A wide field of view (FOV) tabletop light field display (LFD) based on piece-wise tracking and off-axis pickup is presented to display the floating three-dimensional (3D) scene, which is 360° surrounding viewable. The demonstrated LFD is specially designed with an integral imaging display (IID) with 83×83 viewpoints and a full-parallax holographic functional screen (HFS). To improve the FOV, a piece-wise tracking based FOV enhancement method is proposed. The relationship between the viewing zone and the elemental images (EIs) is formulated. A ray-tracing based method using off-axis pickup instead of parallel pickup directly is adopted to render the 3D scene to EIs. Then the piece-wise tracking method of varying the viewing zone by placing the EIs according to the position of viewer is analyzed. The floating 3D scene with a FOV of 70°×70° is experimentally demonstrated with a good 3D perception.

1. Introduction

Three-dimensional (3D) display can transmit 3D image information with the maximum reality to observers. Many researchers have made long term efforts to propose and develop 3D display systems that are capable of expressing 3D images like real objects [1,2]. The 3D display technology which can present 360° surrounding floating 3D scene is one of the most attractive research topics [3–5]. The integral imaging display (IID) shows advantages of full parallax, continuous view-points within the viewing zone and real-time full-color operation, which is one of potential technologies to achieve floating 360° display [6]. However, the integral imaging display also has limitations, such as low spatial resolution, small field of view (FOV), and small depth range [7–15]. To achieve an excellent 360° floating 3D display, a large FOV is essential, and a few of works on enlarging FOV of integral imaging display were presented, such as the display with a curve lens array [14], and the display using two elemental image (EI) masks to increase the incident rays to a lens [15]. Real-time tracking technology was also introduced to increase the FOV of 3D displays and the EIs were rendered and displayed in real-time according the tracked position [16–18]. In IIDs, the EIs are always rendered from multi-view images [19–21], such as the each camera viewpoint independent rendering method. The total rendering time is M×N times of a single viewpoint assuming a viewpoint number of M×N with those methods. In normal real-time tracking IID [17,18], only the viewpoint corresponding to the tracked position was rendered from virtual scene and used to generate the EIs displayed on the 3D display to ensure real-time tracking and display, and nothing could be observed in the non-tracked position.

Our designed LFD is implemented with an IID (composing of a lens array, a liquid crystal display (LCD) panel) and a holographic functional screen (HFS). The optical designed FOV of our LFD is from −20° to 20° in both orthogonal directions, which is not large enough for the tabletop 3D display. To improve the FOV, a tracking based FOV enhancement method is introduced. To achieve a visual effect without aliasing, each viewpoint should also be captured with the same resolution with the LCD [22]. Rendering the EIs for our LFD with 6889 (83×83) viewpoint images with the resolution of 3840×2160 in real-time tracking mode is impossible. It often takes several hours to render one frame with the normal each camera viewpoint independent rendering method [19]. A piece-wise tracking method with a fast response time is introduced to our LFD in order to avoid occurring discontinuous display, and the LFD with the proposed method can provide 3D information for multiple viewers. In the proposed method, a series of EIs are pre-generated, instead of generating from multi-viewpoint images in real-time. A high efficient ray-tracing based EIs rendering method using off-axis pickup is adopted [23]. The EIs containing multi-directional...
perspective information in the FOV are changed only if the viewer exceeds a certain viewing angle threshold. In this way, the LFD can provide 3D information for a viewing zone instead of a tracked viewing position for multiple viewers only if the viewers stay in the tracked viewing zone. The FOV can be wider as far as the aberration of the lens array can be tolerant.

2. Principle of the proposed LFD

2.1. The structure of the designed LFD

The LFD is implemented with an IID (composing of a LCD panel with the resolution of $3840 \times 2160$ and a lens array) and a HFS as shown in Fig. 1(a). The lens array is composed of lenses arranged on the barrier. The focal length of the lens array is $f$, the gap between the LCD panel and lens array is denoted as $l$. The distance between the lens array and the HFS is $L$. HFS is placed at the focused image plane, which is also called as center depth plane. The relationship among $f$, $l$ and $L$ satisfies the Gaussian imaging law, as shown in Eq. (1).

$$\frac{1}{l} + \frac{1}{L} = \frac{1}{f}. \tag{1}$$

HFS is an optical element which is holographically printed with speckle patterns exposed on the proper sensitive material [2], which redistributes the incident light beams with a diffused angle of $\omega$ alone the incident direction as shown in Fig. 1(b). There always exist gaps between the displayed pixels in normal integral imaging displays, which decreases the visual performance [11–14,17,18]. The HFS is introduced to eliminate the gaps and achieve a 3D light field with uniform light distribution as shown in Fig. 1(b). The $\omega$ is designed as Eq. (2) in our LFD, and $p$ is the pitch of the lens array. $A_i$ means the $x$ coordinate of the boundary area of the $i$th EI, which is the position where the ray from the central position of the viewing zone through each boundary of the elemental lens meets the EI plane. All the following formulas consider EI plane as one-dimensional line on $x$ axis for analysis simplification, but they can be expanded to two-dimensional $x$–$y$ plane. The $A_i$ can be calculated as Eq. (3), and $p$ is the pitch of the lens. The position at $(V_x, 0, V_z)$ represents the center of viewing zone, and $n$ is the number of the lens in $x$-direction. The width of an EI in the $x$-direction is defined as $A_{i-1} - A_i$, which is also the distance between the $A_{i-1}$ and $A_i$, and it can be represented by Eq. (4). The width of the viewing zone can be defined as $W$ by Eq. (5).

$$A_i = -\frac{V_x}{V_z} l + \left( i - \frac{n}{2} \right) \left( 1 + \frac{1}{V_z} \right) p \tag{3}$$

$$A_{i-1} - A_i = \left( \frac{1}{V_z} + 1 \right) p \tag{4}$$

$$W = \sum_{i=1}^{n} A_i \tag{5}$$

2.2. The proposed piece-wise tracking method

To enlarge the FOV to satisfy the demand of displaying tabletop 3D scene with a surrounding viewing area, a piece-wise tracking method is proposed. To realize the tracking method, the relationship between the EIs and the center position of the viewing zone is formulated, and a high efficient ray-tracing based EIs rendering method with off-axis pickup is adopted.

The relationship between the EIs and the viewing zone is shown as Fig. 2. The original point of the $x$–$y$ plane locates at the center of the LCD panel, the $z$ plane with $z = 0$ locates at the lens array plane. $A_i$ means the $x$ coordinate of the boundary area of the $i$th EI, which is the position where the ray from the central position of the viewing zone through each boundary of the elemental lens meets the EI plane. All the following formulas consider EI plane as one-dimensional line on $x$ axis for analysis simplification, but they can be expanded to two-dimensional $x$–$y$ plane. The $A_i$ can be calculated as Eq. (3), and $p$ is the pitch of the lens. The position at $(V_x, 0, V_z)$ represents the center of viewing zone, and $n$ is the number of the lens in $x$-direction. The width of an EI in the $x$-direction is defined as $A_{i-1} - A_i$, which is also the distance between the $A_{i-1}$ and $A_i$, and it can be represented by Eq. (4). The width of the viewing zone can be defined as $W$ by Eq. (5).

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$$A_{i-1} - A_i = \left( \frac{1}{V_z} + 1 \right) p \tag{4}$$

$$W = \sum_{i=1}^{n} A_i \tag{5}$$

Fig. 1. (a) The structure of the LFD, (b) the diffuse of the HFS, (c) the viewing zone of the display.

Fig. 2. The relationship between the viewing zone and the elemental images.
A 3D content pickup method with the off-axis camera array is adopted as shown in Fig. 3(a). With the off-axis pickup, the display can generate orthoscopic 3D scene with a large FOV. The number of the pixels under each EI can be defined as \( N \times N, N = A_{i-1} A_i / P_{size} \), and \( P_{size} \) is the size of the pixel of LCD. In the off-axis pickup process, an off-axis \( N \times N \) camera array with the common plane is arranged as in Fig. 3(a). In order to capture the corrected perspective of the object, the image acquisition process should keep consistently with the display process, with the scale \( s \) given as,

\[
W = \left( \frac{V_y}{I} + 1 \right) p. \tag{5}
\]

where \( D \) is the width of the lens array, and \( D' \) is the width of the common plane of the off-axis camera array. \( W \) is the width of the viewing zone, and \( W' \) is the width of the camera array. \((P_x, P_y, P_z)\) is the position of the center camera in the camera array, and the pitch of the camera is defined as \( d, d = W' / N \). To render the EIs, a backward ray-tracing based EIs rendering method is proposed in our pre-work [23], which can directly render the 3D scene to EIs for the LFD, and the process is shown as Fig. 3(b). EIs are directly rendered from the 3D scene by mapping the pixels of the desired EIs to virtual cameras, and emitting the wanted ray from the virtual cameras to hit the virtual 3D scene. A ray emitted from the \( i \)th pixel on the CCD of the \( j \)th camera is denoted as \( O_{ij} \). When the ray hits on the 3D scene, the detail of the hit-point is gotten. Then the ray would intersect at the \( i' \)th pixel of the \( j' \)th EI on LCD, which is defined as \( O_{ij'}(j', i') \),

\[
O_{ij'}(j', i') = O_{ij}, \tag{7}
\]

with

\[
i' = N + 1 - j \quad \text{and} \quad j' = M + 1 - i
\]

where \( i' \) and \( j' \) are within the range from 1 to \( N \), and \( i \) and \( j \) are within the range from 1 to \( M \). \( N \) is the number of the camera array and \( M \) is the number of EIs displayed on the LCD.

The backward ray-tracing based EIs rendering method can render the 3D scene to EIs with the same sampling rate with LCD panel, without the need of rendering the all the 6889 viewpoints in a resolution of \( 3840 \times 2160 \). It takes several seconds with our ray-tracing method to generate EIs for one frame, but a normal rendering method for those viewpoints takes several hours. The rendering process of EIs according to the camera array can be denoted as \( EIs = Synthesis(P_x, P_y, P_z) \), where \( (P_x, P_y, P_z) \) is the central position of the camera array.

To further improve the efficiency of the tracking, the piece-wise tracking strategy is proposed, as shown in Fig. 4. Instead of tracking the viewer’s eyes and generating the EIs in real-time, a set of EIs are pre-generated according to different positions of off-axis camera array. The camera array is moving with a step of \( k_{step} \), and the process can be defined as Eqs. (8)–(10). There exists overlapping region between the adjacent viewing zones aiming to keep the smooth perception of the 3D scene during the tracking process. \( k_{step} \) is restrained with \( k_{step} < N, k_x \) and \( k_y \) are integers, which denote the times of moving in ±x and ±y direction respectively. According to the moving of the camera array, the positions of EIs should also be changed, and the shift of the EIs in \( x \) and \( y \) directions can be respectively derived as \( A_{shx} = k_x A_{size} / N \) and \( A_{shy} = k_y A_{size} / N \) from Eq. (3). With the proposed strategy, the pre-generated EIs should be displayed according to the viewer’s position \((X, Y, Z)\) with \( Z = V_z \), and changed only if the viewer exceeds a certain viewing angle threshold. The corresponding shift in \( x \) and \( y \) directions should be applied to the displayed EIs, and finally the LFD with an enlarged FOV is achieved.

\[
EIs = Synthesis(k_x k_{step} d, k_y k_{step} d, P_z) \tag{8}
\]

if

\[
(k_x - 1/2) k_{step} \cdot d \cdot s \leq X < (k_x + 1/2) k_{step} \cdot d \cdot s
\]

\[
(k_y - 1/2) k_{step} \cdot d \cdot s \leq Y < (k_y + 1/2) k_{step} \cdot d \cdot s
\]

with

\[
k_{step} < N
\]

and

\[
P_z = V_z / s
\]
Fig. 5. The LFD system. (a) The structure of the LFD system, and (b) the experimental tabletop LFD.

Fig. 6. (a) The 3D scene, (b) the generated elemental images.

\[ A_{shift,x} = -\frac{k_x k_{step} d \cdot s}{V_z} \cdot l \] \hspace{1cm} (9)

\[ A_{shift,y} = -\frac{k_y k_{step} d \cdot s}{V_z} \cdot l. \] \hspace{1cm} (10)

3. Experimental results

3.1. Proposed LFD system

The LFD system is shown in Fig. 5. The LFD is implemented with an IID and a HFS. The diagram of the whole display system is shown in Fig. 5(a) and (b) shows the LFD, the EIs and the tracking device. A Kinect is used for tracking to obtain the precise coordinates of viewer’s head. The parameters of the LFD are given in Table 1. A 23.5 in LCD panel with a resolution of 3840 \times 2160 is used, and the number of lenses in lens array is 46(H) \times 27(V). As a tabletop LFD, the display is designed with a viewing distance of 160 cm without any perspective distortion, but the viewing distance can be ranged among [120, 200] cm with a good 3D perception.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of lenses</td>
<td>46(H) \times 27(V)</td>
</tr>
<tr>
<td>Pitch of lens array (p)</td>
<td>11.13 mm</td>
</tr>
<tr>
<td>Focal of the lens (f)</td>
<td>14.48 mm</td>
</tr>
<tr>
<td>Distance between LCD and lens array(l)</td>
<td>16.16 mm</td>
</tr>
<tr>
<td>Distance between HFS and lens array(L)</td>
<td>140 mm</td>
</tr>
<tr>
<td>Number of viewpoints (N x N)</td>
<td>83 x 83</td>
</tr>
<tr>
<td>Resolution of the LCD panel (H x V)</td>
<td>3840 \times 2160</td>
</tr>
<tr>
<td>Viewing distance</td>
<td>160 cm</td>
</tr>
<tr>
<td>The FOV without tracking</td>
<td>40° \times 40°</td>
</tr>
<tr>
<td>The FOV with piece-wise tracking</td>
<td>70° \times 70°</td>
</tr>
</tbody>
</table>

3.2. Results

In our experiment, the moving step \( k_{step} \) of the camera array is set as 40. \( k_x \) and \( k_y \) are set to be 0, ±1, ±2, and the corresponding maximum viewing angle in either direction is 45.6°. The distance of the adjacent virtual cameras is 19.3 mm, and the pickup distance is 230 cm. The
designed viewing distance of the tabletop LFD is 160 cm without perspective distortion. The used 3D scene is given in Fig. 6(a), and the generated EIs with the camera array placed at (−40d, 40d, Z₀), (0, 40d, Z₀), (40d, 40d, Z₀), (−40d, 0, Z₀), (0, 0, Z₀), (40d, 0, Z₀), (−40d, −40d, Z₀), (0, −40d, Z₀), (40d, −40d, Z₀) are respectively given as examples in Fig. 6(b), where Z₀ = 230 cm. The EIs with other camera array position shift values are also generated.

The aberration characteristic of the designed LFD is analyzed. With our LFD with piece-wise tracking, a series of displayed perspective images at different viewing angles are captured with the camera (EOS-60D), and the results are shown in Fig. 7. The definitions of the images captured at different viewing angles show the aberration characteristics of the lens array at different viewing angles. A high definition means a good aberration performance. The FOV of the LFD can be wider as far as the aberration of the lens array can be tolerant. As the viewing position becomes farther from the center of the 3D display, the definition of the captured 3D image decreases. When the viewing angle exceeds 35° in either direction, the definition of the displayed 3D image decreases seriously. Therefore the FOV is restricted to [−35°, 35°] to show a clear definition.

With our proposed method, the FOV can be wider as far as the aberration of the lens array can be tolerant. The tracking system supports a wide FOV. The different display views of the LFD are shown in Fig. 8. The observing angles are provided below the images. All the images are captured when the viewer stands at the corresponding observing positions and faces to the center of the display. The corrected perspective information is provided. All the provided images show good definition.

4. Conclusion

In summary, a novel wide FOV LFD based on piece-wise tracking and off-axis pickup is presented. The relationship between the EIs and the viewing zone is analyzed, and the EIs of the 3D scene are pre-generated based on the backward ray-tracing method. The EIs are displayed and
changed according to the viewer’s position based on piece-wise tracking.

The proposed tracking method is efficient, and the tabletop LFD with a FOV of $70\times 70$° is demonstrated.

Acknowledgments

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References