Self-calibration Three Dimensional Light Field Display Based on Scalable Multi-LCDs

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Abstract: Approach to achieve self-calibration three dimensional (3D) light field display is investigated in this paper. The proposed 3D light field display is constructed up on spliced multi-LCDs, lens and diaphragm arrays, and directional diffuser. The light field imaging principle, hardware configuration, diffuser characteristic and image reconstruction simulation are described and analyzed, respectively. Besides the light field imaging, a self-calibration method is proposed to improve the imaging performance. An image sensor is deployed to capture calibration patterns projected onto and then reflected by the Polymer Dispersed Liquid Crystal (PDLC) film, which is attached to and shaped the diffuser. These calibration components are assembled with the display unit and can be switched between display mode and calibration mode. In calibration mode, the imperfect imaging relations of optical components are captured and calibrated automatically. We demonstrate our design by implementing the prototype of proposed 3D light field display using modified off-the-shelf products. The proposed approach successfully meets the requirement of real application on scalable configuration, fast-calibration, large viewing angular range and smooth motion parallax.

OCIS Codes: 100.6890, 230.0230, 110.4190.

Key Words: Light field, Motion parallax, Self-calibration, PDLC, LCD-based

1. Introduction

Light field 3D displays have experienced an unprecedented development opportunity recently for providing viewers more realism [1-4]. Current multi-view auto-stereoscopic displays, like the parallax barriers style or lenticular lenses style [5,6], are expected to create vivid displays for naked eye observers, while all the proposed equipments suffer some problems [7-9]. One crucial problem is the limited number of distinct views which results in discontinuous motion parallax.

Actually, the motion parallax: seeing different images when the viewer moves is also a crucial cue for human observing objects. It is manifest that conventional 3D displays focus more on providing stereo parallax with high resolution instead of smooth motion parallax. The basic principle to achieve continuous motion parallax is to generate high density-views. However, restricted by existing display resolution, the information data is rather limited for single display device. Yet for the state-of-the-art high density-view systems [10,11], they provide delicate stereo and motion parallax but in small viewing range. While in practice, large viewing range is an essential requirement for numbers of viewers observing at the same time. Alternative approach to obtain continuous motion parallax of large viewing range is to reconstruct the light field of 3D scene in pixel-based methods, i.e. spatial scanning [12-14] or just holograph. Spatial scanning displays perform well in image resolution, but are untouchable and limit in small display area. This is mainly because the display area is always occupied by rotating components. Since single display device suffers the problem of limited resolution, multi-projection is then applied to extend the

3D information data. A large multi-projector light field display is reported in 2010, which seems capable of enhancing volumetric understanding with offering continuous horizontal parallax [15]. This multi-projectors configuration succeeds in achieving large scale display but inevitablely suffers the problems of high-cost and complicated structure for calibration. Besides, the reported equipment is untouchable and unportable yet. In this extent, geometrical calibration is definitely important in evaluating the image splicing accuracy for multiple projection, and has been widely studied in recent years [16,17]. Due to the imperfect imaging relation of multi-projectors, the distortion always turns to be the momentous restriction of obtaining high-quality performance. Camera-based calibration technique has already been used in constructing light field display [18]. However, the present calibration methods on multi-projectors own grand challenges on fast but precise geometrical calibration. This is because fixed patterns are usually implemented in complicated calibration for high-density light field displays and existing approaches are almost configuration independent with display devices. Far less literature has reported the efficient or assembled calibration in other light field 3D displays yet. Actually, the calibration in projection light field display could be implemented more intelligent, efficient and easy-assembling. Therefore, large viewing range, fast calibration, smooth motion parallax and virtual touchable scene, are definitely required when developing cost-control compact natural 3D displays.

In this paper, a scalable touchable light field display assembled with self-calibration is investigated. The optical components of proposed display are capable of achieving motion parallax in large viewing range and the calibration components are apt to improve the imaging performance. Unlike conventional auto-stereoscopic displays, this method aims to reconstruct the light field of 3D scene in pixels-based rather than views-based, thus it creates smooth motion parallax in a large viewing angular range. The simulated analysis is presented in section 2 to validate the display principle. Additionally, assembling the PDLC(Polymer Dispersed Liquid Crystal) film and capture-based calibration on the optical components, the proposed display makes the calibration intelligent and compact, which will be introduced in section 3. Finally, results are given in section 4 to demonstrate that with the self-calibration approach, the proposed multi-LCDs style has compensated the limitation of resolution and behaved potentially to achieve scalable fast-calibration light field display.

2. Principle of LCD-based touchable light field display

2.1 System overview

Fig. 1 shows the basic structure of the proposed 3D light field display unit. Each display unit consists of a flat panel display device (here is a LCD panel) and a lens and diaphragm array. These three parts are composed as optical components to generate light field rays, and has been introduced in Society for Information Display (SID) 2012 Symposium. In this paper, the design is extended by attaching a camera and a PDLC (Polymer Dispersed Liquid Crystal) film in the display unit as self-aware geometrical calibration components.

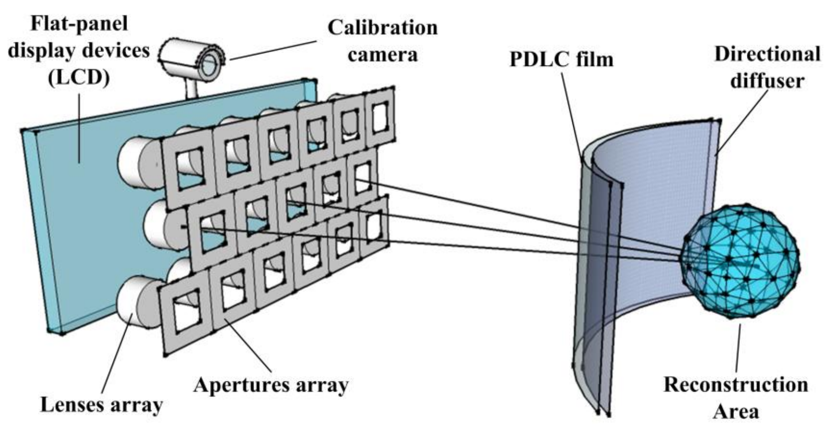


Fig. 1. Illustration of the system structure of the self-calibration LCD-based light field three dimensional display unit.

Specifically, the display devices are divided into numerous sub-display regions (or mosaic images) for cost and compact consideration. Each lens and corresponding LCD display sub-region make up a so-called projector. All the beams projected by so-called projectors converge at the designed position, i.e. the arc center. In such a configuration, each lens projects pixels of a LCD sub-image to a series of directional rays, which then constructs the light field with other rays projected by the lenses array. Hence the 3D image with correct occlusion effect is displayed. The 3D light field display unit is scalable, so that multiple display units are assembled to provide large viewing range in horizontal with feasible modularization and low-cost. 3 display units are prototyped in our experiments and together with a curved directional diffuser, to form the light field of 3D scene in the center region. All three units and the diffuser are set in different concentric arcs. Besides these optical components, a PDLC film is attached to the directional diffuser at the side near to the LCD panels, and acts an electro-optic switch to change the light paths between display mode and calibration mode. In the calibration mode, the PDLC film presents the optical characteristic of low transmission but high reflection. And in the display mode, the PDLC film presents the optical characteristic of high transmission. This makes the imperfect imaging relation of optical components be captured by camera and then be calibrated in the calibration mode.

2.2 Principle of LCD-based light field display

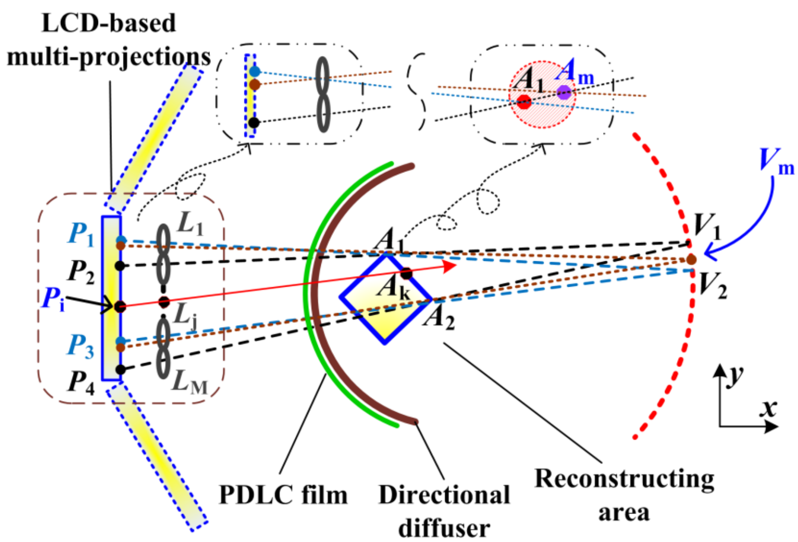


Fig. 2. Schematic of the LCD-based light field display principle.

As illustrated in Fig. 2, for point A_1 and A_2 on the reconstructed 3D object, different pixels P_1, P_2, P_3 and P_4 generate corresponding directional rays to viewing position V_1 and V_2 thus produce stereo parallax and motion parallax. Based on the light field display design, all the analysis is pixels-based instead of views-based in the image generation process. The light ray $\overrightarrow{P_i L_j A_k}$ is not specially designed for certain viewing positions as that of conventional multi-view 3D displays. Here is the image synthesis algorithm.

Firstly, we project the scene point A_k to the lens array to find its projected lens L_j. Then the vector is extended to find the displayed pixel P_i on LCD screen, where i stands for the sequence number of the pixel on LCD, j stands for a certain lens the pixel belongs to, and k stands for the sequence number of the reconstructed point in 3D scene. In such a configuration, rays are distributed according to pixels on LCDs. If pixels on LCDs are dense enough, the adjacent light rays in light field are sufficiently close to make the viewed imagery continuous and without the views jumping. However, in practice, at any close viewing position between V_1 and V_2, i.e. V_m, in the width of eye pupil, the viewer will observe another virtual point A_m reconstructed by another pixel between around pixels P_1 and P_2 projected from LCDs. This virtual point, A_m, is very close to the virtual point A_1 (shown in the zoomed subfigure in the Fig. 2 with different color points) and is reconstructed for viewing poisition V_m. This approximates the actual ray from A_m to V_1. Although the proposed light field display owns such an approximation in the light field imaging, we find it is acceptable because of the tiny interval of lenses. In the experiment part, the display performance illustrates that the approximation does not result in obvious perceptible visual fatigue.

Secondly, given the global *x*-*y* coordinate system representing the spatial position, we then carry out the simplified relation between the reconstructed point A_k (x_1,y_1) and the pixel P_i (x,y) based on tracing the light ray $\overrightarrow{P_i L_j A_k}$, described as Eq. (1):

$$y = \frac{y_1 - y_0}{x_1 - x_0}(x - x_1) + y_1 , \quad (1)$$

where, the lens L_j position (x_0,y_0) is known in the fixed configuration tracing from lens L_1 to L_M, and x is also known as the position of LCDs. After all virtual points of 3D scene A_k is rendered through all lenses, we then get all the pixels information P_i to make up the displayed image sources on the LCDs.

Due to limited viewing angle of each view image, fewer spliced images will be seen at edge viewing positions, resulting less integrity of viewed image. Thus, multiple devices splicing is proposed here to compensate such a problem and with the potential to attain large-sized display. Because we only consider horizontal parallax in this proposed display now, a directional diffuser with the characteristic of small diffuse angle in horizontal to make image brightness continuous but large in vertical to provide enough viewing range, is set between the lens array and viewing area. In this way, right sight of 3D object's image consisted of many stripe images in this case is observed in the optimum viewing distance.

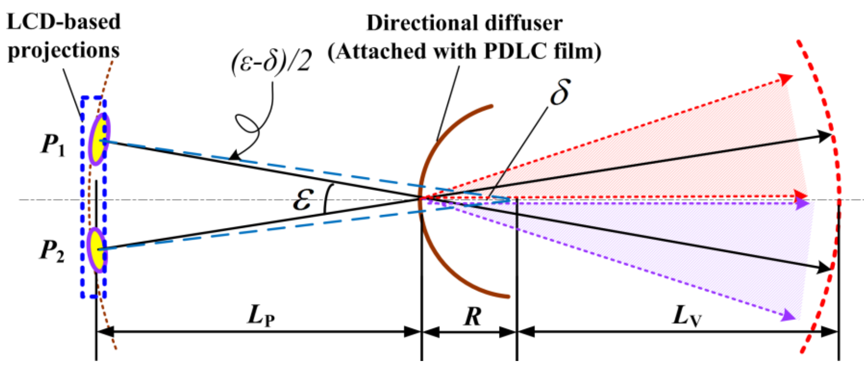


Fig. 3. Geometric relation between appropriate diffuse angle of the diffuser and interval angle of adjacent lenses.

With designed directional diffuser mentioned above, one lens only gives a narrow vertical stripe of image for a certain viewing position. To guarantee the smooth stitch and avoid brightness ununiformity overlap of strips, appropriate diffuse angle of the directional diffuser in horizontal is required. Based on the geometrical relation in Fig. 3, the relation between interval angle of adjacent projectors δ and diffuse angle of the special diffuser ε is defined by Eq. (2):

$$\frac{\sin(\varepsilon/2 - \delta/2)}{R} = \frac{\sin(\delta/2)}{L_P} . \quad (2)$$

As δ and ε are rather small, approximation can be obtained to the optimum diffuse angle of the special diffuser ε , defined by Eq. (3):

$$\varepsilon = \frac{(R + L_P)\cdot\delta}{L_P} . \quad (3)$$

In above analysis, we assume that the apertures of the lenses are emitting points. And this approximation is acceptable because the projecting distance is large enough so that we could use the central light ray to infer the relations.

3. Self-calibration with PDLC-based capturing components

Scalable multiple projections play crucial role in extending the viewing range as mentioned above. Given the system configurations and theoretical analysis, this proposed light field 3D display would attain better imaging performance with appropriate geometrical calibration for splicing accuracy, offset accuracy and projection distortion. Specifically, the distortion in practice rather do harm to imaging performance because of the obliquely projected onto a curved screen which is resulted from the lenses set stagger. The negative effect of which seem more obvious for the edge views. In this section, we discuss the calibration of a single display unit first, and similar process could be inferred for multi-LCDs style with only different patterns and different algorithm applied.

Conventional projection calibration configurations are always independent with display hardware, which means extra configurations are required. Another problem is that existing capturing calibration methods usually require human's participation, which is not intelligent and limits the usage of the display. In this paper, a camera and a PDLC film are assembled in the display unit to make the calibration intelligent and efficient. When the PDLC is turned on, it is approximately transparent and act no influences in the imaging process. While when it is turned off, the PDLC becomes opaque thus provides a certain diffuse characteristic for calibration. In this way, rays projected onto the PDLC film are reflected diffusely, so as to be captured by the camera, which is mounted at the top of the display with fixed relative position and orientation. The display mode and calibration mode can be electronically switched without adding extra configurations. Initially, the optical axis of the calibration camera is aligned with the direction of LCD panel pointing at the PDLC film. Special patterns are projected and then captured. A standard PC connects the LCD panel, the camera and the PDLC film to control the self-calibration process. Computer real-time feedback is utilized to make this calibration method intelligent and efficient.

LCD-based display brings the advantage of flexibly implementing in geometrical calibration of multiple projections. Since we assemble the display components and calibrationcomponents together, the whole system owns the flexibility of switching between the display mode and calibration mode automatically. In terms of calibration mode, three main steps could be operated with the PDLC film turned off: (1) For the display-capture style calibration, extra influencing factors with camera applied need to be taken into account firstly. To calibrate these camera parameters, we use printed chessboard patterns and follow the established method in computer vision research area. (2) Once the intrinsic camera parameters are obtained, we then project known square patterns to calibrate the mini-projectors composed by lens array and LCD panel [19]. In this step, the accurate offset and assembled errors of lens array are calibrated. (3) After independent calibration for each light field display unit, we adopt the modified calibration method taking consideration of the screen shape and the spatial positions and orientations of display units [20]. In the calibration procedures, known square patterns are operated and the middle point of captured image is then extracted as the corresponding point by different cameras. The geometry of the curved screen is computed by triangulating techniques based on correspondences extracted from cameras at different positions. The detailed calibration experiments and results are discussed in next section.

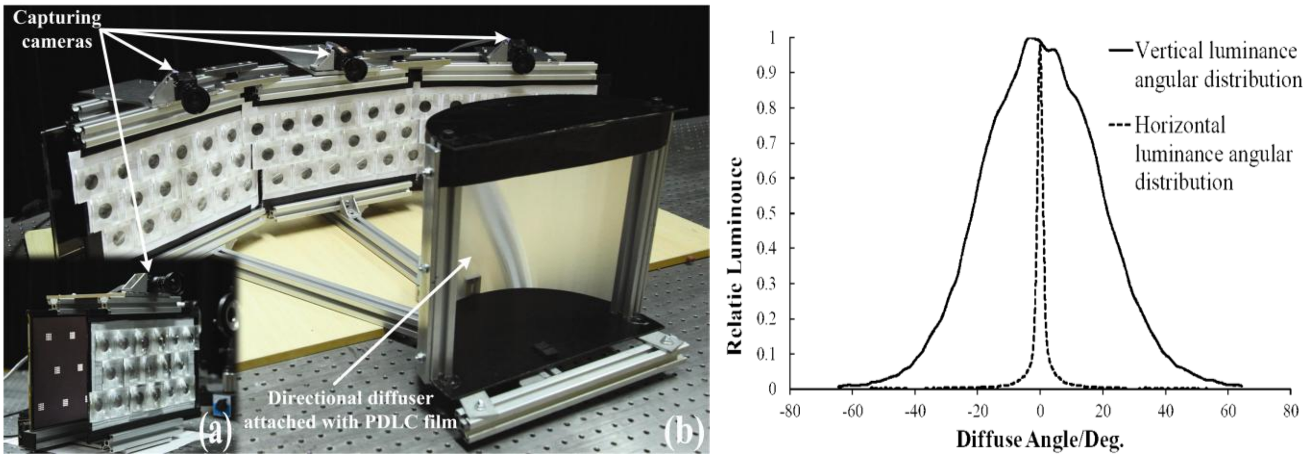
4. Experimental results

4.1 System specifications

To validate the display principle, a prototype is proposed under the specifications shown in Table 1. The light field display unit and its extension with 3 display units are presented in Fig. 4(a)-(c). The display region of each LCD is divided into 17 sub-display images setting stagger vertically with 3 rows to enable the adjacent exit-pupils closer enough, as well as utilizing the pixels region of LCD panel to the maximization. Off-the-shelf Fresnel lens is applied here due to its advantages of small thickness, easy-assembling and low-cost. Commercial used PDLC film is attached to the diffuser as the self-calibration component. The camera used in this prototype is a video camera with 1024×768 resolution and mounted at the top of the display unit. The relative position and orientation of the camera to the display unit is fixed. We implement the modified MCOP (multiple-center-of-projection) algorithm to generate the projected source images based on light field reconstruction principle mentioned above. MCOP algorithms have been widely used in previous displays [12,18]. GPU-based computing and rendering concurrently is also employed here to achieve dynamic display.

Table 1. Specifications of LCD-based Scalable Light Field Display Prototype

Contents	Specifications
Flat-panel display	3 LCDs with each size 15.6 inch
Pixel pitch (mm)	0.178
2D resolution (pixels)	Each 1920 × 1080
Lenses Array	Fresnel lenses with total number 51
Focus of lens (mm)	100
Transmittance of PDLC (%)	85 / On and 40 / Off
Diffuse angle (degree)	Nearly 1.2 in horizontal
Viewing angular range (degree)	Over 60 in horizontal



(a/b) (c)

Fig. 4. The prototype of LCD-based light field display unit (a) and scalable display with multiple units assembled (b), the luminance distribution in horizontal and vertical direction (c) of the diffuser in the prototype.

4.2 Simulated results

In order to better describe our light field imaging process, we attempt to use OpenGL programming to simulate the display performance with the generated images on LCD. The basic simulated process is to get the imaging pixels' distribution on the diffuser screen, which is the image surface of the lenses. Then we capture the viewed image with shooting to the diffuser screen at designed viewing position in the algorithm. This can be regarded as the reconstruction process of the image generation. Fig. 5(a)-(b) shows the original and simulated results of the 3D scene (A cartoon tiger) in three different viewing positions, respectively. From the figures, we can see the major part of the 3D scene is coordinate to that in the original perspective images of the tiger, except for the splicing staggerly and overlap of the "tail" and the "claw". We assert that this is because the display performance in the edge of the 3D scene is not as good as the central area. The vertical black lines in the figure are resulted from the approximation of rasterization in OpenGL programming, which owns no influences on the simulated results. These results validate, the light field imaging principle of proposed system.

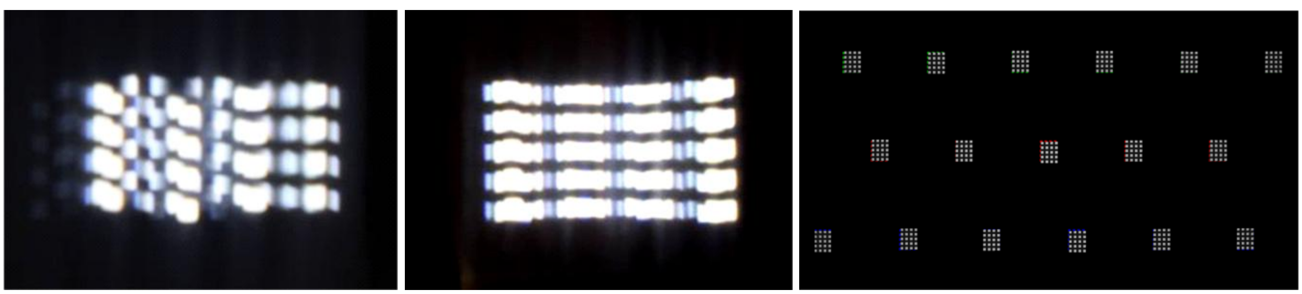
(a)

(b)

Fig. 5 The origin models (a) and the simulated results (b) of the 3D scene in three different perspective viewing positions.

4.3 Calibration results

The splicing accuracy is definitely important in calibration. Here we project designed patterns, i.e. 4*5 square patterns, from the central region of mini-projectors. Ideally, these patterns should be vertically aligned on the screen and horizontally aligned at the reconstruction center, as the display principle requires. However, due to the hardware mismatches and imperfect imagery, it can be observed that the projected patterns are misaligned before the calibration, as Fig. 6(a) shows. In the calibration, offsets of pixels to compensate these misalignments are captured and computed. Fig. 6(b) presents the pattern image viewed from the central viewing position after calibration. Though we could still find some little out-of-flatness in horizontal in the experimental results, which is resulted from limited resolution of capturing CCD, the calibration accuracy is acceptable in existing configuration. And for other displays, it could be increased largely with applying delicate patterns and high resolution cameras. Fig. 6(c) shows the patterns' distribution and offset on LCD panel. The effect of geometrical calibration is verified.



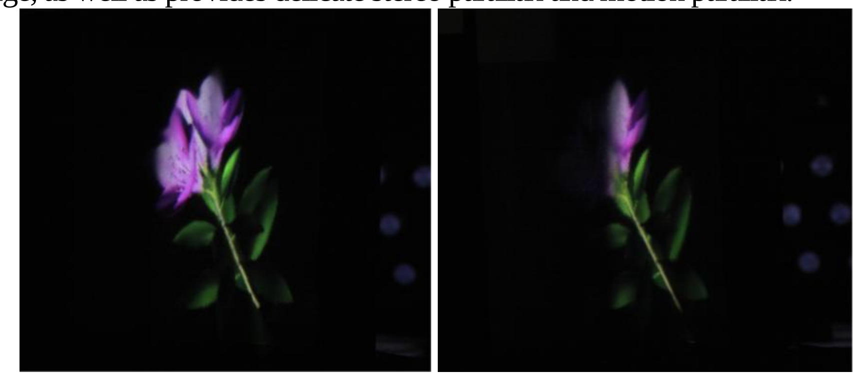
(a) (b) (c)

Fig. 6. The pattern image projected onto the screen captured before the calibration (a) and after the calibration (b), to validate the calibration algorithm, simple 4*5 patterns are implemented here as the test; (c) shows offset of each sub-display region compared with initial position, 4*5 patterns are centered at new sub-display region. Offsets are drawn in colors.

Off-the-shelf PDLC film is adopted in our experiment, which brings the problem that its transmittance indicates a little high yet when turned off, shown in Table 1. That is to say, the reflected and diffused rays captured by calibration camera is limited. In conjunction with the problem of low brightness of LCD-based projection, the captured pattern images behave a little dusky and low contrast in computer processing,. We have implemented several image processing technique to weaken its impact. It is manifest that higher transmittance when turned on and lower transmittance when turned off is expected and would make the self-calibration more precise. And this could be settled to some extent with designed and research-class PDLC film adopted. Therefore, this display-capture self-calibration method is more efficient and compact than conventional calibration methods, and of course make the display precisely scalable.

4.4 Display results

After appropriate calibration, we turn on the PDLC film and generate imaged to reconstruct some 3D scenes. Fig. 7(a)-(b) shows the photos of a 3D flower scene displayed by the prototype. Photos are captured in different horizontal viewpoints. One is in and the other is partly out of the best viewing zone. Obviously, bright vivid 3D scene reconstructed is observed in Fig. 7(a), while in Fig. 7(b) parts of the flower disappear. This confirms to the display principle that at some edge viewing positions 3D image's integrity decreases. This is because we attempt to distribute the pixels to form as uniformity rays as possible in the viewing range. The viewing angular range is about 20 degree for single display unit. And this characteristic is different from some conventional auto-stereoscopic 3D displays that stressing image's integrity in limited views. Therefore, spliced multi-LCDs structure is proposed to enlarge the viewing range, as well as provides delicate stereo parallax and motion parallax.



(a) (b)

Fig. 7. Photos of the reconstructed virtual flower in (a) and out (b) of the best viewing range.

(a) (b) (c)

Fig. 8.(a)-(c) Photos of the reconstructed tiger model from three different viewing positions.

Fig. 8(a)-(c) presents the reconstructed cartoon tiger model from three different viewing positions. The horizontal viewing angular field reaches 60 degree and could be enlarged by assembling more display units together. The curve diffuser screen could also create touching space for observers to interact with the 3D scene, like an embryo of performance stage. The further interaction method could be attached in the future work.

Brightness is rather an crucial problem for LCD-based projection light field display. Our system also suffers a little from this disadvantage. In terms of existing configuration, the emitting rays from backlight of LCD panels distribute in a large angle for daily use, while there are extra loss of brightness resulted from the diaphragms we attached as the exit-pupils of projectors. That is to say, the practical efficiency of emitting rays is low. Besides, this problem requires more high-transmittance PDLC film and directional diffuser. The brightness of rays emitting from LCD panels directly and that of rays passing through whole system are measured. Even 3M DBEF (Dual Brightness Enhanced Film) is added inside the LCD panels to increase nearly 50% of the brightness of projection sources, the brightness decreasing ratio between the LCD and reconstructed field is nearly 20:1, which deserves being improved in further study. Another compelling argument is the approximation we have implemented in the light field imaging algorithm which is discussed in the principle section, the preliminary simulation and the existing performance show no obvious effect of this approximation. While we concede it deserves further discussion and requires taking all factors into consideration from optics and computer graphics. These issues would be the point of further research.

5. Conclusion

In conclusion, an approach to achieve light field display with self-calibration is demonstrated. The LCD-based projection desgin is verified in the prototype to provide compact 3D imaging performance with flexible configuration, continuous viewing positions and large viewing angular range. Based on the PDLC film and capturing camera, the self-aware calibration method is proposed to calibrate both single display unit or assembled display system in an efficient way. And this calibration method owns great potential to be applied to other projection light field displays. Finally, we believe light field displays based on multiple flat panels will see a great potential in commercial applications in near future for its cost-control, easy-manufacturing and fast-calibration.

6. Acknowledgements

This work was supported by research grants from Chinese National Natural Science Foundation (61177015), National Key Fundamental Research Program of 863 (2012AA011902), and Fundamental Research Funds for the Central Universities of China.

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