Image Information Processing System for Hemispherical Screen With Dual 1080P High-Resolution Projectors*

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In this paper, we consider the problem of 3D virtual reality content real-time project on hemispherical screen. The developed hemispherical screen is 1.2 meters in diameter and screen’s shape covers 180 degrees of the vertical and horizontal planes, provides all-encompassing image space for virtual reality simulation. Display equipment of system adopts two high definition front-projectors and uses image stitching for generating fine image and wide-angle view, this reinforces the audiences’ visual feel as if they were actually within the hemispherical display environment. Due to posture of projectors and shape of screen critical influence image accuracy on screen, we design and analyze posture of projector corresponding to original of system. Base on confirmable projectors’ posture, we also take advantage of pre-warping correctional method to adjust image warping and alpha-mask method to reduce intensity of overlapping area. Besides, we stitch wide-angle seamless content by mosaicicked image taken by cameras in 3D VR. To connect various correctional processes in 3D VR software, a real-time content will display on hemispherical screen.

Keywords: hemispherical screen, virtual reality, visual immersion, wide-angle seamless, pre-warping correction, alpha-mask technique

1. INTRODUCTION

The main elements of virtual reality are the high level of visual immersion, the rich room for imagination, and the real-time interactive feedback. Among human perceptions, vision is the sensitive and most direct to receive nearby conditions. All kinds of imagery stimulate people’s imagination, and it is easy to lead people immerse in visual image. At the outset, multi-projector tiled displays [1-4] have been described for building up an immersed experience. These systems stitched each smaller projection for creating a large and detailed planar image, let people rudimentary grasp immersed feelings of larger display. Tiled displays provided a solution inadequate could be changed to insufficient image resolution in large screen displays, and were a great contribution to later various tiled displays. However, human visual can’t concentrate due to planar display belongs to a half-open space. Thus wider fields of view became as important as large images. This resulted in the development of CAVE, cylindrical, surrounding [5-9], and hemispherical or called hyperboloid screen [10-18] developed in succession. It reinforces the audiences’ feel as if they were actually within the virtual reality environment. Nature of the immersive display makes the audience’s vision focuses on the displayed image, whatever cave, surrounding, and cylindrical screens. However, hemispherical screen displays the

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image covering 180 degrees top, bottom, left and right four directions, and then it is the most optimal match for the human field of view.

Hemispherical screen provides the best spatial coverage where distance to any part of the screen always remains from a viewpoint located at the center of the screen; this means that there is no sense of confinement in what is being perceived. A single fisheye lens projector [10, 11] equipped with a specially designed lens can be used to project an image on to two curved surfaces that resemble a hemisphere. Its advantage is that a single fish-eye lens can be used to provide the image output without requiring complex image correction techniques. Its disadvantage however is the inferior resolution when a single projector is used for large displays.

The scope of our system belongs to a personal display system according to screen’s dimension is 1.2 meters in diameter, and two projectors are arranged to vertical and horizontal aspect ratios of 16:9. Each projector is rotated 90 degrees and used for projection onto left and right area of hemispherical screen, as the system uses two high definition (HD) projectors it is referred to as "TwinHD". The system don’t adopt any hardware for correcting image warping and alpha-mask on image stitching, all correctional methods are implemented in algorithm part.

In program development, we conclude by looking at how capturing hemispherical field of view in 3D virtual reality by utilizing wide-angle seamless correction. And then we build pre-warping correction and alpha-mask technique within 3D virtual reality software “Virtools”. While wide-angle seamless images and correctional procedure are developed within the same software, wide-angle seamless images directly pass through the pre-warping and alpha-mask correctional procedure. At last, the system will project wide-angle image on hemispherical screen correctly. In other words, by processing the wide-angle seamless images of 3D virtual reality through the defined procedural framework of TwinHD, the system is able to put hemispherical wide-angle image and 3D virtual reality together. The rest of this paper is organized as follows. Section 2 describes the design and analyze of the projection mechanism. The principles of wide-angle seamless, pre-warping and alpha-mask correctional technologies will be explained in section 3; the hardware and software of system will be described in section 4. The experimental results are provided in section 5. Conclusions are given in section 6.

2. DESIGN AND ANALYSIS

The impact of projection area on high-curvature hemispherical screen is very significant. If no extra camera is deployed to determine the projection area, the position and rotating angle of the projector are important factors to be verified before image correction.

2.1 Design of Projectors Position

In general, the standard position of projector is arranged at ahead of screen. The aspect ratio of the projected image’s height and width was 16:9, it was easier to set two projectors front of screen to cover the entire hemispherical screen of aspect ratio of 1:1 (as illustrated in Fig. 1 (b)). And then an aspect ratio of 1:1 rectangular area stitched with
left and right projection image with overlapping region, it illustrated clear from the front view as Fig. 1 (c). If the viewer was located at the center of the screen however they may physically block the projectors and cast a shadow on the screen (see position A, as illustrated in Fig. 1 (a)), the projector’s light path must avoid the viewer’s body [13, 14]. The positioning of the projectors in our system takes into consideration the projectors’ specifications and the need to avoid the location of the viewer. The projectors were therefore suspended from above to project the image downwards on the screen, this allowed for advanced planning and placement of the projection screen and projectors (see position B, as illustrated in Fig. 1 (a)) [6, 15, 16].

When projectors suspended above on position B, the same also applied to the left edge of the right-side projector as illustrated in Figs. 1 (d) and (e). The position and orientation of the projectors showed that a combined image covering the entire screen could be achieved with two projectors. The result was that the viewer must sacrifice some viewing area and move their point of view 30cm away from the center of the screen to avoid blocking the image as Fig. 1 (a). According to the designed projector angle and location and perspective algorithm, the minimum distance between the eyepoint and the screen has to be 30 cm in order to prevent forming of the shadow. However, the image projected on the screen is determined via the D-H principle and pre-warping method. So the image displayed on the screen is non-distorted half-space image. When the eyepoint is at 30 cm from the center, its impact on the visual sense is a visual angle change of 126 degrees. Except decrease in visual emersion, it does not result in visual distortion. The spatial sensitivity of human eyes is higher at foveal. Therefore, most of the visual sense will be fixed on the center of the image.

![Fig. 1. Different projection area is cause of projector’s position and orientation.](image-url)
2.2 Analysis of Projection Mechanism

To determine the orientation and position of the projector in relation to the system origin, center of hemispherical screen, their relations are analyzed gradually via the joint \( J_i \) and link \( L_i \) of the mechanism. The projection mechanism is so designed that the projector is attached to a support unit to give the projector “tilt” and “pan” and functions (as illustrated in Fig. 2 (a)) that allow the projector to be hung or tilted at any angles to project the image at the hemispherical screen. Meanwhile, it is required that the entire screen be covered. The mechanism total has four joints, include system original, projector lens and main wall mount mechanism. The center of the screen is the datum point of the mechanism. Joints number from 0 to 3 starting from the original of mechanism, which is taken as 0. According to the mechanism diagram of the projection system (as illustrated in Fig. 2 (b)), \( J_0 \) is the center of the hemispherical screen, \( J_1 \) and \( J_2 \) is the pan and tilt function of the projection system, and \( J_3 \) is the position of the projection lens. The diagram is redefined by the D-H principle and illustrated via point-line drawing (as illustrated in Fig. 2 (c)).

![Fig. 2. The mechanism diagram of projection system.](image)

As illustrated in Fig. 2 (c), the coordinate relationship between each adjacent joint \( J_i \) includes rotation \((\alpha_i, \theta_i)\) and transformation \((a_i, d_i)\). According to the coordinate definition of the D-H structure diagram, four homogeneous matrixes (as show in Eq. (1)) can be multiplied to determine the transfer matrix \( A_i \) of each pair of adjacent coordinates \( J_i \). The transfer matrix is described by four parameters \((a_i, d_i, \alpha_i, \theta_i)\).

\[
A_i = R(z, \theta_i) \cdot T(z, d_i) \cdot T(x, a_i) \cdot R(x, \alpha_i) \quad (1)
\]

- \( a_i \): is the length along \( x_i \) from \( J_i \) to the intersection of the \( x_i \) and \( z_{i-1} \) axes.
- \( d_i \): is the offset along \( z_{i-1} \) from \( J_{i-1} \) to the intersection of the \( x_i \) and \( z_{i-1} \) axes.
- \( \alpha_i \): is the twist angle between \( z_{i-1} \) and \( z_i \) measured about \( x_i \).
- \( \theta_i \): is the angle between \( x_{i-1} \) and \( x_i \) measured about \( z_{i-1} \).

The mechanism diagram (Fig. 2 (c)) of our projection system is analyzed. The parameter relations of each section between the coordinate system of the projection lens \( J_3 \) and the coordinate system of the screen center \( J_0 \) are all recorded in the Link Parameter Table (as listed in Table 1). Stand on Table 1; we determine the transfer matrix \( A_i \) of each
Table 1. Link parameter of projective mechanism.

<table>
<thead>
<tr>
<th>Link</th>
<th>(a_i)</th>
<th>(d_i)</th>
<th>(\alpha_i)</th>
<th>(\theta_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(L_1)</td>
<td>(M_1)</td>
<td>0</td>
<td>(\theta_1)</td>
</tr>
<tr>
<td>2</td>
<td>(L_2)</td>
<td>(M_2)</td>
<td>(\pi/2)</td>
<td>(\theta_2)</td>
</tr>
<tr>
<td>3</td>
<td>(L_3)</td>
<td>(M_3)</td>
<td>0</td>
<td>(\theta_3)</td>
</tr>
</tbody>
</table>

* \(L_1\)–\(L_3\) and \(M_1\)–\(M_3\) is constant.

section, enabling us to further determine the transfer matrix of the entire mechanism according to continued product of \(A_i\) of each section, its result as shown in Eq. (2). The matrix element \(R_{0}^3\) (3 \(\times\) 3) within \(T_0^3\) refers to the rotational direction of the lens \(J_3\) corresponding to the screen center \(J_0\) (as shown in Eq. (3)). Matrix \(d_{0}^3\) (3 \(\times\) 1) is the corresponding amount of position movement (as shown in Eq. (4)). Finally, based on the amount of rotation \((\alpha, \theta)\), we can determine the angular direction \((u^T, v^T, w^T)\) and position \(d^T\) of \(J_3\) corresponding to \(J_0\).

\[
T_0^3 = A_1 \cdot A_2 \cdot A_3 = \begin{bmatrix} R_{0}^3 & d_{0}^3 \\ 0 & 1 \end{bmatrix}
\]  (2)

\[
R_{0}^3 = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} = \begin{bmatrix} u^T \\ v^T \\ w^T \end{bmatrix}
\]  (3)

\[
\begin{align*}
&u_x = (C_{\theta_1} \cdot C_{\theta_2} - S_{\theta_1} \cdot S_{\theta_2}) \cdot C_{\theta_3} \\
&u_y = (C_{\theta_1} \cdot C_{\theta_2} + S_{\theta_1} \cdot S_{\theta_2}) \cdot C_{\theta_3} \\
&u_z = S_{\theta_3} \\
&v_x = -(C_{\theta_1} \cdot C_{\theta_2} - S_{\theta_1} \cdot S_{\theta_2}) \cdot S_{\theta_3} \\
&v_y = -(C_{\theta_1} \cdot S_{\theta_2} + S_{\theta_1} \cdot C_{\theta_2}) \cdot S_{\theta_3} \\
&v_z = C_{\theta_3} \\
&w_x = C_{\theta_1} \cdot S_{\theta_2} + S_{\theta_1} \cdot C_{\theta_2} \\
&w_y = S_{\theta_1} \cdot S_{\theta_2} - C_{\theta_1} \cdot C_{\theta_2} \\
&w_z = 0
\end{align*}
\]

\[
d_{0}^3 = \begin{bmatrix} u_x \cdot L_3 + w_x \cdot M_3 - w_y \cdot L_2 + C_{\theta_3} \cdot L_4 \\ u_y \cdot L_3 + w_y \cdot M_3 + w_x \cdot L_2 + S_{\theta_3} \cdot L_4 \\ S_{\theta_3} \cdot L_3 + M_2 + M_1 \end{bmatrix}
\]  (4)

3. PROJECTION CORRECTIONAL PRINCIPLE

The optimal content of a picture formed on the screen is to conform to the shape of a hemispherical screen. Shooting through fisheye lens, however, is rarely seen now. This
paper therefore will attempt to determine the 3D environment in section 3.1 and turns it into a wide-angle image. As we desire to project the wide-angle image onto the hemispherical screen, we will then in section 3.2 discuss how to utilize the advanced mesh-morphing method according to the positioned angle of the projector in section 2.1 to correct the image in advance in order to ensure accurate outcome after it is projected on the screen. Following geometric correction and induction, considering the fact that in the combined picture of two projectors the brightness of the picture of the overlapped area is greater than that of the non-overlapped area, we employ the alpha-mask technique in section 3.3 to mitigate the overly-high brightness of the overlapped area, so the brightness of the mosaicked area will be consistent.

3.1 Wide-angle Seamless Correction for 3D Content

The projection screen of the system is a complete hemisphere, which is most suitable for the image content of a hemispherical screen – a wide-angle image encompassing 180 degrees in all directions. However, photos or motion pictures taken by cameras rarely contain wide-angle content. When a camera attempts to capture a 180-degree image in a 3D virtual environment, the surrounding area will be so distorted the image becomes indistinguishable. Therefore the images taken by various cameras are mosaicked into a wide-angle image. The 3D space is regarded as a cube that contains an inscribed sphere, which and the cube share the same center $O$. Each plane of the cube is projected from $O$, and we can find corresponding area on the spherical curved surface. Considering that the hemisphere is half of the space (as illustrated in Fig. 3 (a)), referencing four planes, $P_U$, $P_D$, $P_L$ and $P_R$, will allow us to encompass the hemispherical curved surface. The point $b(b_x, b_y, b_z)$ of each plane is projected along the direction of the spherical center onto the point $f(f_x, f_y, f_z)$ of the hemispherical curved surface – namely, the position where transfer of the space plane to the hemispherical curved surface should land.

As illustrated in Fig. 3 (a), on the right plane $P_R$ between point $b(b_x, b_y, b_z)$ and spherical center $o(0, 0, 0)$, any point $n(n_x, n_y, n_z)$ on its straight line $ob$ (vector is $d(d_x, d_y, d_z)$) in between can be expressed via parametric equation as shown in Eq. (5). The
curved surface equation of the inscribed sphere is shown in Eq. (6). At the intersection of \( ob \) and the hemispherical curved surface, we can determine the homogeneous matrix \( H^h_p \) (as shown in Eq. (7)); namely, any point \( b \) on \( P_h \) following \( H^h_p \) transfer will generate a corresponding point \( f \) on the hemispherical curved surface. After the point on \( P_h \) is completely transferred to the curved surface, we obtain the grid set \( P_h \) on the hemispherical curved surface corresponding to \( P_h \). After we finish plane projection of the other three directions (\( P_U, P_D \) and \( P_L \)) to the hemispherical curved surface (as illustrated in Fig. 4 (a)), we can determine corresponding grid sets (\( P_U, P_D \) and \( P_L \)) on the hemispherical curved surface. Linking of the four corresponding curved surfaces gives us a wide-angle grid \( P \) (as illustrated in Fig. 4 (b)).

\[
\begin{align*}
  \begin{cases}
    n_x = b_x + t \cdot d_x \\
    n_y = b_y + t \cdot d_y, \quad t \text{ is arbitrarily} \\
    n_z = b_z + t \cdot d_z
  \end{cases}
\end{align*}
\]

\((n_x - o_x)^2 + (n_y - o_y)^2 + (n_z - o_z)^2 = r^2, \quad r \text{ is radius of sphere}\)

\[
\begin{bmatrix}
  f^T \\
  1
\end{bmatrix} = H^h_p \begin{bmatrix}
  (b-o)^T \\
  1
\end{bmatrix}
\]

\[
H^h_p = \begin{bmatrix}
  \eta & 0 & 0 & -\eta \\
  0 & \eta & 0 & -\eta \\
  0 & 0 & \eta & -\eta \\
  0 & 0 & 0 & 1
\end{bmatrix}, \quad \eta = \frac{r}{\sqrt{(b_x - o_x)^2 + (b_y - o_y)^2 + (b_z - o_z)^2}}
\]

(a) Four directional mesh in cube (perspective view).  
(b) Corresponding meshes \( \hat{P} \) on hemispherical surface (orthogonal view).

Fig. 4. Wide-angle seamless mesh stitch from four directional meshes.

### 3.2 Pre-Warping Correction

In most of the cases, projected images are applied to plane screen. If it is replaced by non-plane screen, images projected on the hemispherical screen will be contorted to
certain degree. This warping, however, is not purely ladder deformation. Therefore, we are unable to employ the ladder correction function for hardware processing. We instead utilize the perspective projection method to obtain the shape of the image that requires changes before it is projected onto the screen, so this pre-transformed image may generate a correct, contortion-free projection on the screen.

As illustrated in Fig. 5 (a), any point \( s(s_x, s_y, s_z) \) of space \( XYZ \): Taking the origin as the vanishing point, we can transfer this point to point \( c(c_x, c_y, c_z) \) on plane \( P_d \) (where \( Z = d \) of \( XYZ \) coordinate system through a perspective transformation homogeneous matrix \( P \) (as shown in Eq. (8)).

\[
\begin{bmatrix}
  c_x \\
  c_y \\
  c_z \\
  1
\end{bmatrix} = P \begin{bmatrix}
  s_x \\
  s_y \\
  s_z \\
  1
\end{bmatrix} \Rightarrow \tilde{c} = P \cdot \tilde{s} \tag{8}
\]

\[
P = \begin{bmatrix}
  d & 0 & 0 & 0 \\
  0 & d & 0 & 0 \\
  0 & 0 & d & 0 \\
  0 & 0 & 1 & 0
\end{bmatrix} \tag{9}
\]

To determine that the pre-warping grid \( \Psi \) comes from the hemispherical grid (as illustrated in Fig. 5 (b)): Suppose the mesh consists of \( n \) number of mesh points. Any point \( s \) on \( \Psi \) can be defined according to the spherical coordinate. When it is described via a rectangular coordinate, we can use Eq. (10) to indicate the relationship of the rectangular coordinate and the spherical coordinate, where \( r \) denotes the radius of the hemisphere, \( \theta \) represents the azimuth angle, and \( \phi \) stands for the zenith angle.

\[
s = \begin{bmatrix}
  s_x \\
  s_y \\
  s_z
\end{bmatrix}^T = \begin{bmatrix}
  r \sin \phi \cos \theta \\
  r \sin \phi \sin \theta \\
  r \cos \theta
\end{bmatrix}^T \tag{10}
\]

Based on the Eq. (8), all the point \( s \) on \( \Psi \) are transferred one by one through \( P \) to point \( c \) on \( P_d \). \( \Psi \), the aggregation of all point \( c_i \), is the mesh formed by projection on \( P_d \).
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according to the origin. Therefore, if the origin is the projection center, projection of set \( \Psi \) from \( P_d \) onto the hemispherical curved surface will result in mesh \( \Psi \). In other words, if we imagine \( P_e \) to be the image plane of the projector, then following perspective homogenous matrix transformation \( \Psi \) will be the pre-warping mesh that can be used to generate projection \( \Psi \) correctly on the hemispherical curved surface. The projector, however, is not positioned on the origin of the \( XYZ \) coordinate. According to projector arrangement considerations in section 2.2, the projector is hung on the frame for skewed projection. Therefore, besides perspective projection transformation, we need to take into account rotational matrix \( R_{3 \times 3} \) and position vector \( T_{3 \times 1} \) in order to transfer the hemispherical mesh to plane \( P_e \) whose distance to the origin of coordinate \( xyz \) is \( (z = d) \) (as illustrated in Fig. 5 (b)).

Assuming the rotational angles of \( P_e \) against the three axes of coordinate \( xyz \) are \( (\alpha, \beta, \gamma) \), the position vector from the origin of coordinate \( xyz \) to the origin of coordinate \( XYZ \) is \( (t_x, t_y, t_z) \), hemispherical mesh \( \Psi \) can be transferred to \( \Psi \) on \( P_e \) via perspective transformation expressed by transformation function \( H_c \) (as shown in Eq. (11)). \( H_c \) comprises three transformation functions \( P \cdot R \cdot T \) (as shown in Eq. (12)). Matrix \( P \) does not change with displacement or rotation. Meanwhile, rotational transfer matrix \( R \) according to the rotation \( (\alpha, \beta, \gamma) \) of \( P_e \) against the three axes of coordinate \( xyz \), we obtain a homogeneous rotation matrix. The displacement of \( t \) coordinate \( xyz \) from coordinate \( XYZ \) can also be expressed by homogeneous position transfer matrix.

\[
\hat{\Psi} = H_c^e \cdot \Psi \quad (11)
\]

\[
\Psi = \begin{bmatrix}
    s_1^T \\
    s_2^T \\
    \vdots \\
    s_n^T \\
    1
\end{bmatrix}
\]

\[
\hat{\Psi} = \begin{bmatrix}
    c_1^T \\
    c_2^T \\
    \vdots \\
    c_n^T \\
    1
\end{bmatrix}
\]

\[
H_c^e = P \cdot \tilde{R} \cdot \tilde{T} \quad (12)
\]

\[
\tilde{R} = \tilde{R}(\alpha) \cdot \tilde{R}(\beta) \cdot \tilde{R}(\gamma) = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & 0 \\
    r_{21} & r_{22} & r_{23} & 0 \\
    r_{31} & r_{32} & r_{33} & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}, \quad \tilde{T} = \begin{bmatrix}
    1 \\
    -t^T
\end{bmatrix}
\]

Based on the Eqs. (8) and (12), we can determine the product \( H_c^e \) of three homogeneous transfer matrices \( P \cdot R \cdot T \) (as shown in Eq. (13)). Through transfer of \( \Psi \) on \( P_e \) via \( H_c^e \), plane mesh \( \Psi \) is generated. Therefore, in describing the plane of \( P_e \) after transfer of any point \( c \) to coordinate \( xyz \), only components \( \hat{c}_x, \hat{c}_y \) are meaningful (as shown in Eq. (14)).

\[
H_c^e = P \cdot \tilde{R} \cdot \tilde{T} = \begin{bmatrix}
    d \cdot r_{11} & d \cdot r_{12} & d \cdot r_{13} & -d \cdot r_{11} \cdot t_x - d \cdot r_{12} \cdot t_y - d \cdot r_{13} \cdot t_z \\
    d \cdot r_{21} & d \cdot r_{22} & d \cdot r_{23} & -d \cdot r_{21} \cdot t_x - d \cdot r_{22} \cdot t_y - d \cdot r_{23} \cdot t_z \\
    d \cdot r_{31} & d \cdot r_{32} & d \cdot r_{33} & -d \cdot r_{31} \cdot t_x - d \cdot r_{32} \cdot t_y - d \cdot r_{33} \cdot t_z \\
    0 & 0 & 0 & 1
\end{bmatrix} \quad (13)
\]
The projection system employs two projectors for creating mosaicked image on the curved surface of the screen. The positions and angles of the two projectors on both sides are slightly different, and their corresponding pre-warping meshes $\hat{\Psi}_l$ and $\hat{\Psi}_r$ are also different. According to the determined outcome $H_C$ (as shown in Eq. (13)), we will obtain the pre-anti-warping mesh on the hardware (as shown in Fig. 6 (b)).

(a) Transfer of $\Psi$ on $P_E$ via $H_C$.
(b) Pre-warping mesh $\hat{\Psi}_l$ and $\hat{\Psi}_r$.

Fig. 6. Each projector correspond a pre-warping mesh.

3.3 Intensity Blending Correction

Mosaicking of projection images is prone to generating an overlapped area of higher brightness. For consistency of the screen and for preventing visual interruption caused by the brightness, we normally employ the alpha blending techniques for processing. Literatures on plane mosaicking projection utilize the alpha-mask of quadratic curve. Through the help of an extra camera, we observe each projection screen and according to the overlapped projection zone we determine the corrected alpha-mask.

To solve the boundary blending brightness, this paper also utilizes alpha blending techniques to determine alpha-mask. Yet the way it determines the alpha-mask does not involve the use of an extra camera to film the picture of each projector. It instead employs 3D graphics. According to the positions and angles of the projectors in section 2.2 and based on the projection method, it determines the projected image point $v_i$ of each projector $P_i$ on the screen. All the projection points $v_i$ on the screen make up image zone $V_i$. Combining all the union sets of $V_i$ gives us the image overlapping zone $\Phi$.

As illustrated in Fig. 7, in mosaicking of two simple rectangular projections, the superposed brightness of any pixel $m$ within $\Phi$ is the result of brightness superposition of the two projectors. To make the brightness identical to that of non-superposed image, we will calculate the distance between point $m$ within $\Phi$ and each projector via linear weight proportion as shown in Eq. (15).
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Fig. 7. Alpha-mask for two rectangular projections.

\[ I(m) = \alpha_L(m) \cdot P_L(m) + \alpha_R(m) \cdot P_R(m) \]

\[ \alpha_L(m) = \frac{d_L}{d_L + d_R} \]

\[ \alpha_R(m) = \frac{d_R}{d_L + d_R} \]

When it is not simple linear overlapping of projection zones, the weight proportion of \( \alpha_P(m) \) corresponding to any pixel \( m \) within \( \Phi \) can be described by the minimum distance \( d_P(m) \) between pixel \( m \) and the border of each projector \( P_i \) (as shown in Eq. (16), here, \( d_P(m) \) is made up of \( w(m) \) and \( d_P(m) \) multiplied). The condition of \( w(m) = 1 \) is that pixel \( m \) following function \( H_C \) (as shown in Eq. (13)) transfer will fall within the image plane \( P_E \) of \( P_i \). If following the transfer the projection point does not fall on the image plane of \( P_i \), then \( w(m) = 0 \).

\[ \alpha_P(m) = d_P(m) \left/ \sum_{j=1}^{n} d_P(m) \right. \]

\[ d_P(m) = w(m) \cdot d_P(m) \]

According to the angles and positions of the projectors arranged for this paper, we determine the projection on the hemispherical screen. Through our alpha-mask algorithm, we determine each alpha-mask as shown in Fig. 8, \( A_{PL} \) and \( A_{PR} \), in which \( A_{PL} \) and \( A_{PR} \) correspond to projectors \( P_L \) and \( P_R \).

Fig. 8. Alpha-mask for our projection system.
4. SYSTEM

4.1 Hardware of System

The hardware part of the system, the screen itself was built using a complete 1.2 meters hemisphere screen made from fiberglass reinforced plastics (FRP). The information technology hardware consisted of only one computer and two high definition projectors. The specification of IT is listed in Table 2, the system adopt nVidia 7900GTX VGA cards to improve graphic processing unit efficiency while rendering high resolution images to display. The personal hemispherical image system’s main framework was made up of extruded aluminum components. It is used to support the hemispherical screen, suspended projectors, adjustable chair and surrounding speakers set up as illustrated in Fig. 9 (c) and take picture of hardware equipment as illustrated in Fig. 9 (b). Wall mount were used in order to allow minute adjustments to the projector alignment. The 5.1 channel surrounding speakers suspended in three places for feeling of live.

![Fig. 9. Structure of hemispherical display system.](image)

(a) TwinHD appearance. (b) System implements. (c) Skeleton of structure and components.

<table>
<thead>
<tr>
<th>Category</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>AMD K8 3000+</td>
</tr>
<tr>
<td>Memory</td>
<td>1GB</td>
</tr>
<tr>
<td>VGA</td>
<td>nVidia 7900GTX with dual DVI port (without SLI technology)</td>
</tr>
</tbody>
</table>

4.2 Software of System

Real-time combination of 3D virtual reality content and the image correction pro-
gram module from section 3 gives us a real-time image information processing system, which is integrated and established on the 3D development environment tool VT. The VT program is constructed via various programs of visualized script, so constructing 3D digital content on VT will be more time-efficient than development tools structured on ordinary program codes. Based on the basic logic algorithm module of VT, three image correction modules are constructed for the system, includes wide-angle seamless, pre-warping and alpha-mask correction modules.

### 4.2.1 Wide-angle seamless correction module

Wide-angle seamless image correction is obtained via deduction through half of a cube. The module correction process is shown in Fig. 10 (a). Based on observation position, cameras pickup modules for four directions are set up within VT to capture images (as shown in Fig. 10 (b)) of four directions from the point of view, mapping the images taken from each direction real time to the corresponding pre-warping mesh $P_1$ (shown in Fig. 10 (c)). The entire wide-angle mesh $P$ will incorporate images of 4 directions to present seamless image as illustrated in Fig. 10 (d).

![Wide-angle seamless correction process](image)

#### Fig. 10. Wide-angle seamless correction process.

### 4.2.2 Pre-warping correction module

Two mosaicking projectors project the pre-warping meshes $\hat{\Psi}_L$ and $\hat{\Psi}_R$ on to the hemispherical screen, we can show the accurate hemispherical mesh $\Psi$ as illustrated in Fig. 11 (a). Therefore, we map the wide-angle seamless image onto $\hat{\Psi}_L$ and $\hat{\Psi}_R$ (as
illustrated in Fig. 11 (b)), we will have pre-warping image before projection (as illustrated in Fig. 11 (c)).

4.2.3 Alpha-mask correction module

Through left-right mosaicking $\hat{\Psi}_L$ and $\hat{\Psi}_R$ are projected onto the hemispherical screen with an overlapped area $\Phi$. According to weighted calculation outcome of $\alpha_{\Phi}(m)$ in section 3.3, $A_{PL}$ and $A_{PR}$ (as illustrated in Fig. 8) are blended on the pre-warping image. Its alpha-mask result is shown in the Fig. 12 (b).

5. EXPERIMENTS AND RESULTS

According to system design planning, a hemispherical image information system is produced to integrate various image correction modules in section 4.2 with system VT development platform. Experiment outcomes are shown in Fig. 13. Non-compensated rectangular mesh and post-compensated mesh, the $\hat{\Psi}_L$ and $\hat{\Psi}_R$, are projected and mosaicked on the hemispherical screen (as illustrated in Figs. 13 (a) and (b)). It can be seen clearly in Fig. 13 (b) that on the hemispherical screen we obtain a complete hemispherical mesh $\Psi$. The image of Fig. 13 (c) is the pre-warping image projected on the hemispherical screen according to Fig. 11 (a). Here, the overlapped projection area shows higher brightness. Therefore, the alpha-mask technique is employed to reduce the brightness of the overlapped area. As shown in Fig. 13 (d), the difference between the two is quite conspicuous.
6. DISCUSS AND RESULT

Based on system design and correction techniques, the hemispherical image information system is completed. The following goals are attained. First, the projection equipment utilizes mechanism D-H analysis method to determine the relationship between the screen and the angles and positions of the projectors. The corresponding pre-warping mesh and alpha-mask are also determined and verified. Second, the system is integrated in the 3D VR content. Through real-time pickup of the wide-angle image it is extended to the hemispherical image for follow-up processing, including image pre-warping and blending of the brightness of overlapped area, for real-time correction of the hemispherical image. Third, single-unit computing system and high-definition image specification mosaicked and applied to the hemispherical screen. Introduction of high-definition projector reduces redundant deployment of PC, network communication and projector. The imaging system is completed via less complicated system layout. Fourth, in the TwinHD projection system, skewed projection of images avoids blocking by human body. Final estimate determines that about 78.5% of valid pixel lands on the screen, image resolution is about 87 pixels/cm², pixel distance is about 1.0 mm and the overall pixel is similar to the outcome of a 4-projector system is listed in Table 3.

Table 3. Compare with others projection system.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Diameter (meters)</td>
<td>1.2</td>
<td>1.68</td>
<td>2</td>
</tr>
<tr>
<td>Fisheye Lens</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Aspect ratios</td>
<td>16:9</td>
<td>4:3</td>
<td>4:3</td>
</tr>
<tr>
<td>Computer(s)</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Projector(s)</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Network</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Resolution/per set</td>
<td>1920 × 1080 pixels</td>
<td>1024 × 768 pixels</td>
<td>1024 × 768 pixels</td>
</tr>
<tr>
<td>Estimation of available pixels</td>
<td>1,969,920 pixels</td>
<td>589,824 pixels</td>
<td>1,890,631 pixels</td>
</tr>
<tr>
<td>Estimation of pixels on 1.2M screen</td>
<td>87.0 pixels/cm²</td>
<td>26.1 pixels/cm²</td>
<td>83.6 pixels/cm²</td>
</tr>
</tbody>
</table>
We complete the deduction and produce an imaging system encompassing projection-related image correction techniques. Use of projectors of high definition and wide screen ratio is a major consideration of the “TwinHD” system. Since the system completes display toward the hemispheric screen within limited personal space, simplified equipment makes it necessary to use a single PC to integrate 3D virtual reality and correctional algorithms, every one of which is required for real-time imaging of the hemispheric picture. The simplified hardware system is able to maintain the overall definition quality. Because of establishment of this system prototype, we are hopeful that through the overall correction framework and process of this paper we will be able to display digital content, which is highly demanding on space span, on the hemispherical image system real time.

REFERENCES


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