Demonstration of full-parallax three-dimensional holographic display on commercial 4 K flat-panel displayer

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A novel method for a full-parallax three-dimensional (3D) holographic display by means of a lens array and a holographic functional screen is proposed. The process of acquisition, coding, restoration, and display is described in detail. It provides an efficient way to transfer the two-dimensional redundant information for human vision to the identifiable 3D display for human eyes. A holo-video system based on a commercial 4 K flat-panel displayer is demonstrated as the result.

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Based on the principle of the holographic stereogram, we have published Letters to realize a full-color and real-time holographic display by means of a holographic functional screen (HFS) combined with a system formed by a camera-projector array. In practice, it is difficult to integrate the whole system due to the calibration of each individual camera-projector; meanwhile, the high cost of adapting masses of camera-projectors makes such a system unacceptable for public consumption.

Integral photography theoretically seems like an ideal approach for both the acquisition and restoration of three-dimensional (3D) light fields; however, it is difficult to overcome the inherent inconsistency formed by the micro-lens between the sub-image quality and the resolution of the final 3D display because of diffraction effect of the lens aperture. Therefore, a satisfactory 3D display is a challenge that has yet to be overcome.

In this Letter, we propose a novel approach to realize a perfect holographic display perceived by human eyes. It is equivalent to the setup in Refs. [1-5], while the optical axis of each individual camera-projector is parallel to each other, i.e., anchored at an infinitely far point. It could be thought of as a successive technical innovation derived from our proposed physical concepts named the hoxel and spatial spectrum, which are properly defined by the four-dimensional Fourier transform of the wave function of this nature. The purpose is for the most compact design to carry out the application at the lowest cost.

There are four steps in our innovation:
1. Parallel acquisition of the spatial spectrum.

Figure 1 is the sketched map for the parallel acquisition of the spatial spectrum. L1 is a plate of lens arrays comprised by M × N small lenses with the same imaging parameters, which are denoted by a1 for the aperture of each lens, d1 for the concentric distance, and f1 for the focal length. The viewing angle of each lens could be expressed as \( \tan(\Omega/2) = a_1/2f_1 \). As the optical axis of each individual lens is parallel to each other, the spatial spectrum \( I_{mn}(j, k) \) \( (m = 1 \text{ to } M, n = 1 \text{ to } N) \) of a 3D object O acquired by each lens inside its viewing angle \( \Omega \) corresponds to what we have described before in Refs. [1-5]. The sampling angle of acquisition could be denoted as \( \omega_{mn} = d_1/l_1 \), and \( l_1 \) is the distance between the lens plate L1 and the object O. S is a light-sensitive component (such as film, CCD, or CMOS, etc.) placed near the focal plane of \( L_1 \) with a distance \( l_1' \) to the lens plate to record the spatial spectrum \( I_{mn}(j, k) \). \( J * K \) is the resolution of the digital light-sensitive component corresponding to each imaging unit of the lens plate: \( j = 1 \) corresponds to \( J \), and \( k = 1 \) corresponds to \( K \). The corresponding hoxel is denoted as \( H_{jk} \), i.e., the acquired object \( O \) is constructed by \( J * K \) voxels, \( H_{jk}(m, n) \). The distance between object \( O \) and the reference surface \( P_R \) is \( l_3 \), and the reference point \( R \) is located at the center of \( P_R \). Field aperture \( M_j \) is placed between \( S \) and \( L_1 \) to prevent the crosstalk of each \( I_{mn} \). Compared with the traditional integral...
photography, the lens array here is not a microlens array; the aperture $a_1$ of each lens is big, so as to acquire enough of a distinct image of each spatial spectrum, but it is never bigger than $d_1$. The focal length $f_1$ determines the viewing angle $\Omega$ of each individual lens. The bigger the $\Omega$ of the lens, the bigger the scope of the 3D object it can acquire. Here, we suppose that $\Omega$ is big enough to make at least one lens near the center $(M/2, N/2)$ of the lens array acquire the whole object $O(j, k)$, as shown in Fig. 1.

Compared with the work we have described in Refs. [1–5], where the anchoring acquisition was adopted, except for the spatial spectrum image $I_{(M/2)(N/2)}(j, k)$ at the center of the lens array, which is exactly the same, other sub-images are shifted a phase factor of $\delta_{mn}$ on the spectrum surface corresponding to the original spatial spectrum $I_{mn}(j, k)$ acquired by the anchoring acquisition. They are then trimmed by the field aperture $M_1$ to make the reference point $R_{mn}$ on each sub-image of the original object $O$ overlap at the same position $R$ after imaging back to the original space. In Figs. 2 and 3, the corresponding coordinates of the reference point $R$ and its sub-image $R_{mn}$ inside each spatial spectrum are respectively compared. The phase factor $\delta_{mn}$ is the inherent character for parallel acquisition described in this Letter; it could be the accordance of each spatial spectrum shift when the 3D data is acquired by the anchoring acquisition and playing back in a parallel situation or vice versa.

2. Holographic coding of the spatial spectrum.

It is necessary here to create holographic coding by making use of the $J \times K$ pixels of each $M \times N$ spatial spectrum acquired from Fig. 1 to generate the $J \times K$ holographic coded spatial spectrum $S_{jk}(m, n)$. The details are shown in Fig. 4. We can use a computer to pick the $(j^{th}, k^{th})$ pixel $P_{mnjk}$ of the image $I_{mn}(j, k)$ to fill the inside of a certain hoxel $H_{jk}$ of the object space shown in Fig. 1 to get the coded spatial spectrum $S_{jk}(m, n)$ of this hoxel. The significance of such holographic coding is as follows: (1) We can efficiently realize coordinate transformation between “image and spectrum” to eradicate the fatal drawback of “pseudo-scope imaging.” (2) Such a coding method is versatile and can be used in any kind of 3D display system; the holographic coded image $S_{jk}(m, n)$ can be directly broadcasted by the lens array, or treated as the “hogel” to print the 3D hologram dot by dot [7]. (3) By means of simply magnifying or reducing the pattern size of $S_{jk}$, the size of the hoxel $H_{jk}$ could be arbitrarily changed to get a magnified or reduced display of a 3D object,. (4) According to the details of acquiring or displaying a 3D space (such as resolution, depth, and viewing angle, etc.), the maximum sampling angle $\omega_{mn}$ could be designed for perfect 3D displays by the minimum spatial spectrum number $(M, N)$ for the most efficiency.


After a simple treatment involving magnifying or reducing, $J \times K$ frames of holographic coded image $S_{jk}$ are
displayed at the corresponding positions on a flat-panel display \( D \), which has a resolution bigger than \( M \times N \times J \times K \). Figure 5 is the sketched map for the formation of the integral discrete spatial spectrum, where lens plate \( L_2 \) is located in front of \( D \) with a distance of \( l_2 \). \( l_2 \) is equivalent to \( l_1 \) in Fig. 1 when the hoxels \( H_{jk} \) are correspondingly reduced or magnified. \( L_2 \) is still comprised by \( J \times K \) small lenses with the same imaging parameters denoted by \( a_2 \) for the aperture of each lens and \( d_2 \) for the concentric distance (here is just the hoxel size of the preset \( J \)).

4. Integral reconstruction decoded by HFS.

As shown in Fig. 5, we placed a corresponding HFS, which is described in our previous work\(^1\),\(^2\), at the position of \( O' \) to make the expanding angle of each discrete spatial spectrum input \( S_{jk} \) the same as the sampling angle \( \omega_{mn} \) shown in Fig. 1; i.e., to make each coded spatial spectrum \( S_{jk} \) combined together but not severely overlapped (the appearance here is a uniform bright background because the edge features of each lens are just smeared together by the HFS). This forms an integrally continuous output of the spatial spectrum. Human eyes can then observe a real holographic 3D image \( O' \) floating on the HFS. It should be noted that the HFS should be located at the above-mentioned place; this is the most efficient way to display a certain sampling angle \( \omega_{mn} \). The HFS could be regarded as the standard plane straddled by the displayed 3D space with the depth determined by \( \omega_{mn} \). When the HFS is not correctly located to make the broadcasting angle much bigger or smaller than the sampling angle, the displayed space would lack the original 3D data, which would result in severe crosstalk or a nonlinear appearance.

In order to make our innovation more comprehensible, the following analysis was done of the imaging quality:

1. Spatial spectrum description of 3D information:

Suppose \( \Delta_{jk} \) is the size of a preset hoxel \( H_{jk} \) in a 3D space, and \( \Delta Z \) is the depth of that space, then the corresponding sampling angle can be expressed as \( \omega_{mn} = \Delta_{jk} / \Delta Z \). That is to say, a 3D object \( O \) constructed by \( J \times K \times \Delta Z \) individual small cubic irradiators (\( \Delta_{jk} \))\(^3\) can be completely derived by \( M \times N \times J \times K \) individual light tapers, in which the apex of each light taper is located inside the plane of the HFS, while the divergent angle is \( \omega_{mn} \). The viewing angle of this 3D object is \( \Omega = \Sigma \omega_{mn} \).

Here, we have \( \Delta Z = \Delta_{jk} \times \Delta_{jk} / \omega_{mn} = M \times N \), because \( M \times N \) spatial spectra are included inside the hoxel \( H_{jk} \).

2. Spatial spectrum description of human vision:

Some basic parameters of human eyes are as follows:

(1) pupil distance (the average distance of two eyes) \( d_E \approx 6.5 \text{ cm} \), (2) pupil diameter (2–8 mm, depending on the brightness), on average, is \( a_E \approx 5 \text{ mm} \), (3) angular resolution limitation: \( \omega_E \approx 1.5 \times 10^4 \), and (4) viewing angle in the stationary state: \( \Omega_E \approx 90^\circ \). When human eyes are fixed on a certain position, human vision is able to express \( J \times K \approx (\Omega_E / \omega_E)^2 \approx (\pi / 2) / (1.5 \times 10^4)^2 / 10^8 \approx 10^8 \) hoxels and needs only two spatial spectra (\( M \times N = 2 \)) to form the binocular stereoscopic image. There are \( 10^8 \) spatial spectra identified by human eyes, included in two hoxels \( H_R \) and \( H_L \) to form the objective 3D knowledge acquired by human eyes submerged into such hoxel oceans.

3. Effective acquisition and restoration:

Aiming at the spatial spectrum expression described in 1 and 2, the visible 3D space information could be fully acquired by the lens array plate \( L_1 \) shown in Fig. 1, and also could be fully restored by the lens array plate \( L_2 \) shown in Fig. 5. The detailed requirements are as
follows: $a_1 = 2\lambda l_1/\Delta_{jk}$, $a_2 = 2\lambda l_2/\Delta_{jk}$, $\lambda$ is approximately 550 nm, which is the average wavelength of visible light, $\omega_{mn} = d_1/l_1 = d_2/l_2$, $\tan(\Omega/2) = a_1/(2f_1) = a_2/(2f_2)$. Here, the sizes of the lens apertures ($a_1$ and $a_2$) determine the size of hoxels $\Delta_{jk}$ or the cubic voxels $(\Delta_{jk})^3$ that are acquired or restored; the concentric distances ($d_1$ and $d_2$) determine the sampling angle $\omega_{mn}$ of the space acquired or restored, and therefore determine the depth of this space $\Delta Z = \Delta_{jk}/\omega_{mn}$. The focal lengths ($f_1$ and $f_2$) determine the viewing angle $\Omega$ of this space, which behaves as the processing capability of a lens unit in the spatial spectrum information, i.e., $\Omega = \Sigma \omega_{mn}$. Because we adopt the HFS to compromise the nonlinear features of the lens array, the microlens paradox for integral photography could be completely avoided. The key is achieving a high-enough resolution of the corresponding sensor (S in Fig. 1) and displayer (D in Fig. 5) to identify and display the spatial spectrum information composed by above-mentioned $J \times K \times M \times N$ individual pixels.

By making use of a commercially available 4 K flat-panel displayer KKTV LED39K60U with the resolution of 3840 $\times$ 2160, according to the above-mentioned principles, we have achieved a digital holographic display with full color and full parallax. The details of the parameters are as follows: (1) hoxel size is 2.5 mm $\times$ 2.5 mm, (2) number of hoxels is $J' \times K' = 337 \times 188$, (3) the number of the spatial spectrum is $M \times N = 36 \times 36$, and (4) the viewing angle is $\Omega = 30^\circ$.

Figure 6 is the sketched map of the holographic coded pattern of the spatial spectrum inside each small lens; here, the process of acquisition is replaced by directly rendering the computer-simulated 3D models. In order to fully use the limited pixels on the 4 K displayer, we aligned 3818 small lenses with the aperture $a_2 = 10$ mm diameter in a honeycomb array. Figure 7 is the picture taken from one direction before the HFS is applied. No detailed features can be identified in the picture, only discrete light rays from the hoxel $H_{jk}$. Figure 8 is the picture taken from one direction after the HFS is applied. All features are properly decoded by the HFS as the final displayed hoxel $H'_{jk}$. Figure 9 shows the pictures taken from multiple directions of the holographic displayed digital 3D models formed by the coded spatial spectrum shown in Fig. 6; the smooth color restoration and the full parallax relationship of the displayed space can be distinctly seen. Figure 10 is another result of a holographic display “skull” in which each profile is clearly expressed.
In conclusion, we demonstrate the design and experimental result of identifiable holographic display for human vision. The key is to transform the visual redundant pixels into an identifiable hoxel display. Although the available 4 K flat-panel displayer could only obtain a 2.5 mm hoxel size, the developing 8 K or even 16 K flat-panel displayer would eventually improve the final hoxel resolution for the eye-catching level if the lens aperture is bigger than the human pupil. We expect this novel device would find its first application in medical imaging, with the obvious advantage of seeing $36 \times 36$ pictures in real 3D form simultaneously.

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References

Fig. 10. Pictures taken from multiple directions of the holographic display digital 3D “skull.”