Low-Cost Smart Projector for Home Entertainment*

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A projector can support a large-screen display at a lower cost than a television which is currently the most useful home entertainment device. Because most families live in small spaces, they cannot easily make full use of the benefits of projectors. This work solves the problem of projecting the largest possible display image in a small space, without limiting the projective distance or area. A camera connected with the projector is adopted to capture information about the screen surface and environment. Plane homographies are then used to correct distortions of the input image caused the projection surface. The display image then seems to be displayed on a virtual screen toward the viewer. The proposed method solves of skewed display image caused by oblique projections. The experimental results demonstrate that the proposed system can change the display environment for home entertainment.

Keywords: plane homography, smart projector, projective geometry, image warping, multiple-plane projection

1. INTRODUCTION

Television plays a vital role in home entertainment due to the convenience of watching larger-screen displays. Hence, electronic appliance companies continuously innovate in various television display technologies, such as flat-panel liquid-crystal and plasma display, generating a large commercial market. Manufacturers of household appliances have invested much capital to study how to improve television displays reduce their prices. However, the traditional television as a primary display device of home entertainment has many physical limitations. For example, the display size is restricted to that of the artificial canvas, constraining the maximum screen size, refresh rate, and power consumption [1]. Conversely, because projection capability is improving and reducing in price, projectors are used not only in conferences, official business, and teaching, but also using increasingly in the family home. A projector can produce a larger display than a television set, and has a smaller volume and lighter weight at a lower price, making it more suitable for a home theater in a family home. The major disadvantage of projectors is their low brightness compared to television display is. However, manufacturers are continuously improving the brightness of projectors [2], such that viewers are increasingly satisfied with modern projectors.

Projective geometry indicates that in a small-scale indoor space, a projector can only be project images on the monochromatic and front plane limiting the projector’s convenience and practicability. Since the indoor space of a typical family home is small,
it cannot provide enough projection distance to obtain the expected display size on the front wall or the screen. Only a projected image can be obtained that smaller than that of a TV. Fig. 1 illustrates a rectangular space with proportions similar to those of a typical sitting room where \( P_1, P_2, \) and \( P_3 \) denote the positions of the projector at different projective directions. The projection area widths that they can produce on the wall are \( W_1, W_2, \) and \( (W_{31} + W_{32}) \), respectively. Thus a projector located at \( P_3 \) can create a larger projection area than a projector at the traditional location (i.e., \( P_1 \)) even in a small space. However, locating a projector at \( P_3 \) leads to serious distortions in the projected image preventing its use as a location. This work develops a projector system with an extra camera to sense the projective environment and to simulate the viewer’s position. Systems that use information about the screen surface and environment are called smart projectors [1]. Smart projectors correctly pre-distorted the projected image will be based on principles of projection geometry before projection so that the display image seems to be projected onto a virtual screen toward the viewer. The experimental results show that the proposed system solves the problem caused by distorted projections.

Some research papers in the literature address the topic of camera-projector systems as well as the related topic of calibration technologies. First, the original work for projecting an image on a plane or multiple planes was demonstrated in SIGGRAPH98. The method employs structured light technology to re-construe the 3D environmental model and assume the parameters of the camera are known. However, this approach will consume too much time. Raskar and Beardsley [3] estimate the direction of the vertical projection plane using a tilt sensor for automatic calibration. The camera and projector were fixed on a frame for making a stereo pair thus that restricts the range of the application. Bimber et al. [4] compare the differences of a video between the original and playing images for projector calibration. While Okatani and Deguchi [5, 6] employ multiple projectors or a projector at different places to project the calibration patterns and calibrate the projectors by the projections of the calibration patterns captured by cameras. Also, the method by Sukthankar et al. [7] derives the transforms from planar homography that the used features are generated by a laser pointer. However, the above methods all need extra hardware equipments that are unsuitable for home applications. Ashdown [8] extended planar homography for the projection environment with multiple planes. It projects sets of horizontal and vertical lines and finds the turning points of lines which form the intersection line of two adjoined planes. However, it is difficult for accurately determining the position of the turning point.

The proposed system includes a standard projector for receiving videos or images from the computer. A low-price camera is employed to point and simulate the position of the viewer. First, a display image from the camera which includes information of both the projection area and the distorted projection image (see Fig. 2 (a)), is taken using the camera. Then correspondences of features between the display image and the uncorrected image are constructed by corner detection. The transformation relation is estimated by
feature correspondences and is used to correct the geometry of the input image, which is re-projected as a corrected image for the viewer (refer to Fig. 2 (b)). Two cases were processed and analyzed in the proposed work with the projective surface composed of a single plane and a pair of adjacent planes. The proposed system is available for most indoor projection environments. One additional camera was adopted for the whole projector system. Therefore, the total price of the projector system is cheap and continually falling. Hence, the proposed system provides high values popularizing the use of a projector.

The rest of this paper is organized as follows. Section 2 describes the principle of planar homography that used in projective geometric transforms. Section 3 explains the processes of features extraction and finding maximum inside rectangle. Section 4 describes the projection for the case of multiple planes. Section 5 illustrates the implementation results and accuracy analysis. A brief conclusion and future extension are presented in section 6.

2. PLANAR HOMOGRAPHY

The mapping relationship from points on a plane to points on another plane using perspective geometry is known plane projective transformation, the plane-to-plane projection or the 2D-2D projective mapping [9]. A homography is described by a \(3 \times 3\) non-singular matrix, and is a bi-directional mapping for two planes. This section introduces the basic geometric properties used in the proposed paper. Three coordinates systems defining the global 3D space, the camera and the image plane are first described. Mapping relationships among three coordinate systems are found from the projection theorem. The points on the input image corresponding to points on the projection surface are obtained from the mapping. The input image is then corrected and projected onto the projection surface according to the viewing position of the viewer.

This work adopts the World Coordinate System (WCS), which is a right-handed 3D Euclidean coordinate system in 3D space. The three coordinate axes are given by \(X_W\), \(Y_W\), and \(Z_W\) (see Fig. 3). The camera is modeled as a pinhole camera, and defined by another coordinate system, called the Camera Coordinate System (CCS) whose three coordinate axes are given by \(X_C\), \(Y_C\), and \(Z_C\). The origin of CCS is the center of projection (COP) of the camera, and \(Z_C\) is superimposed with the optical axis. Additionally, the image of the camera is a plane expressed with a 2D coordinate system called the Image Coordinate
System (ICS), defined with axes $U$ and $V$. The normal vector of image plane parallels to $Z_C$ of the CCS and passes through the center of image plane. The axes $U$ and $V$ are parallel to $X_C$ and $Y_C$, respectively. The distance between the image plane and COP is the focal length $f$. Fig. 3 shows the geometric configurations of these three coordinate systems.

### 2.1 Estimating the Homography

Let $P_C = (X_P, Y_P, Z_P)^T$ denote a point in CCS and projected onto the image plane at $p$: $(x_p, y_p, f)^T_{ICS}$. Their mapping relation can be expressed as

\[
\lambda \begin{bmatrix} x_p \\ y_p \\ f \end{bmatrix} = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix},
\tag{1}
\]

where $\lambda$ is a scale factor. The following relationship is obtained from the homogeneous coordinates for the points and Eq. (1).

\[
\begin{bmatrix} f X_p \\ f Y_p \\ f \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/f & 0 \end{bmatrix} \begin{bmatrix} X_P \\ Y_P \\ Z_P \\ 1 \end{bmatrix} = M \begin{bmatrix} X_P \\ Y_P \\ Z_P \\ 1 \end{bmatrix}
\tag{2}
\]

Let $P_W = (X_{WP}, Y_{WP}, Z_{WP})^T$ denote a point in WCS which can also be expressed as $P_C = (X_P, Y_P, Z_P)^T$ in CCS. The geometric relationship of a point in these two coordinate systems is represented by

\[
P_C = R P_W + T,
\tag{3}
\]

where $R$ and $T$ are the rotation matrix and the translation vector, respectively. The elements of $R$ and $T$ are the functions of extrinsic parameters of the camera. Eq. (3) is expressed in the homogeneous coordinates as

\[
\begin{bmatrix} X_P \\ Y_P \\ Z_P \\ 1 \end{bmatrix} = \begin{bmatrix} R_{3 \times 3} & T_{3 \times 1} \\ 0_{1 \times 3} & 1 \end{bmatrix} \begin{bmatrix} X_{WP} \\ Y_{WP} \\ Z_{WP} \\ 1 \end{bmatrix}
\tag{4}
\]
From Eqs. (2) and (4), the projective relation of a point from WCS to CCS can be written in matrix form

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} = M_1 \begin{bmatrix}
  X_P \\
  Y_P \\
  Z_P
\end{bmatrix} = M_1 \begin{bmatrix}
  R & T & 1 \\
  0 & 1 & 0 \\
  1 & 0 & 1
\end{bmatrix} = M_2 M_1 \begin{bmatrix}
  X_{WP} \\
  Y_{WP} \\
  Z_{WP}
\end{bmatrix} = M_3 \begin{bmatrix}
  P_{WP} \\
  1
\end{bmatrix} = M_4 \begin{bmatrix}
  P_{W}
\end{bmatrix}
\]  

(5)

where \( M_4 \) is a 3 \times 4 matrix.

In this paper, we define the projective plane is the \( X_W-Y_W \) plane. The point \( P_W(X_{WP}, Y_{WP}, 0)_{WCS} \) is thus on the projection plane. From Eq. (5), the correspondent point of \( P_W \) on the image plane is \( p \) and can be described as

\[
p = \begin{bmatrix}
  u' \\
  v' \\
  w
\end{bmatrix} = \begin{bmatrix}
  h_{11} & h_{12} & h_{13} & h_{14} \\
  h_{21} & h_{22} & h_{23} & h_{24} \\
  h_{31} & h_{32} & h_{33} & h_{34}
\end{bmatrix} \begin{bmatrix}
  X_{WP} \\
  Y_{WP} \\
  1
\end{bmatrix} = \begin{bmatrix}
  h'_{11} & h'_{12} & h'_{13} & h'_{14} \\
  h'_{21} & h'_{22} & h'_{23} & h'_{24} \\
  h'_{31} & h'_{32} & h'_{33} & h'_{34}
\end{bmatrix} \begin{bmatrix}
  X_{WP} \\
  Y_{WP} \\
  1
\end{bmatrix}
\]  

(6)

where \( H \) is the homographic matrix. Eq. (6) can be rewritten as

\[
\begin{align*}
  u &= \frac{u'}{w} = h_{11} X_{WP} + h_{12} Y_{WP} + h_{13} \\
  v &= \frac{v'}{w} = h_{31} X_{WP} + h_{32} Y_{WP} + h_{33}.
\end{align*}
\]  

(7)

Now consider four known corners, \( P_W: (X_W, Y_W, 0), i = 1, 2, 3, 4 \), which define the display area on the projection plane and their correspondent points \( p_i: (u_i, v_i) \) on the image plane. Eq. (7) gives

\[
\begin{bmatrix}
  X_{W_1} & Y_{W_1} & 1 & 0 & 0 & 0 & -u_1 X_{W_1} & -v_1 Y_{W_1} & h_{11} \\
  0 & 0 & 0 & X_{W_1} & Y_{W_1} & 1 & -v_1 X_{W_1} & -v_1 Y_{W_1} & h_{12} \\
  X_{W_2} & Y_{W_2} & 1 & 0 & 0 & 0 & -u_2 X_{W_2} & -v_2 Y_{W_2} & h_{13} \\
  0 & 0 & 0 & X_{W_2} & Y_{W_2} & 1 & -v_2 X_{W_2} & -v_2 Y_{W_2} & h_{14} \\
  X_{W_3} & Y_{W_3} & 1 & 0 & 0 & 0 & -u_3 X_{W_3} & -v_3 Y_{W_3} & h_{21} \\
  0 & 0 & 0 & X_{W_3} & Y_{W_3} & 1 & -v_3 X_{W_3} & -v_3 Y_{W_3} & h_{22} \\
  X_{W_4} & Y_{W_4} & 1 & 0 & 0 & 0 & -u_4 X_{W_4} & -v_4 Y_{W_4} & h_{23} \\
  0 & 0 & 0 & X_{W_4} & Y_{W_4} & 1 & -v_4 X_{W_4} & -v_4 Y_{W_4} & h_{24}
\end{bmatrix}
\]  

\[\triangleq M(P_W, p) H_v = K(p)\]

and
The image plane
\[ Z_w = 0 \]

The projection plane

Fig. 4. The geometric relationship between the projection plane and the image plane.

\[ P(X_{wp}, Y_{wp}, Z_{wp}) \]

\[ p(u', v', w) \]

Fig. 5. The correspondences of corners between the displayed and input images.

\[ H_V = M^{-1}(P_{w'}, p)K(p) \]

where the homographic matrix \( H \) can be obtained from \( H_V \) such that the 2D-2D projective mapping between the projection plane and the image plane is obtained (Refer to Fig. 4).

2.2 Projection Geometry

The screen surface area in the projector display environment is a rectangle that defined by four corners which respectively correspond to four corners in the input image. Fig. 5 illustrates the mapping relationship of the screen surface to the input image. By the corner detection, we can find the correspondence between two sets of four corners \( A: \{a_1, a_2, a_3, a_4\} \) and \( B: \{b_1, b_2, b_3, b_4\} \). The mapping transformation \( H \) can be determined using Eq. (9)

\[ H_1 = M^{-1}(A, B)K(B). \]

Consider a rectangular area to be projected on the projection surface, defined by a set of four corners \( C: \{c_1, c_2, c_3, c_4\} \) plotted in Fig. 6. Their corresponding area in the input image can be determined from the plane homography obtaining a set of four corners \( D: \{d_1, d_2, d_3, d_4\} \). The points inside the area defined by \( D \) are projected onto the predefined rectangular area in the projection surface. To project the whole input image onto the predefined rectangular area, the input image needs to pre-distort into the area defined by \( D \) (refer to Fig. 7), producing another 2D-2D projective mapping given by \( H_2 \). From the correspondence of \( B: \{b_1, b_2, b_3, b_4\} \) and \( D: \{d_1, d_2, d_3, d_4\} \), we obtain
The correspondences of corners between the largest inside rectangle in the display and input images.

Fig. 6. The correspondences of corners between the largest inside rectangle in the display and input images.

(a) Before.                        (b) After.

Fig. 7. The image warping for the original image.

\[ H_2 = M^{-1}(B, D)K(D) \]  

(11)

The mapping function in Eq. (7) is appropriate for all points on the area defined by \( B \). Therefore, the whole input image can be pre-distorted into the area defined by \( D \). The residual part of the corrected input image is assigned the black pixels (see Fig. 7 (b)).

3. IMAGE PRE-PROCESSING

The correspondences of features from both the projected image and the input image must first be extracted to obtain the planar homographic matrix. The proposed method adopts corners defining the ranges of the uncorrected and input images. When the projector is changed to a new position, the system will perform the following tasks:

(1) Project a single color image, like an uncorrected image, on the display surface,
(2) Capture the image by camera,
(3) Find the corresponding features by image pre-processing,
(4) Calculate two required planar homographies.

Therefore, these images require pre-processing. Fig. 8 shows the pre-processing flow chart.
3.1 Corners Detection

Because the projection plane, i.e., the wall or the silver screen, is a plane, the projected uncorrected image forms a rectangle, and the edge is a straight line. The feature points out can be obtained directly with corner detection methods [10, 11]. However, this method is not sufficiently accurate [12]. This work first applies the Hough Transform [13, 14] to find the edge lines, then computes the coordinates of the intersection points defined by the edge lines bordering the images. The Hough Transform is an intensive operation, but is only applied in the off-line planar homographic calculation, and thus does not affect the overall efficiency. Following the Hough Transform, four lines are extracted from the Hough space. The feature points are the points where the extracted lines intersect with the edge lines.

3.2 Maximum Inside Rectangle

As in Fig. 4, the set of four corners about the uncorrected image is given by \{a_1, a_2, a_3, a_4\}. However, the uncorrected image is distorted, and does not support a comfortable viewing area with respect to the viewer. A new display area, with the largest possible size, must be defined on the inside of the uncorrected image. The new display area is called the maximum inside rectangle (MIR), and is the projected area of the corrected image. The MIR can be defined in its size manually by the viewer or automatically by the system under typical height and width ratios (i.e., 3:4 or 9:16). The MIR is defined by the set of four corners \{c_1, c_2, c_3, c_4\} (see Fig. 9). To locate these corners, a rectangle based on the predefined size ratio is horizontally and vertically extended starting from the center of the
uncorrected image until one of the corners of the rectangle reaches the boundary of the uncorrected image. Once \( \{c_1, c_2, c_3, c_4\} \) is determined, the correspondences of the corners to the input image are obtained from Eq. (6). These correspondences can be adopted as the four control points to construct a rectangle denoting the target area defining the input image how to be geometric correction. The geometrically corrected projection is a simple linear warping (or rubber sheet) transform [11].

4. MULTIPLE-PLANE PROJECTION

Section 3 describes the process of the proposed method in the case of the projection surface with a single plane. This section introduces an extension of the method based on multiple-plane projections. In a multiple-plane projection, the display image is spanned on two or more neighbor planes. Fig. 10 shows this case. The case of two-plane projection is introduced to simplify the case.

![Fig. 10. The uncorrected projective geometry of the multiple planes.](image)

The multiple-plane projection uses the same geometric principles as the single-plane projection. The transform matrix is obtained by corresponding feature points from the uncorrected and input images. However, each separable plane of a multiple-plane projection surface has its own plane homography. The individual mapping relationship for each plane needs to be estimated. Moreover, feature points between two adjacent planes must be included in the mapping, as well as the four corners of a projection area. The new feature point, and its corresponding position on the input image, are obtained differently from in the single-plane projection, as explained in the following sections.

4.1 Planes Partitioning

Large-screen display areas with multiple planes are often in the home environment [15]. The display image is projected onto two or more planes. For this complicated case, the planes are separated by utilizing the property of change in shadow between the different planes. The intensities of planes observed from the same viewing direction are dependent on the inner product of two vectors, namely, the surface normal of the plane and the directional vector of light from the projector. Because the angle of two adjacent planes in home space is close to 90\(^\circ\), the difference in intensities of the planes is significant. Hence, two planes can be separated, and their boundary points can be extracted on
the intersection line by edge detection. For the purpose of accuracy, Hough transform is also applied to find the intersection line as the single-plane case. The feature points are the two intersection points formed by the boundary of the display area and the intersection line of the two planes. Fig. 11 displays the six feature points \( \{ e_1, e_2, e_3, e_4, e_5, e_6 \} \) of two adjacent planes.

4.2 Feature Extraction and Projection

The obvious difference between single-plane and multiple-planes projection cases is that the points \( f_2 \) and \( f_5 \) on the input image, the correspondent points of \( e_2 \) and \( e_5 \), cannot be found directly. These two feature points are not mapped to the corners of the input image unlike the other four points \( e_1, e_3, e_4, \) and \( e_6 \), which are one-to-one mappings with the four corners of the input image. Hence, the correspondent points of \( e_2 \) and \( e_5 \) on the uncorrected image must be firstly determined from the input image.

(a) Linear scanning: The structured light methods of the active sensing [8, 16] are employed to check the correspondence of feature points between the uncorrected and input images. First, a vertical scan line given by its column address in the input image is projected onto the projection surface. The vertical scan line shifts right horizontally. If the vertical scan line passes through the points \( e_2 \) and \( e_5 \) on the uncorrected image (refer to Fig. 12), then the correspondence of the feature point \( e_2 \) (or \( e_5 \)) is located in the point with the same column address and in the upper (or bottom) boundary of the input image. Because the scanning time is proportional to the display size, \( n \) colored scan lines are applied to scan the projection surface simultaneously. The \( n \) scan lines with particular colors can prevent ambiguity over the correspondences and reduces the scanning time by a factor of \( n \). However, a low-cost camera, e.g., a web cam, has a low dynamic range for colors, and should not use a large number of colored scanning lines since this increases the scan processing required.

(b) Geometry corrected projection: After the obtaining the correspondence of the feature points, the multiple-plane display surface is separated into individual simple rectangles for each plane. The corners of each rectangle and their corresponding corners on the input image are also found. For each plane, the method in section 3 is used to correct the correspondent portion of the input image and re-projected onto the projection surface. The whole geometry-corrected projection procedure is described as follows: (refer to Fig. 13).
The projection of the scan line

(a) The vertical scan line shifts in the input image along the x-axis.
(b) The linear scanning in the multiple-planes uncorrected image.

Fig. 12. Establishing the correspondences of corners between the input image and the multiple planes uncorrected image.

Fig. 13. The partitioning relationship between multiple-plane uncorrected and original images.

**Definition**

Let Planes 1 and 2 of the multiple-planes projection surface be defined by two sets of four feature points, denoted as \(E_1: \{e_1, e_2, e_4, e_5\}\) and \(E_2: \{e_2, e_3, e_5, e_6\}\), respectively. The correspondences of \(E_1\) and \(E_2\) in the input image are \(F_1: \{f_1, f_2, f_4, f_5\}\) and \(F_2: \{f_2, f_3, f_5, f_6\}\), respectively. The maximum inside rectangle on the uncorrected image is separated into two planes defined by two set of feature points \(G_1: \{g_1, g_2, g_4, g_5\}\) and \(G_2: \{g_2, g_3, g_5, g_6\}\) respectively. The correspondences of \(G_1\) and \(G_2\) in the input image are given \(P_1: \{p_1, p_2, p_4, p_5\}\) and \(P_2: \{p_2, p_3, p_5, p_6\}\) respectively.

**Procedure**

**Step 1:** Calculate the homography \(H_3 = M^{-1}(E_1, F_1)K(F_1)\) from Eq. (9) based on the correspondence of \(E_1\) and \(F_1\).

**Step 2:** Substitute \(H_3\) and \(G_1\) into Eq. (7) and obtain \(P_1\).

**Step 3:** Use the correspondence of \(E_2\) and \(F_2\) to calculate the homography \(H_4 = M^{-1}(E_2, F_2)K(F_2)\) from Eq. (9).

**Step 4:** Substitute \(H_4\) and \(G_2\) into Eq. (7) and obtain \(P_2\).

**Step 5:** Use the correspondence of \(F_1\) and \(P_1\) to calculate the homography \(H_5 = M^{-1}(F_1, P_1)K(P_1)\) from Eq. (9).

**Step 6:** Substitute \(H_5\) and points on the area defined by \(F_1\) into Eq. (7), and calculate the correspondent points in the input image.

**Step 7:** Use the correspondence of \(F_2\) and \(P_2\) to calculate the homography \(H_6 = M^{-1}(F_2, P_2)K(P_2)\) from Eq. (9).

**Step 8:** Substitute \(H_6\) and points on the area defined by \(F_2\) into Eq. (7) to calculate the correspondent points in the input image.

**Step 9:** Build the corrected image defined by \(P_1\) and \(P_2\).
Due to the homographies from the projector to two display planes are estimated independently, the projection at the both sides of the intersection line is no guarantee that they are consistent. According to the fact that the point on the intersection line will be transformed on the same position by two homographies, thus constraints between homographies are added. After two planar homographies were determined, multiple horizontal lines in the input image are projected and pass through the intersection line of the display planes. The intersection points between these projected lines and the intersection line were detected. When two planar homographies do not consist with the true geometry structure, two intersection points from the same projected line at two planes will be different. The constraint, two intersection points were replaced by their midpoint, is employed to refine two planar homographies. Thus the planar homography of the corresponding plane is estimated by four corners and multiple midpoints that will increase the accurate at the elements of the homographic matrix. This refinement will be executed until the change of the elements of the homographic matrix is under a predetermined threshold or a limited iterative execution number.

5. EXPERIMENTAL RESULTS

The section presents the results of the proposed system on both single-plane and two-plane projection surfaces. The developed smart projector system includes a consumer LCD projector, a CMOS webcam and a personal computer.

5.1 Single-plane Projection Surface

The left column in Fig. 14 shows the uncorrected images on a single-plane projection surface. The right column of Fig. 14 shows the predistorted projected images for a particular viewer following the geometry-corrected projection. The variation of the corrected images with respect to locating error of four corners is studied. The four corners are varied by noise with different variances, and then performing geometric correction for the predistorted projected image to investigate the robustness and effectiveness of the method. Fig. 15 depicts the variation of 81 tested points in the corrected image, where each points is tested 50 times, and the standard deviations ($\sigma$) of noises at four corners are 1, 2, and 3. We observe that the purposed method is robust.

5.2 Two-plane Projection Surface

The left column in Fig. 16 shows the uncorrected images on a two-plane projection surface. The right column in Fig. 16 shows the predistorted projected images for a particular viewer after plane partition and geometry-corrected projection. The variation of the corrected images with respect to locating error of the two intersection points between two planes is studied. The two intersection points (i.e., $e_2$ and $e_5$) are varied by noise with different variances, and then performing geometric correction for two sub-images of the predistorted projected image to investigate the robustness and effectiveness of the method. Fig. 17 depicts the variation of 11 tested points in the intersection line of the corrected image with by various noises, and the standard deviations ($\sigma$) of the noises at two intersection points are 1, 2, and 3.
Fig. 14. The experimental results on a single-plane projection surface; the left column show the uncorrected images and the right column shows the predistorted projected images.

Fig. 15. The displacement errors of 81 tested points on the single-plane projection surface after 50 times. (In pixels)

The effect of the refinement of two planar homographies by the added constraint is also verified. The experimental result without the constraint is shown in Fig. 18 (a). The projection of a straight line is not connected in two adjacent planes. After the refinement, the projection is corrected and shown in Fig. 18 (b). Fig. 18 (c) depicts the variation of 11 tested points on the intersection line of two projection surfaces, and the added various noises with standard deviations ($\sigma$) 1, 2, and 3. From the experimental results, the displacement errors of the refinement of two planar homographies by the added constraint in the purposed method are low and stable. It can be seen from these experimental results that in the middle part of the planar boundary without constraint can raise a larger error. It also shows all error’s SD is lower than 3 pixels at all of the tested points with constraint.
Fig. 16. The experimental results on a multiple-plane projection surface; the left column shows the uncorrected images and the right column shows the predistorted projected images.

Fig. 17. The displacement errors of 11 tested points on the two-plane projection surface after 50 times experiments. (In pixels)

5.3 Display Sizes

Table 1 compares different positions of the smart projector. Three different positions of projectors, A, B, and C have various projection distances to the same projection surface, which can be denoted as $d_A$, $d_B$, and $d_C$. The degrees of distortion of the display images are proportional to the projection distance, i.e., $d_A < d_B < d_C$. Therefore, the screen surface area is also proportional to the projection distance. The sizes of three MIRs increase similarly following geometry corrected projection. Fig. 19 shows the results of three MIRs.
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Fig. 18. The experimental results of the refinement of the planar homographies.

(c) The displacement errors of 11 tested points on the intersection line of two projection surfaces under two cases.

Table 1. Comparison of display sizes based on different projector’s positions. (in cm)

<table>
<thead>
<tr>
<th>Item</th>
<th>Position</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>0</td>
<td>106</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>The width of the MIR</td>
<td>128</td>
<td>133</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>The height of the MIR</td>
<td>97</td>
<td>103</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>The vertical distance between the ground</td>
<td>107</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>and the projector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 19. The projection results by three different positions of projectors, A (left), B (middle), and C (right).

According to the geometry of the projection, the field of view of the viewer and the projection space of the projector can be two rectangular cones with apexes at the viewer and the projector. The projection region $P_1$ is formed by the intersection of the display surface and the rectangular cone made by the projector. Let the intersection region of the display surface and the rectangular cone made by the viewer on the front of the display surface be $P_2$. Because the distance from the projector to the display surface is longer than the distance from the viewer to the display surface, we can always find the display area
on $P_1$ is larger than the area of $P_2$. Due to the relationship between the ratio of the shrinking and viewing angle is complex, the complete locating strategy of the projector is difficult to find. For a home environment, we can expect the viewer to set the projector in a proper location that is convenient for their enjoyment. The projector proposed in our method will provide the maximum display area (e.g., MIR).

5.4 Lighting Situations

Three different lighting situations and these results are shown in Fig. 20. The surveyed lighting cases are: ambient lighting, extra lighting, and two extra light sources. Because the planar homographies are defined by six corners under the case of two planes in the purposed method, we will check the locations of the six corners. Three uncorrected images under three different lighting situations are shown in the left column of Fig. 20. The results by pre-processing are in the center column and the predistorted projected images in right column. The displacements of the six corners under three different lighting situations are summarized in Table 2, which shows that the displacement of each corner is small, even in the complex lighting situation. The major reason for displacement is the threshold of binarization that adopts a high contrast uncorrected image to determine an accurate threshold value.

![Fig. 20. Experiments of under three different lighting situations; (a) The case of ambient lighting; (b) extra lighting on the right side, and (c) two extra light sources on the right and left sides. Column (1): the uncorrected images; column (2) the results after binarization; column (3) the predistorted projected images.](image-url)
Table 2. The displacement and coordinates of six corners in Fig. 20. (in pixels)

<table>
<thead>
<tr>
<th></th>
<th>Corner $e_1$</th>
<th>Corner $e_2$</th>
<th>Corner $e_3$</th>
<th>Corner $e_4$</th>
<th>Corner $e_5$</th>
<th>Corner $e_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>The ambient lighting</td>
<td>(94, 82)</td>
<td>(187, 72)</td>
<td>(265, 101)</td>
<td>(96, 208)</td>
<td>(202, 195)</td>
<td>(271, 213)</td>
</tr>
<tr>
<td>Extra lighting</td>
<td>(92, 81)</td>
<td>(189, 72)</td>
<td>(265, 101)</td>
<td>(97, 208)</td>
<td>(202, 195)</td>
<td>(271, 213)</td>
</tr>
<tr>
<td>Extra lighting</td>
<td>(2, 1)</td>
<td>(2, 0)</td>
<td>(0, 0)</td>
<td>(1, 0)</td>
<td>(0, 0)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Two extra light sources</td>
<td>(91, 81)</td>
<td>(190, 72)</td>
<td>(266, 102)</td>
<td>(96, 208)</td>
<td>(202, 196)</td>
<td>(272, 212)</td>
</tr>
<tr>
<td>Two extra light sources</td>
<td>(3, 1)</td>
<td>(3, 0)</td>
<td>(1, 1)</td>
<td>(0, 0)</td>
<td>(2, 1)</td>
<td>(1, 1)</td>
</tr>
</tbody>
</table>

6. CONCLUSION AND FUTURE WORKS

The work develops a simple, low-cost smart projector system, which does not require the viewer to perform complicated operations. The proposed method, achieves a larger display screen than that of a traditional television for home entertainment. For projection constrains from the space, a systemic method is provided to solve two cases: single plane projection surface and multiple planes projection surface. The plane homography is applied to estimate the mapping relationship. This approach has the advantage of simple computation, making it suitable for video display in real time. The experimental results show that the performance of geometry corrected projection is fully automatic, fast and accurate.

Notably, although the proposed method can employ either a single-plane or multiple-plane projection surface, in the home can be composed of, it must adopt a plain white surface. A colored projection surface would cause the colors of the display image to be mixed with that of the projection surface [17-19]. Therefore, a color alignment is needed before the corrected image is projected to such a surface. The work is based on the illuminating condition and the reflectance of the projection surface, which are captured from the extra camera. Significantly, the projection surface comprises arbitrary shape surfaces [20]. A 3D shape model of the projection surface can be constructed based on the active sensing technology, allowing the color and geometry correction to be executed. These works will be studied in future.

REFERENCES

5. K. Okatani and K. Deguchi, “Autocalibration of a projector-screen-camera system:


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