pmatrix} wx' \\ wy' \\ w \end{pmatrix} = H_{d\text{-}o} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \tag{5}$$

where x, y and x', y' denote the pixel coordinates of the scaled original input image and the prewarped image, respectively. w is a arbitrary scaling factor, and h_{ij} (i = 1, 2, 3, and j = 1, 2, 3) are the elements of homography $H_{d\text{-}o}$. After homography $H_{d\text{-}o}$ is determined for every mesh, the coordinates of the prewarped image can be obtained, and a prewarping table can be generated for all of the pixels in the image to expedite the time-consuming prewarping process. The resolution of the prewarping image is identical to that of the original input image, and the projector finally outputs the prewarped image on the projection surface so that the user can see a compensated image with a rectangular shape. In fact, we use the rectangular pattern other than the triangular pattern, which enables us to find the most accurate 2D geometric information of the projection surface. This is mainly because of high computational efficiency for practical application of the proposed method. Therefore, we need to increase the dot resolution of the pattern to obtain the more accurate 2D geometric information of the complex arbitrary shaped projection surface with some sacrifice of computational efficiency.

4. Experimental Classification Results and Analysis

To assess the performance of the proposed method, we implemented a computer program in C++ and conducted experiments using a PC with a 2.66 GHz processor, a USB camera, and a projector. A landscape image was tested on projection surfaces with four different types of geometric shapes. The resolutions of the original input image, the prewarped image, and the projector used for the experiments were identical at 800-by-600 pixels, and the resolution of the camera was 720-by-480 pixels.

4.1 Compensation Results

Fig. 4 shows the visual results for geometric image compensation on tilted, bent, waved, and arbitrarily shaped surfaces, which are often found in the mobile projection environment where a planar screen is not available. Columns A, B, and C are images distorted by the four types of

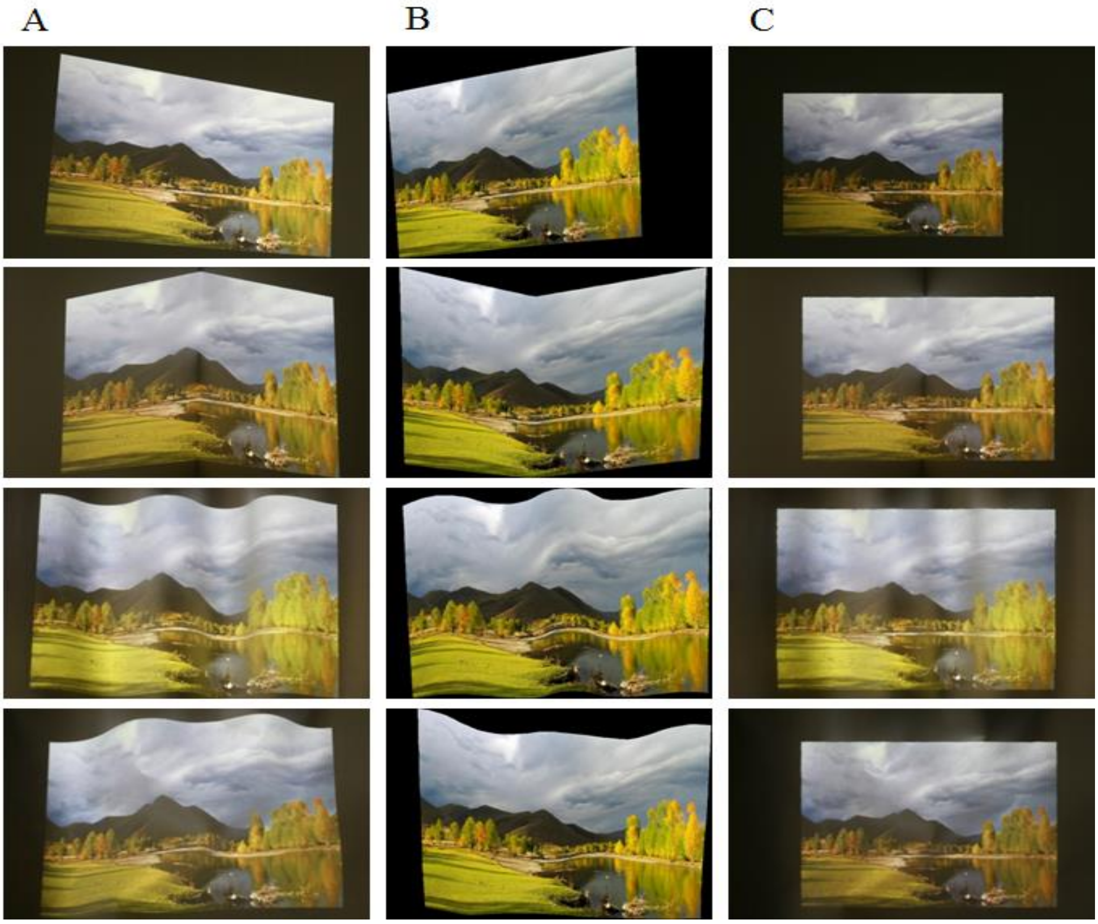

Fig. 4. Results of the proposed geometric image compensation method(tilted, bent, waved and arbitrarily shaped surfaces from top to bottom): (A) Distorted images projected on the four different types of projection surfaces; (B) Prewarped images; (C) Final compensated images.

projection surfaces, prewarped images for compensation, and final compensated images viewed from the user's view point, respectively. On a tilted surface, the direction of the projector's beam is slanted, and a bent surface is shaped as the center of the projection surface is folded in a 90-degree angle. A waved surface consists of multiple waves like a curtain, and an arbitrarily shaped surface contains randomly distorted curvatures. As seen in column C, the sizes of compensated images are somewhat smaller than those of distorted images, as shown in column A, which is a consequence of setting the optimal compensation area. However, the compensated images clearly demonstrate that the proposed method is very effective in compensating for the four types of geometric distortions.

4.2 Processing Time

For an evaluation of the computational efficiency of the proposed method, we measured processing times of each individual compensation step, and the total processing times of the conventional method [4][5] and the proposed method at four different dot resolutions (48, 300, 1200, and 4800) of pattern images with a 2.66 GHz processor PC. Then, the measured processing times are averaged over the cases of tilted, bent, waved, and arbitrarily shaped projection surfaces.

As shown in **Table 1**, the average processing times of the proposed method, including the extraction of the 2D geometric information, setting of the compensation area, and generation of the prewarping table, are 0.86, 1.31, 3.11, and 8.96 seconds at dot resolutions of 48, 300, 1200, and 4800, respectively. These three steps are required only once at an initial setup stage for a certain type of projection surface. Then, the step of the prewarped image generation using the generated prewarping table is repeated for every input image of the projector. Generating a prewarped image required only 0.04 seconds regardless of the dot resolution, which indicates that a video clip with a resolution of 800-by-600 pixels can be processed almost in real-time at 25 frames per second.

For comparison, **Table 2** shows the average processing times of each step and the total processing times required by the conventional method [4][5] in an environment identical to that of **Table 1**. Average processing times were measured for the steps of camera calibration (excluding manual setup time for calibration), 3D surface modeling, prewarping table generation, and prewarped image generation. First, we calibrated the camera using 10 images [6]. Then, we calculated the camera projection matrix and the projector projection matrix of each mesh, and then performed 3D modeling of the projection surface using the linear triangulation method [8]. Finally, we conducted prewarping with the 3D information required from the respective projection surfaces. As shown in **Table 2**, the conventional method required 62.22%, 66.67%, 159.05%, and 821.44% more processing time on average, respectively, than did the proposed method for pattern image resolutions of 48, 300, 1200, and 4800 dots, respectively. Therefore, it is obvious that the proposed method is more computationally efficient than the conventional method. In particular, processing times for 3D surface modeling in the conventional method increased substantially for waved and arbitrarily shaped projection surfaces because pattern images of higher dot resolutions must be used to obtain accurate geometric information.

Table 1. Average processing times of the proposed method
(Resolutions of original input image and projector are 800-by-600 and camera resolution is 720-by-480)

Step	Average processing time (second)			
	48 dots	300 dots	1200 dots	4800 dots
Extraction of the 2D geometric information	0.14	0.62	2.40	8.14
Setting of the compensation area	0.03	0.04	0.03	0.04
Prewarping table generation	0.69	0.65	0.68	0.78
Prewarping image generation	0.04	0.04	0.04	0.04
Total processing time	0.90	1.35	3.15	9.00

Table 2. Average processing times of the conventional method[4][5]
(Resolutions of original input image and projector are 800-by-600 and camera resolution is 720-by-480)

Step	Average processing time (second)			
	48 dots	300 dots	1200 dots	4800 dots
Camera calibration	0.56	0.56	0.56	0.56
3D surface modeling	0.15	0.95	6.86	81.62
Prewarping table generation	0.71	0.70	0.70	0.71
Prewarping image generation	0.04	0.04	0.04	0.04
Total processing time	1.46	2.25	8.16	82.93

4.3 Measurement of Accuracy

Table 3 displays the results of compensation accuracy measured from the user's perspective. In order to extract geometric data of the projection surface, we used a pattern image with 1200 dot resolution in our experiment, and the original image was used as the pattern image to examine how accurately the dot pixel positions of the compensated image were compensated compared to the original image. From 1200 dots, we sampled 120 that were positioned with an equal space interval for comparison. The figures shown in **Table 3** are the sum of distances(SOD) among the pixels of the corresponding dots between the original image and the compensated image. SOD is defined as follows:

$$\text{SOD} = \sum_{i=1}^{120}\left(\sqrt{(x_i' - x_i)^2 + (y_i' - y_i)^2}\right) \tag{6}$$

where x_i' and y_i' denote the position of the characteristic point in the original image, and x_i and y_i the position of the corresponding dot in the compensated image. SOD is the sum of the distances among the corresponding 120 dots (i=1~120). Because the resolution of the original image is different from that of the compensated image, we scaled the original image to coincide with the compensated image for accurate SOD measurement. For comparative evaluation of the SOD of the proposed method, we measured SOD without compensation, with one of conventional methods developed by Park [4][5], and with the proposed method on tilted, bent, waved, and arbitrarily shaped projection surfaces. As shown in **Table 3**, without compensation, SODs among 120 corresponding dots on the four types of projection surface were 8239, 8325, 10698, and 6279. Using the conventional method, SODs were 218, 204, 239, and 221. Using the proposed method, SODs were 226, 213, 195, and 173. Comparing with the conventional method, the proposed method did not yield significant differences on tilted and bent planes. However, SODs on waved and arbitrarily shaped planes improved by 18.41% and 21.72%, respectively. Overall, the proposed method displayed a 9.52% improvement from the conventional method on the four types of projection surface.

4.4 Subjective Evaluation

In order to perform subjective picture quality evaluation of the proposed method, we conducted a survey among 16 volunteers with normal vision aged between 20 and 30 with compensated images. For the experiment, we used the original image shown in **Fig. 5** and conducted evaluation of the uncompensated image, image compensated with the conventional method [4] [5], and image compensated with the proposed method. The images were comparatively evaluated using the ITU-T Rec. P.910 Pair Comparison method according to 5 levels (excellent:4, good:3, fair:2, poor:1, bad:0) [9]. **Fig. 5** (a)–(d) displays result images from experiments performed on tilted, bent, waved, and arbitrarily shaped surfaces, respectively. On the first and second rows are the images compensated using the pattern images of 48 and 1200-dot resolutions, respectively. The images on

Table 3. Measurement of SOD for compensated result image(dot resolution is 1200)

Compensation Method	Sum of Distances(SOD)			
	Tilted	Bent	Waved	Arbitrarily Shaped
None	8,239	8,325	10,698	6,279
Park's method	218	204	239	221
Our method	226	213	195	173

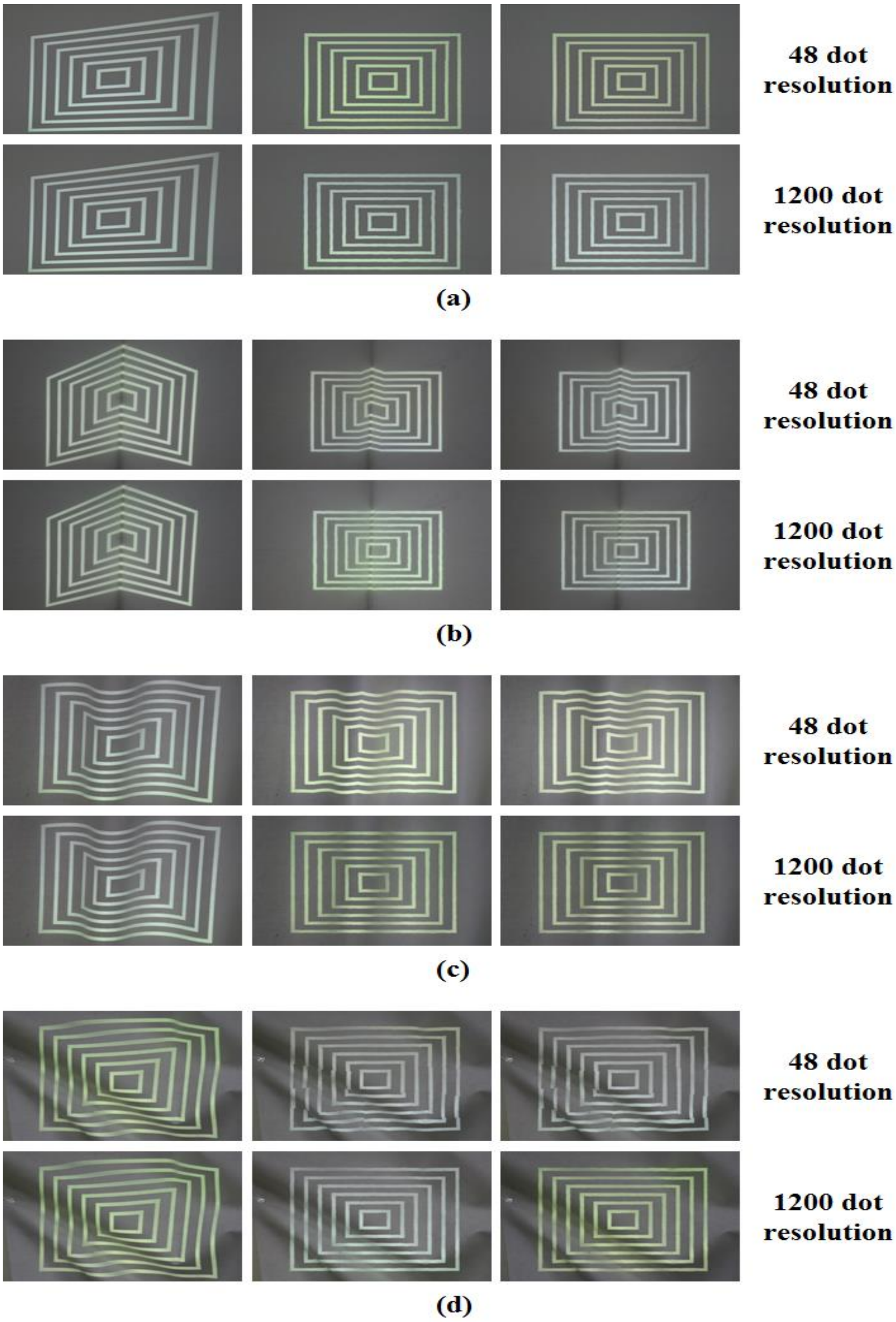

Fig. 5. Compensation results according to two different dot resolutions on four types of projection surfaces: (a) Compensation results for tilted surface; (b) Compensation results for bent surface; (c) Compensation results for waved surface; (d) Compensation results for arbitrarily shaped surface.

Table 4. Average Picture Quality Evaluation Scores Using ITU-T Rec. P.910 Pair Comparison (16 evaluators, scores out of 4)

Compensation Method	Distorted Plane	48 Dots	300 Dots	1200 Dots	4800 Dots	Average
None	Tilted	0.8				0.8
	Bent	0.5				0.5
	Waved	0.5				0.2
	Arbitrarily Shaped	0.2				0.2
Park's Method	Tilted	3.6	3.8	3.8	3.8	3.8
	Bent	1.9	3.3	3.5	3.6	3.1
	Waved	1.5	2.5	3.6	3.7	2.8
	Arbitrarily Shaped	1.5	1.0	3.5	3.6	2.4
Our Method	Tilted	3.6	3.9	3.8	3.8	3.8
	Bent	2.1	3.4	3.7	3.6	3.2
	Waved	1.2	2.8	3.6	3.7	2.8
	Arbitrarily Shaped	1.5	2.9	3.7	3.6	2.9

the left, middle, and right columns are uncompensated, compensated using Park's method [4] [5], and compensated using the proposed method, respectively. **Table 4** displays the picture quality scores evaluated using the ITU-T Rec. P.910 Pair Comparison method [10] on the uncompensated image of **Fig. 5**, image compensated with the conventional method, and image compensated with the proposed method. We have also added experimental results on the images compensated using pattern images of 300 and 4800 dot resolutions. On average, the images compensated with the proposed method earned picture quality scores 3.0, 2.7, 2.6, and 2.7 higher than uncompensated images on tilted, bent, waved, and arbitrarily shaped planes, respectively. Compared with the images compensated with the conventional method [4] [5], even though process time for 48, 300, 1200, and 4800 dot resolutions were reduced by 62.22%, 66.67%, 159.05%, and 821.44%, respectively, the picture quality evaluation scores of images compensated with Park's method and our method were similar, as shown in **Table 4**. This suggests that the proposed method is able to achieve visual effects similar to techniques based on 3D modeling on conventional projection surfaces while significantly reducing the processing time until prewarping table creation. The proposed method yielded varying results in terms of picture quality evaluation for various shapes of projection surface. Because a tilted plane's distortion is generally planar and regular, compensation using the proposed method was very effective regardless of dot resolution, earning an average score of 3.78. A bent plane has regular distortion on both sides of a vertically bent line, and a higher score was obtained than waved and arbitrarily shaped planes when using a pattern image with an identical dot resolution. However, when using a pattern image with the lowest resolution of 48 dots, the evaluation score was lower than that of the tilted plane. We believe this is because the dots are not near the vertically bent line, causing the compensated image to become distorted around the line. On the other hand, we were able to obtain satisfactory compensation results on waved and arbitrarily shaped planes when 1200 or more dots were used. This suggests that for complex and irregular distortion, dot resolution of the pattern image should be increased so that the geometric properties of the projection surface can be extracted with higher accuracy, and that computational complexity can increase significantly.

Consequently, the proposed geometric image compensation method can effectively compensate for geometric distortions of images projected on not only tilted and bent projection surfaces, but also waved and arbitrarily shaped projection surfaces. Moreover, while the proposed method uses 2D geometric information without cumbersome camera/projector calibration and extraction of 3D information, it delivers excellent compensated image quality. Based on further optimization of software and dot resolution of the pattern image according to the shape of the projection surface, the proposed method is expected to be implemented as an inexpensive and practical embedded system with reduced initial setup time and real-time image compensation for videos of 30 frames per second or higher. The proposed method also needs to be combined into video compression technologies for the multimedia information [10][11] and watermarking technologies for the multimedia security [12-14].

5. Conclusion

This paper proposed a geometric image compensation method for portable projectors to compensate for geometric distortions of images projected on various types of nonplanar projection surfaces including arbitrarily shaped surface. The proposed method is based on extraction of the 2D geometric information of a projection surface, setting of the compensation area, and prewarping using 2D homography between the original input image and distorted image on the projection surface. Experimental results confirm that the proposed method offers visually effective compensation for various types of distorted projection surfaces, including waved and arbitrarily shaped surfaces often found in mobile environments in which a dedicated planar screen is not readily available. Furthermore, the proposed method is more computationally efficient than the conventional methods based on 3D geometric information acquired from the projection surface. The proposed method allows users to overcome limitations, such as having to install a dedicated screen or install the projector vertically with reference to a planar projection surface, and is applicable to portable video projectors.

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