Fixed-Center Pan-Tilt Projector and Its Calibration Methods

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Abstract

We describe a new steerable projector, whose projection center precisely corresponds with its rotation center, which we call a "fixed-center pan-tilt (FC-PT) projector." This mechanism allows it be set more easily to display graphics precisely on the planes in the environment than for other steerable projectors; wherever we would like to draw graphics, all we have to do are locate the FC-PT projector in the environment, and directing it to the corners of the planes whose 2D sizes have been measured. Moreover, by describing multiple planes in the environment by an integrated 2D coordinate system, it can display even a graphic that lies across a boundary line of two planes in a similar way to a paper poster folded along the planes.

1 Introduction

Displaying visual information wherever in the real world has recently been attracting increasing attention in many research areas; human interfaces, ubiquitous computing, computer vision, and so on. And also there are many approaches to draw them. The most popular ways are using display devices, such as a display embedded in the environments and a head-mounted display. As they are getting thiner, smaller and lighter, they are expected to be used in more situations in our daily lives. However, they have some disadvantages: In the case of the embedded one, its drawable area is so restricted (only on its display, of course) that we need a lot of such displays to cover the environment, and of course it costs a lot. In the case of the head-mounted one, it is in fact very convenient because it is so small that it can be worn any time and can be used wherever its user is existing. However, to accomplish the geometrical consistency between the visual information and the environment. we have to measure the 3D structure of the environment and its 3D position and orientation precisely, which are too hard to be measured precisely.

On the other hand, there is also way by a projector. This way has the advantages that they are easy to set afterward in the environment, and that the visual information displayed in the real world can be observed easily for us, especially compared with the small Head-Mounted Displays. Moreover, if it has rotatable mechanism it can display on a wider are in the environment, and in addition to it, if there exist multiple such rotatable projectors, they may draw on almost all surfaces in the environment, and can draw larger images by projecting simultaneously.

Just by rotating the projector, as shown in Figure 1, projected graphics are distorted according to the relative orientation between the projector and the projected plane. To draw the undistorted graphics on the plane, we have to input the inversely distorted graphical information to the projector. In this paper, the rotatable projector is designed so that
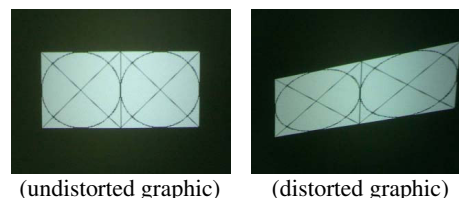

(undistorted graphic)   (distorted graphic)

Figure 1: Distortion of projected graphics

its projection center precisely corresponds with its rotation center. We call such a steerable projector a "fixed-center pan-tilt (FC-PT) projector." With the FC-PT mechanism, setting and controlling the FC-PT projector are much easier than for other usual steerable projectors, as described in Section 2. After calibration of the FC-PT projector, which is described in Section 4, we simply need to set it in the environment, and direct it to the corners of planes whose 2D areas have been measured. And after these operations, we can obtain graphical information at any position where we would like to draw it on the planes without distortion. We describe this calibration method in Section 4, and the projection method in Section 5.

Moreover, by assuming that multiple planes in the environment are expanded into one plane and describing all the planes by an integrated coordinate system, it can display a graphic that lies across the boundary line of two planes in the same way as a paper poster folded along the planes. We describe this function in Section 6.

There are several related works: In [1], they developed a hand-held projector with a camera. Although it can display undistorted graphics wherever the user hope, known patterns have to be projected preliminary and a partial 3D structure of the environment has to be reconstructed every time we settle the projector. In [2], they developed a steerable projector. However, as it is not designed in order that the projection center corresponds precisely at its rotation center, we have to project preliminary the patterns on every plane in the environment. In another study [3], graphics can be displayed on multiple planes; however, the projector is fixed.

2 The Advantages of the FC-PT Projector

2.1 The Fixed Projector

Only when the projector is settled perpendicular to the plane, we can display graphics of the same shape as the input of the projector. Unless this condition is achieved, the graphics projected on the plane is distorted according to the projector's orientation. And the sizes of the graphics are changed according to the relative position of the projector and the plane. Because of these, to display graphics whose size, shape and position we specify, we have to preliminary
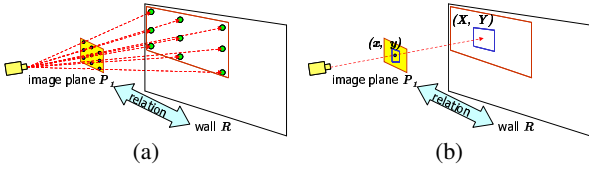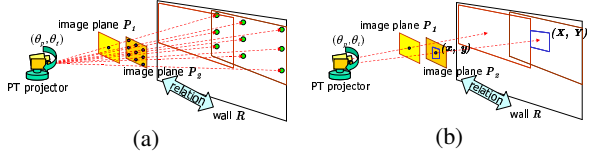
Figure 2: Projection using a fixed projector

Figure 3: Projection in a different direction using a PT projector

Figure 4: Projection using the FC-PT projector

calculate the relation between the input image P_1 of the projector and the plane R. To obtain this relation, known patterns (grid patterns, for example) are generated on the image plane P_1, projected onto the wall R, and measured (Figure 2(a)). As the relation between these coordinate systems is described by a 3×3 homography matrix [5], a minimum of four pairs of coordinates are needed to obtain the relation before the projector can display undistorted images on the wall (Figure 2(b)).

2.2 The Pan-Tilt Projector

To display graphics on a wider area in the environment, the projector is placed on a rotatable stage that pans and tilts electrically. We call such a projector a "pan-tilt projector." As with the fixed projector, the relation between the image plane and the wall must be obtained. However, for the pan-tilt projector, this is more complex.

In Figure 2.2, for example, if we rotate the projector to a different direction, as a result of which the image plane moves from P_1 to P_2, we now have to obtain the new relation between P_2 and R (Figure 2.2(a)). Then, similarly, we must repeat the process again, as for the initial direction, after which the projector can display undistorted graphics on the wall (Figure 2.2(b)). By repeating the process for various directions, finally we can display graphics precisely wherever we would like to display it. In the case of the pan-tilt projectors, because the relative positions of the projection center and the rotation center are unknown and hard to measure, we can not avoid these complicated operations.

In addition to the problem above, there is also another problem that moving graphics, which force it to rotate while projecting, can not be displayed by the methods. This is because the projector can take only specific directions which are taken when it has displayed the known patterns to the plane.

2.3 The FC-PT Projector

In this study, we present the FC-PT projector, whose projection center precisely corresponds with the rotation center in space. This mechanism is similar to the FV-PTZ camera [4]. The FC-PT projector can overcome the problem discussed in Section 2.2.

With the FC-PT projector, since the projection center does not move according to changes of direction, we can calculate the relation between the image planes at different directions only from the rotation angles (Figure 4(a)). Here,
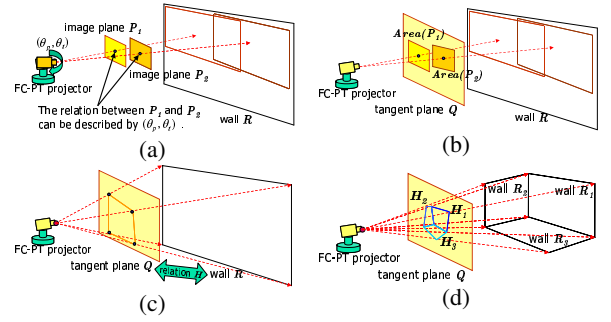
we introduce a plane to integrate all the image planes of different orientations. We call it the "tangent plane" (Figure 4(b)). The image plane of the FC-PT projector is projected on this tangent plane, and this projected region (called "projectable area" in Section 4), and the relation between the coordinates of the tangent plane and this projection area can be calculated. Therefore, as a result, we can treat the image coordinates for the arbitrary directions on the tangent plane. The calculation for this description calibrates the FC-PT projector, and its details are described in Section 4.

After calibration, the relation between the tangent plane and the plane in the environment must be obtained. The tangent plane does not move according to the rotation. Therefore, we need only to specify the information of directions of four points on the plane (its four corners, for example) (Figure 4(c)). Moreover, this operation can be extended easily to multiple planes in the environment; not only a wall but also other walls, floors, ceilings and so on (Figure 4(d)).

3 Implementation of the FC-PT Projector System

3.1 Fixing the Projection Center

We prepare a rotatable stage that pans and tilts electrically, as shown in Figure 5. The pan and tilt axes must cross each other, and the position of their intersection is fixed independently of the stage's orientation. To construct the FC-PT projector, its projection center must precisely correspond with this intersection. However, the complexity of obtaining the position of the projection center in space is such that we cannot directly fix the projection center precisely at the rotation center. Here, we apply a two-step method for constructing the FC-PT projector: rough estimation of the projection center's position, and precise fixing.

First, we roughly estimate the position of the projection center. A planar board is placed vertically and then horizontally as shown in Figure 6, and the boundary lines of the projected light are recorded. We then calculate the intersection of these lines, and treat the intersection as the roughly estimated position of the projection center.

Next, the projector is placed on the rotatable stage in so that the roughly estimated position of the projection center corresponds with the rotation center. The projector can be three-dimensionally repositioned on the stage along the x, y and z axes. There are two screens in front of the projector, and the nearer one (screen 1) has a small hole. When the projector is turned on, only the light that goes through this hole reaches at the further screen (screen 2). If the projection center is precisely at the rotation center, the projected point on screen 2 does not move even when the stage pans and tilts in any direction. This is because the light always originates from the same point. Inversely, the further the
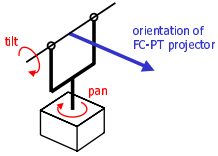
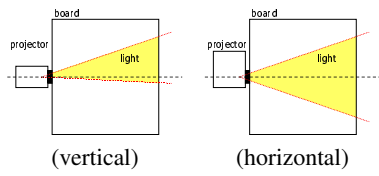Figure 5: Structure of rotatable stage
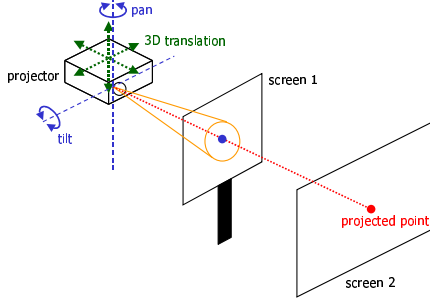

Figure 6: Rough estimation of projection center
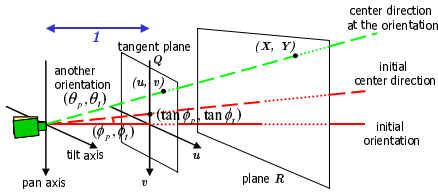

Figure 7: Precise fixing

Figure 8: Tangent plane

projection center is from the rotation center, the more the projected point moves. Therefore, the projector is continuously repositioned on the stage to search for the best position, where the projected point does not move at all.

3.2 System Configuration

By the process described in Section 3.1, the projection center is fixed precisely at the rotation center of the stage. A PC is then connected to the FC-PT projector; input images for the projector are transmitted from the PC, which also captures and controls orientation of the rotatable stage. We refer to this configuration as the "FC-PT projector system."

4 Calibration of the FC-PT Projector

For calibrating the FC-PT projector, we define the "tangent plane" as the plane that is in front of the projector and parallel to the pan and tilt axes of the stage at the initial orientation, as shown in Figure 8. We further assume that the distance between the tangent plane and the projection center is equal to 1. As is clear from the definition, the tangent plane is fixed independently of the orientation of the FC-PT projector. In this Section, we show that we can easily manipulate the image coordinates on this tangent plane at any orientation of the FC-PT projector.

First, we set the FC-PT projector to be at the initial orientation $\theta_p = \theta_t = 0$, where θ_p and θ_t denote the pan and tilt angles of the projector respectively. Grid points (x_i, y_i) $(i = 1, 2, 3, \cdots)$ each of whose coordinates on the image plane P are known, are projected at (X_i, Y_i) on the plane R in the environment. Here, these coordinates fulfill the equation below:

$$\begin{pmatrix} X \\ Y \\ 1 \end{pmatrix} = H_{PR} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}, \quad (1)$$

where H_{PR} denotes a 3×3 matrix having 8 degrees of freedom, which is called the homography matrix [5]. We can calculate H_{PR} linearly from a minimum of four pairs of (x_i, y_i) and (X_i, Y_i) [1].

Next, we project a point at the center of the image plane, onto the plane in the environment. We call this ray to the center of the image plane the "center direction." In an ordinary projector, the center direction is different from the orientation of the projector, so that the intersection point (u_c, v_c) of the center direction and the tangent plane is not $(0, 0)$ but $(\tan \phi_p, \tan \phi_t)$ on the tangent plane as shown in Figure 8, where ϕ_p, ϕ_t denote the difference between the front direction and the center direction of the projector. Therefore, when we rotate the projector to (θ_p, θ_t), the intersection (u, v) on the tangent plane is calculated as follows:

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \sim \begin{pmatrix} \lambda u \\ \lambda v \\ \lambda \end{pmatrix} = Rot_{(y, \theta_p)} Rot_{(x, \theta_t)} \begin{pmatrix} \tan \phi_p \\ \tan \phi_t \\ 1 \end{pmatrix}, \quad (2)$$

where $Rot_{(w, \theta)}$ denotes a matrix which rotates a coordinate at an angle θ around the w axis, and "$\sim$" denotes a equivalence in the projective geometry. We next rotate the projector to other orientations $(\theta_{pi'}, \theta_{ti'})$ $(i' = 1, 2, 3, \cdots)$, and project the center point of the image plane. For each orientation, we measure the projected point $(X_{i'}, Y_{i'})$ on the plane in the environment [2], and calculate the intersection $(u_{i'}, v_{i'})$ on the tangent plane from Equation (2). Note that the projection center is always fixed in the case of the FC-PT projector, so that $(u_{i'}, v_{i'})$ on the tangent plane is perspectively projected to $(X_{i'}, Y_{i'})$ on the plane in the environment. Therefore, $(u_{i'}, v_{i'})$ and $(X_{i'}, Y_{i'})$ also fulfill the following equation:

$$\begin{pmatrix} X \\ Y \\ 1 \end{pmatrix} = H_{QR} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}. \quad (3)$$

In a similar way to Equation (1), from a minimum of four pairs of $(u_{i'}, v_{i'})$ and $(X_{i'}, Y_{i'})$, we can calculate H_{QR} linearly. From Equations (1) and (3), we can obtain the equation below:

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = H_{QR}^{-1} H_{PR} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = H_{PQ} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}. \quad (4)$$

Because P denotes the image plane at the initial orientation, by substituting the coordinates of the four apices and the center of the image plane $((\pm 1024/2, \pm 768/2)$ and $(0, 0)$ in XGA, for example) to (x, y) in Equation (4), we can obtain the directions of these apices $(u_j^{(init)}, v_j^{(init)})$ $(j = 1, \cdots, 4)$ and the center $(u_c^{(init)}, v_c^{(init)})$, where $(u_j^{(init)}, v_j^{(init)})$ determine the projectable area on the tangent plane at the initial orientation, and $(u_c^{(init)}, v_c^{(init)})$ denotes the center of the projectable area.

By using the projectable area and the center on the tangent plane at the initial orientation, we gets able to calculate those at arbitrary orientations easily. This is because the relative directions between 3D vectors $(u_j, v_j, 1)^T$ and

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[1] To obtain (X_i, Y_i), we use a camera. The image captured by the camera is undistorted using Tsai's method [6]. On the plane we draw four points whose metric positions are known. By capturing the projected points and these four points, we can obtain (X_i, Y_i).

[2] In the same way as measuring (X_i, Y_i), we can measure them by the camera.

$(u_c, v_c, 1)^T$ in arbitrary orientation remain unchanged from $(u_j^{(init)}, v_j^{(init)}, 1)^T$ and $(u_c^{(init)}, v_c^{(init)}, 1)^T$. Therefore, we can calculate the projectable area at any orientation simply by rotation of the vectors.

For example, when would like to obtain the projectable area $(u_j^{(new)}, v_j^{(new)})$ from the center direction $(u_c^{(new)}, v_c^{(new)})$ they can be calculated by the following process sequence.

When we direct the center direction of the FC-PT projector to $(u_c^{(new)}, v_c^{(new)})$, its orientation $(u_o^{(new)}, v_o^{(new)})$ is calculated as follows:

$$\begin{pmatrix} u_o^{(new)} \\ v_o^{(new)} \\ 1 \end{pmatrix} \sim Rot_{(y,-\phi_p)} Rot_{(x,-\phi_t)} \begin{pmatrix} u_c^{(new)} \\ v_c^{(new)} \\ 1 \end{pmatrix}. \quad (5)$$

When we rotate the FC-PT projector to $(\theta_p^{(new)}, \theta_t^{(new)})$, its orientation is calculated as follows:

$$\begin{pmatrix} u_o^{(new)} \\ v_o^{(new)} \\ 1 \end{pmatrix} \sim Rot_{(y,\theta_p^{(new)})} Rot_{(x,\theta_t^{(new)})} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$= \begin{pmatrix} \sin\theta_p^{(new)} \cos\theta_t^{(new)} \\ -\sin\theta_t^{(new)} \\ \cos\theta_p^{(new)} \cos\theta_t^{(new)} \end{pmatrix}. \quad (6)$$

As $(u_o^{(new)}, v_o^{(new)})$ has been calculated in Equation (5), we can calculate $(\theta_p^{(new)}, \theta_t^{(new)})$ from Equation (6).

$$\theta_p^{(new)} = \tan^{-1} u_o^{(new)}, \quad (7)$$
$$\theta_t^{(new)} = -\tan^{-1}(v_o^{(new)} \cos\theta_p^{(new)}). \quad (8)$$

Once we have obtained $(\theta_p^{(new)}, \theta_t^{(new)})$, we can easily obtain the projectable area on the tangent plane at this orientation:

$$\begin{pmatrix} u_j^{(new)} \\ v_j^{(new)} \\ 1 \end{pmatrix} \sim Rot_{(y,\theta_p^{(new)})} Rot_{(x,\theta_t^{(new)})} \begin{pmatrix} u_j^{(init)} \\ v_j^{(init)} \\ 1 \end{pmatrix}. \quad (9)$$

5 Projection onto a Plane

After calibration, the relation between the tangent plane Q and a plane R_1 on which we will display graphics is needed. As this relation is described as a homography matrix H_{QR1} and can be calculated only by Equations (2) and (3) with four pairs of coordinates on these planes, we need to measure the orientations of the center direction to the four corners of the plane R_1, whose 2D metric coordinates have been obtained. The FC-PT projector's orientations can be obtained by directing manually its center direction to these corners. Hereafter, obtaining the relation between Q and R with the corners' coordinates is referred to as "plane registration."

We now describe the calculation for the FC-PT projector to display graphical information without distortion on the plane R_1 in the environment. Assume, for example, that a rectangular graphic is displayed whose apices are $(a_k^{(gra)}, b_k^{(gra)})$ $(k = 1, \cdots, 4)$, defined by their own metric coordinate system as shown in Figure 9. To display the rectangle precisely, we have to calculate the apices on the
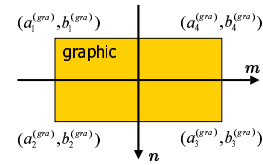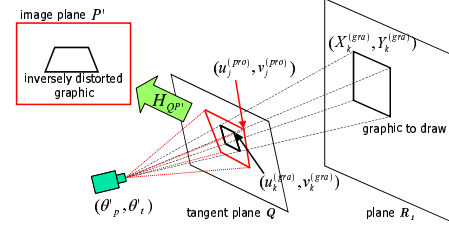

Figure 9: Coordinates of graphic

Figure 10: Process for a plane

image plane $(x_k^{(ans)}, y_k^{(ans)})$ according to the orientation of the FC-PT projector (θ_p', θ_t'), as shown in Figure 10. As we have obtained the relation H_{QR1}, this can be solved as follows.

First, the system records the orientation (θ_p', θ_t') of the FC-PT projector, and describes the center direction on the tangent plane as (u_c, v_c) by Equation (2). Next, (u_c, v_c) is projected onto a plane in the environment. The projected point (X_c, Y_c) is calculated by:

$$\begin{pmatrix} X_c \\ Y_c \\ 1 \end{pmatrix} = H_{QR1} \begin{pmatrix} u_c \\ v_c \\ 1 \end{pmatrix}. \quad (10)$$

The graphic is displayed at (X_c, Y_c) on the plane in the environment, and the four apices of the graphic are calculated as follows:

$$X_k^{(gra)} = a_k^{(gra)} + X_c, \quad (11)$$
$$Y_k^{(gra)} = b_k^{(gra)} + Y_c. \quad (12)$$

The for apices are then projected onto the tangent plane:

$$\begin{pmatrix} u_k^{(gra)} \\ v_k^{(gra)} \\ 1 \end{pmatrix} = H_{QR1}^{-1} \begin{pmatrix} X_k^{(gra)} \\ Y_k^{(gra)} \\ 1 \end{pmatrix}. \quad (13)$$

As described in Section 4, when we have obtained (θ_p', θ_t') we can also easily obtain the projectable area on the tangent plane at this orientation from Equation(9), as follows:

$$\begin{pmatrix} u_j^{(pro)} \\ v_j^{(pro)} \\ 1 \end{pmatrix} \sim Rot_{(y,\theta_p')} Rot_{(x,\theta_t')} \begin{pmatrix} u_j^{(init)} \\ v_j^{(init)} \\ 1 \end{pmatrix}. \quad (14)$$

From Equations (13) and (9), we have described the projectable area and the graphic on the tangent plane in the orientation (θ_p', θ_t'). We next have to obtain the apices of the graphic on the image plane P' in this orientation to project to the plane R_1. As $(u_j^{(pro)}, v_j^{(pro)})$ correspond to the apices $((\pm 1024/2, \pm 768/2)$ in XGA$)$ on P', we can calculate a homography matrix $H_{QP'}$ that transforms the coordinates on Q to those on P'. By applying $H_{QP'}$ to $(u_k^{(gra)}, v_k^{(gra)})$ in Equation (13), we can obtain $(x_k^{(ans)}, y_k^{(ans)})$, which de-
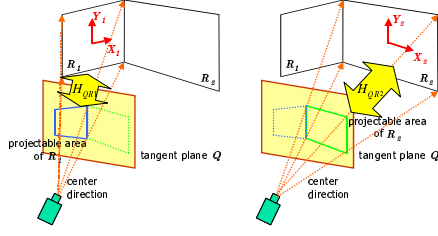
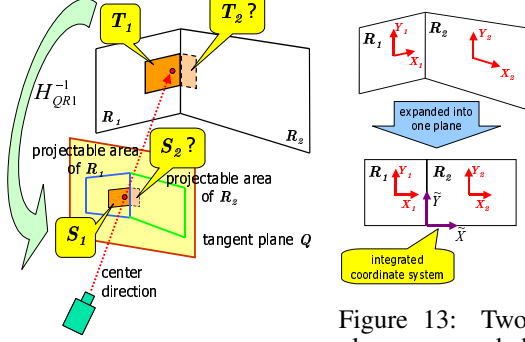Figure 11: Registration of two planes (using two coordinate systems)

Figure 12: Projection to the boundary line (failure)

Figure 13: Two planes expanded into one plane

Figure 14: Registration of two planes (using the integrated coordinate system)

Figure 15: Projection to the boundary line (success)

fines the graphic that should be input to the projector:

$$\begin{pmatrix} X_k^{(ans)} \\ Y_k^{(ans)} \\ 1 \end{pmatrix} = H_{QP'} \begin{pmatrix} u_k^{(gra)} \\ v_k^{(gra)} \\ 1 \end{pmatrix}. \tag{15}$$

6 Projection onto Multiple Planes

There are many planes in the environment, on which it is desirable to be able to display graphics. The FC-PT projector is appropriate for such demands because the projection method for a plane described in Section 5 can be extended to that for multiple planes. As the plane registration can be done by measuring the direction of the four corners of the plane, we can register even multiple planes in the environment, as shown in Figure 6. H_{QRm} $(m = 1, 2, \cdots)$ which define the relation between Q and R_m are obtained by this registration.

However, this method has a problem that the graphics lying across boundary lines of the planes cannot be displayed precisely. This is because the 2D coordinate system of each plane is defined independently. In Figure 12 for example, when the center direction goes near the boundary line, only the part T_1 of the graphic can be determined on R_1, and then S_1 can be calculated by H_{QR1} and the apices of T_1. On the other hand, the part T_2 cannot be determined because the coordinate system of R_2 is different from that of R_1.

To overcome this problem, we introduce the "integrated coordinate system" instead of the unique coordinate systems of the planes. The integrated coordinate system is defined as an arbitrary 2D coordinate system on the expanded plane of all the planes. In the case of two walls for example, it is easy to understand that these walls are expanded into one plane and $\tilde{X}$ and $\tilde{Y}$ axes of the integrated coordinate system are defined as horizontal and vertical line of the room respectively, as shown in Figure 13. After determining the integrated coordinate system on all the planes R_m, we calculate $\tilde{H}_{QRm}$ which define the relation between the coordinate of Q and the integrated coordinate of R_m.
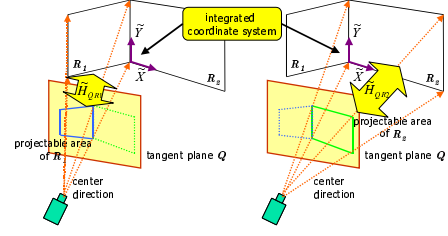
By the introduction of the integrated coordinate system, the graphic can be displayed precisely even on the boundary line of the planes. When we display the graphic on the boundary line as shown in Figure 15, the part T_2 can be determined on R_2 as well as T_1 on R_1 because both T_1 and T_2 are described by the same coordinate system. And as $\tilde{H}_{QR1}$ and $\tilde{H}_{QR2}$ have been calculated in the registration process, the apices of S_1 and S_2 on Q, which correspond to T_1 and T_2 respectively, can be calculated. After obtaining these apices, we can calculate the apices of the graphic on the projector's image plane by the same way as Section 5.

7 Experimental Results

Figure 16 shows the FC-PT projector. It consists of a projector (V3-131, Plus Vision) and a rotation stage that pans and tilts electrically. We prepared two walls as shown in Figure 17, and measured the lengths of the vertical and horizontal edges of those walls. We then directed the projector to the six points shown in Figure 17 and recorded their directions.

Figure 18 and Figure 19, show the experimental results. We control the projector to always display a $40\text{cm} \times 20\text{cm}$ rectangle on the walls. As shown in (a), (b) and (c) of Figure 18, we can display the rectangle on each wall; and in (i)–(iv) of Figure 19, we can see the same size rectangle lying across the boundary line of two planes, as if a paper poster were pasted there folded along the planes. Moreover, as (i)–(iv) represent a time sequence , we confirmed that the rectangle remains continuously undistorted even while moving.

8 Conclusions

We have described a new steerable projector, the FC-PT projector, whose projection center precisely corresponds with its rotation center. We also presented calibration methods for the FC-PT projector. Due to this unique architecture and calibration, we can project visual information at any position on a plane in the environment. Furthermore, we expanded the projection methods to encompass multiple
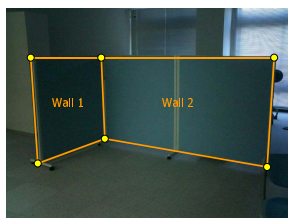
Figure 16: FC-PT projector
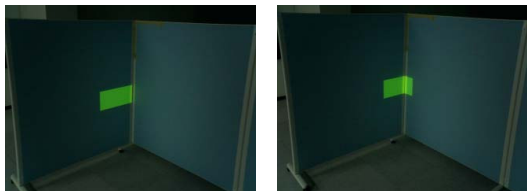

Figure 17: Walls for projection

(a)

(b)

(c)

Figure 18: Projection on each wall

(i)

(ii)

(iii)

(iv)

Figure 19: Projection on the boundary line

Figure 20: Three planes in the environment

(a)   (b)   (c)

Figure 21: Three possible expanded planes

planes, enabling us to use the FC-PT projector for numerous applications.

Future work will include the following:

- Our method for projection onto multiple planes applies the fixed integrated coordinate system. Therefore, In the case of three planes each of which is connected to the others as shown in Figure 20, there are three possible expanded planes shown in Figure 21. However, whichever expanded plane is chosen, there is a boundary line on which the graphic cannot be displayed precisely. For example, when the expanded plane (a) is chosen, the connection between R_1 and R_2 cannot be recognized so that the graphic cannot be displayed on the boundary line of them. To avoid this problem, the expanded plane has to be changed dynamically according to which plane is mainly projected on.

- In the current implementation, the system needs the metric 2D shape of each plane; these must be measured them before projection. To overcome this prob-
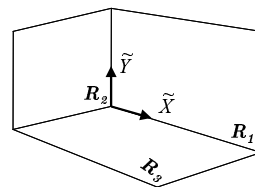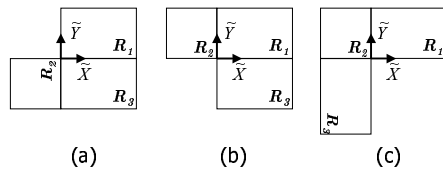
lem, we are now developing methods in collaboration with camera systems to automatically detect and register multiple planes in the real world.

- Although the FC-PT projector can display visual information over a wider area than other fixed projectors, it is inadequate for certain applications. For example, it cannot display visual information on the floor following a person walking a wide area, or display images whose size are larger than the capacity of one FC-PT projector. We therefore wish to place multiple FC-PT projectors in the environment, and control them simultaneously. However, when two or more images are projected, they usually do not overlap precisely because of the errors. Overcoming this problem is another important topic.

Acknowledgments

References

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