Full-parallax Colorful 3D Imaging Using Orthogonal-stacked Lenticular Sheets and Computer-generated Stereogram

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Abstract. This paper proposes a true-color full-parallax three-dimensional (3D) imaging method based on OLS. The optical imaging effects of OLsS and micro-lens array (MLA) are analyzed using optics simulation software, and the OLS is used to realize the stereoscopic display instead of MLA. 2D multi-view images array of virtual objects is obtained, and the full-parallax pixels (FPPs) are generated by cordining pixels of these images, which are synthesized together to obtain the colorful full-parallax stereogram (FPS). The size of full-parallax pixels of FPS is accurately matched with the measured grating pitch of the lenticular sheets. When the FPS printed ,Colorful 3D image with full-parallax can be observed by matching the printed FPS with the OLS.

Introduction

Integrated imaging is one of the common-used 3D display techniques and it doesn't need complicated operation or wearing any special glasses to achieve the 3D imaging results. Therefore, this technique becomes an important research direction in 3D display [1-4]. The integral imaging can eliminate visual fatigue generally existed in binocular disparity of stereoscopic vision, and can provide horizontal and vertical parallaxes by using special optical elements such as micro-lens array [5]. With the technique development of manufacturinglenticular sheets, 3D display implemented with lenticular sheetshas aroused much attentions. integral imaging using orthorgnal-stacked lenticular sheets(OLS) can provide horizontal and vertical parallaxes as similar to integral imaging using mirco-lens arrays, and the observers can also view the 3D image in two-dimensional directions [6-10].

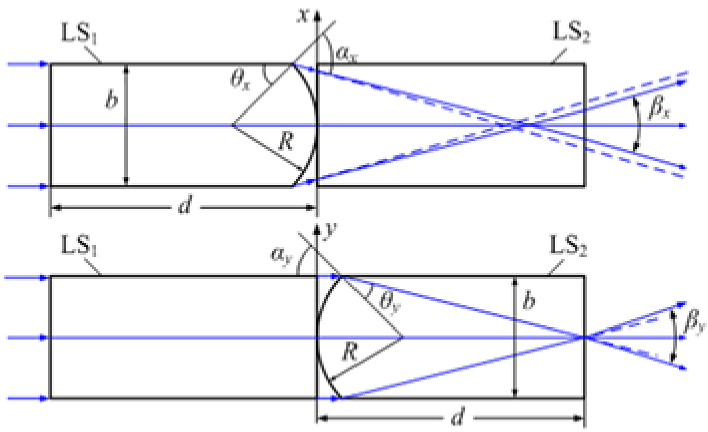


Fig. 1 Schemetic diagram of light propogating through a single lenslet of OLS

In the previous research, the optical imaging effects of MLA and OLS has been analyzed using optical simulation software. It was proved that the imaging effect of MLA is similar to that of OLS. In this paper, we introduced thegeneration method of full-color stereogram with full-parallax used for 3D imaging based on the principle of integral imaging [11] and the viewing angle of 3D imaging using OLS were analyzed theoretically and then measured in the 3D imaging experiment.

Viewing Angle Calculation of OLS

Fig. 1 illustrates the light propagating through a single lenslet of OLS. We can calculate the viewing angles in the x and y directions according to the refraction law, and the viewing angles β_x and β_y can be formulated as

$$\beta_x = 2(\alpha_x - \theta_x)\ ; \beta_y = 2\,\mathrm{asin}\left(n\sin\left(\alpha_y\text{-}\theta_y\right)\right).$$

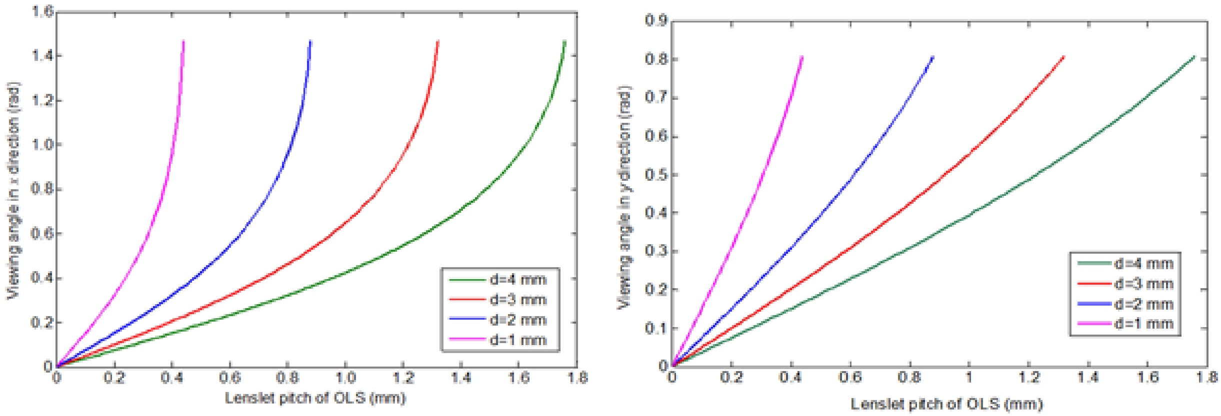
Where,

$$\alpha_x = \mathrm{asin}\,(\frac{nb}{2R}),\ \theta_x = \mathrm{asin}\,(\frac{b}{2R}),\ \alpha_y = \mathrm{asin}\,(\frac{b}{2R}),\ \theta_y = \mathrm{asin}\,(\frac{b}{2nR});$$

where, n is the refractive index of lenslet, and b is the lenslet pitch of OLS. R is the curvature radius of cylindrical surface of the lenslet, and $R = (n-1)d/n$ (d is the thickness of lenticular sheet). Accordingly, the viewing angles β_x and β_y in the x and y directions can be described as

$$\beta_x = 2\left(\mathrm{asin}\,(\frac{nb}{2R}) - \mathrm{asin}\,(\frac{b}{2R})\right); \beta_y = 2\,\mathrm{asin}\left(n\sin\left(\mathrm{asin}\,(\frac{b}{2R})\text{-}\mathrm{asin}\,(\frac{b}{2nR})\right)\right).$$

Fig. 2 shows the variation trends of viewing angles in the x and y directions along with the changes of the lenslet pitch and the thickness of the lenticular sheet. The refractive index of lenticular sheet is set as 1.4935. We note that the variation trends of viewing angles of OLS in the x and y directions are a little different.



(a) (b)

Fig. 2 Virations of viewing angles in the x and y directions along with the changes of the lenslet pitch and the thickness of the OLS. (a) x direction; (b) y direction.

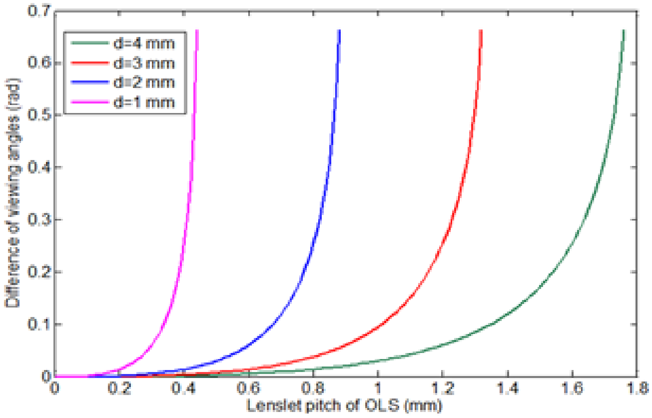


Fig. 3 Difference of viewing angles in the *x* and *y* directions

As shown in Fig. 3, the difference of viewing angle in the *x* and *y* directions increases non-linearly with the increasing of the lenslet pitch of the OLS. The difference of viewing angle can reach to the same value despite the thickness value of OLS. If the lenslet pitch getting smaller but thickness keeping constant, the difference of viewing angle in the *x* and *y* directions will decrease. For example, if the thickness of lenticular sheet is set as 3 mm, the difference of viewing angles in *x* and *y* directions is 0.0376 rad when the lenslet pitch is set as 0.8 mm, and the difference of viewing angles in *x* and *y* directions decreases to 0.0135 rad when the lenslet pitch decreased to 0.6 mm. That is, in order to keep the difference of viewing angle small, the lenslet pitch of OLS is generally set as an appropriate small value but at the expense of decreasing of viewing angle.

Generation of Full-color Stereogram with Full-Parallax for Integral Imaging

The Acquisition of the Full-parallax Images Array. We used 3Ds max version 7.0 to design and acquisit the two-dimensional parallax images of 3D objects. As shown in Fig. 4, a virtual target camera array arranged at a certain intervals were used to captured the colorful parallax images.

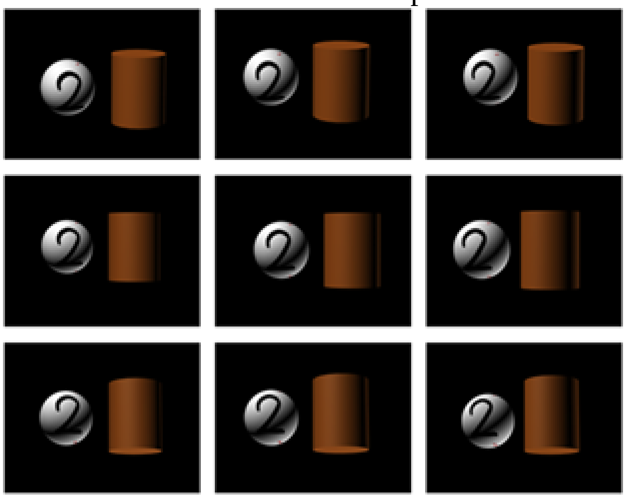


Fig. 4 Parallax image array (3×3 images in the array)

The The captured full-parallax images array is shown in Fig. 5. The pixels of parallax image acquiring by 3Dsmax set as 181pixel×201pixel, and the number of angle of views set as 41×41. The center distance of adjacent cameras (*dx*, *dy*) is 6.3mm in the Fig. 6. The distance from the path plane to the target point which is denoted by D is set as the focal length of the camera. Some of the acquired full-parallax images are shown in Fig. 4.

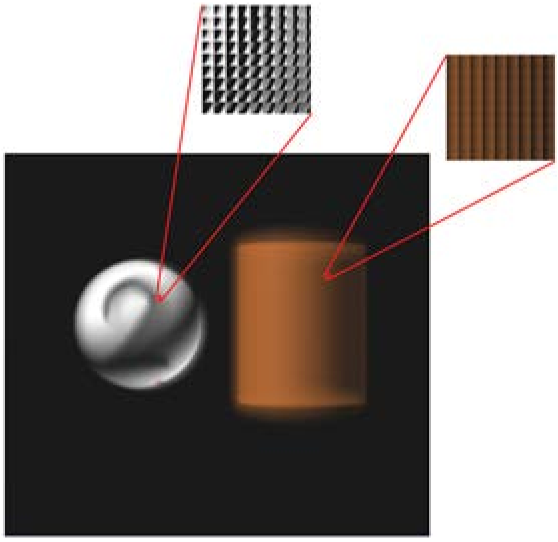


Fig. 5 Full-parallax stereogram calculated by the proposed method. (the top right insets are the enlarged FPPs in the FPS)

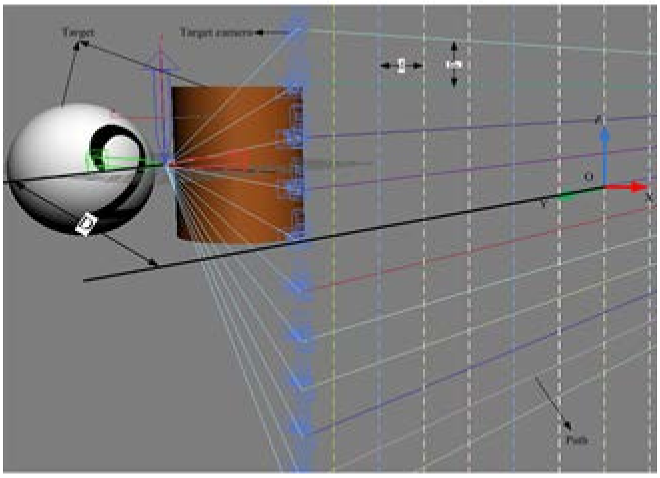


Fig. 6 Schematic diagram of the acquisition method of full parallax images array

Synthesis of the True-color Full-parallax Stereogram. The large-area hologram is divided into many small units to be recorded in synthetic hologram, and then these small units are exposed successively to synthesize a complete large-area hologram. Because of the differences between observing the objects though cylindrical lens and directly exist not only in the stereoscopic effect of display but also in the order of images, the order of all the viewpoints turns into inverted sequence after going through the cylindrical lens. Therefore, while synthesizing the pixels, there won't be any deviation from original pixel only if extracting the pixels at the same position of perspective images array in inverted sequence of the shooting images. And then, restore the image when observers see the best stereoscopic effect.

$M \times N$ perspective images are acquired using the target-camera of 3Ds max, and each perspective image contains all the light intensity information of this angle of view. The pixels at the same position of perspective images array are extracted in inverted sequence of the shooting images, then these pixels are synthesized into a full-parallax pixel in the sequence of the shooting images. The size of each full-parallax pixel in the synthesized full-parallax stereogram is equivalent to the pitch of lenslet. $T(i,j,k)$ denotes the k th primary color channel of the full-parallax pixel, and it includes all of the pixelsat the same pixel position of all the perspective images, and can be formulated as Eq. 1.

$$T(i,j,k)=\begin{bmatrix} V(M,N)\cdot p(i,j,k) & V(M,N-1)\cdot p(i,j,k) & \dots & V(M,1)\cdot p(i,j,k) \\ V(M-1,N)\cdot p(i,j,k) & V(M-1,N-1)\cdot p(i,j,k) & \dots & V(M-1,1)\cdot p(i,j,k) \\ \dots & \dots & \dots & \dots \\ V(1,N)\cdot p(i,j,k) & V(1,N-1)\cdot p(i,j,k) & \dots & V(1,1)\cdot p(i,j,k) \end{bmatrix}_{M\times N} \quad (1)$$

Where, $V(M,N)\cdot p(i,j,k)$ is one of the pixels in the perspective image $V(M,N)$; M denotes the number of horizontal angle of view, and N denotes the number of vertical angle of view.Each perspective image includes $I\times J$ pixels ($i=1,2,3,\dots,I$, and $j=1,2,3,\dots,J$) with R (red), G(green), and B(blue) primary color channels.

Recombine the pixels of full-parallax images array to full-parallax pixels, and the 181×201 full-parallax pixels are obtained. Every full-parallax pixel contains 41×41 sub-pixels. The full-parallax stereogram is the array of all of the full-parallax pixels, as shown in Fig. 5, where the top right insets are the enlarged full-parallax pixels.

Experiment and Results

In our experiment, two kinds of lenticular sheets with different parameters were used to testing the 3D imaging results. The parameters of the two lenticular sheets were listed in Table 1.Each OLS consists of two lenticular sheets with the same parameters orthogonally stacked in curve-curve form, and the full-parallax stereogram is placed in front of it.

Table 1 The parameters of the two lenticular

Parameters	LS1	LS2
Material	PMMA	PMMA
Index	1.4935	1.4935
Thickness(mm)	3.0	2.0
Nomial pitch of lenslet(mm)	0.7938(32 lines per inch)	0.6048(42 lines per inch)
Measured pitch of lenslet (mm)	0.8002	0.6073

The computer-synthesized full-parallax stereogram is then printed onto the photo paper using laser printer with highest resolution of 5760×1440 dpi. In order to accurately match the full-parallax stereogram with OLS1 and the OLS2, the size of each full-parallax pixel is adjusted to 0.8002mm×0.8002mm and 0.6073mm×0.6073mm, respectively. The printed full-parallax stereograms are accurately matched with the OLS1 and OLS2, respectively. And then the full-color 3D images with full-parallax can be observed from continuously changed viewpoints .

Conclusion

This paper analyzed the optical properties of true-color full-parallax 3D imaging method based on OLS. The optical imaging effects of OLS are similar with that of MLA, so the OLS was used to realize the stereoscopic display instead of MLA. Full-parallax images array of virtual object in 3D scene was obtained by 3Ds max, and full-parallax pixels were generated by recombining pixels of parallax images array, which were synthesized together to obtain the true-color full-parallax stereogram using Matlab. The size of full-parallax pixels were matched accurately with the practical measuring grating spacing of lenticular sheets, and the true-color full-parallax stereogram was printed onto the photo paper using high resolution laser printer. The printed paper was accurately matched with the OLS, and the true-color full-parallax stereogram could be observed from different viewpoints clearly, brightly and continuously.

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