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The holographic display of three-dimensional medical objects through the usage of a shiftable cylindrical lens

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ABSTRACT

Through the creative usage of a shiftable cylindrical lens, a wide-view-angle holographic display system is developed for medical object display in real three-dimensional (3D) space based on a time-multiplexing method. The two-dimensional (2D) source images for all computer generated holograms (CGHs) needed by the display system are only one group of computerized tomography (CT) or magnetic resonance imaging (MRI) slices from the scanning device. Complicated 3D message reconstruction on the computer is not necessary. A pelvis is taken as the target medical object to demonstrate this method and the obtained horizontal viewing angle reaches 28°.

1. Introduction

Three-dimensional (3D) medical imaging has proven to be beneficial for medical diagnoses. Tomographic medical imaging, such as magnetic resonance imaging (MRI) and computerized tomography (CT), has been widely used to reconstruct and display 3D medical objects on a 2D screen [1]. But a 2D screen cannot effectively express depth cues of 3D objects [2]. The absence of high-dimensional data presentation may make doctors encounter confusion while doing accurate diagnosis. So, 3D medical objects' display with depth cues in true 3D space is needed urgently.

Binocular parallax technology has been developed to display 3D medical objects [3]. But motion parallax cannot be reproduced without wearing a tracking device. In addition, due to the distance conflict between accommodation and convergence, visual fatigue keeps being a problem for the binocular parallax technology. Integral photography (IP) was also used for displaying 3D medical objects [4] with the help of a microlens array. Although the displayed object has full parallax, problems on depth, resolution and viewing angle hinder IP's further extension in the medical field. Computer generated hologram (CGH) was thought as an ideal 3D display technique which provides a natural spatial effect. However, limited by the space bandwidth product characteristics of the spatial light modulator (SLM), the viewing angle of the display is too small for actual applications [5].

In this paper, for employing a shiftable cylindrical lens, we implement holographic 3D medical objects' displayed with a wide viewing angle based on time-multiplexing. The merit of this developed system is that only a group of 2D slices along one direction are used as source images.

2. Schematic diagram and principle of the developed holographic display system

Fig. 1 shows the schematic optical diagram of the developed system in the horizontal x–z plane. A phase SLM is placed at the front focal plane of the Fourier lens. One couple of parallel sides of the SLM is set along the x-direction. Through the Fourier lens, CGH fed to the SLM (with a side length of D along the x-direction) generates a 3D image around the focal plane (FP plane) of the Fourier lens (f_1). Along the x-direction, the projected 3D image is located between points O_1 and O_2 of the FP plane. Through two lenses L_1 and L_2, the reversed image of the projected 3D image appears around the object plane (OP plane). FP and OP planes are at focal planes of L_1 and L_2, respectively. The distance between two lenses is $2d$ and their focal lengths are identicalto f_3. The Fourier lens is coaxial with L_1 and L_2 and this common axis is taken as the optical axis of the system. A shiftable cylindrical lens (f_2) is introduced into the system at the FP plane to refract the 3D images projected from the SLM, which is called Direction Lens (DL) in the paper. The DL can move along the x-direction and its axial direction is perpendicular to the x–z plane. The x-direction message of the SLM is first imaged onto the imaging plane IP_1 through Fourier Lens and DL with a magnification of f_2/f_1, and then

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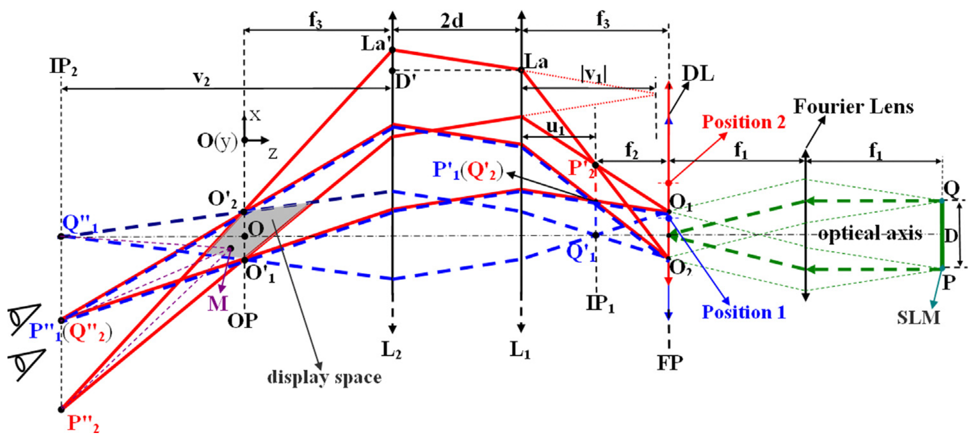

Fig. 1. Schematic optical diagram of the display system with a shiftable cylindrical lens (DL).

imaged onto the imaging plane IP_2 through L_1 and L_2. It shall be minded that the *y*-direction message of the SLM cannot be imaged onto these two planes due to DL's constant phase modulation along the *y*-direction.

When the DL arrives at different positions, the *x*-direction images of the SLM are directed to different locations on IP_1 and IP_2 planes. As shown in Fig. 1, with the DL at Position 1, the *x*-direction images are directed to $P'_1Q'_1$ and $P''_1Q''_1$ on the IP_1 and IP_2 planes, respectively. But when the DL moves to Position 2, the *x*-direction images are directed to $P'_2Q'_2$ and $P''_2Q''_2$ accordingly. Differently, the distribution spaces of reversed images of the refracted 3D images do not translate with the shifting of the DL. They overlap with each other around the OP plane and stay between points O'_1 and O'_2 of the *x–z* plane along the *x*-direction. This overlapping space is the display space of the target medical object. The shadow region in Fig. 1 shows the horizontal section of the display space.

For any displayed point *M* in the display space, its viewing angle region changes from $\angle Q''_1MP''_1$ to $\angle Q''_2MP''_2$ with the DL shifting from Position 1 to Position 2. According to geometric optics, when the space interval between the two positions is set as $(f_2/f_1)D$, the *x*-direction images of the SLM are able to link up spatially along the *x*-direction. As shown in Fig. 1, the Positions 1 and 2 being set as $0.5Df_2/f_1$ and $1.5Df_2/f_1$ away from the optical axis respectively, the point P'_1 will coincide with Q'_2 in the IP_1 plane and P_1'' will coincide with Q''_2 in the IP_2 plane. When the DL is shifted to the two positions alternatively and the corresponding CGHs of the point *M* are encoded onto the SLM synchronously, the adjacent viewing regions $\angle Q''_1MP''_1$ and $\angle Q''_2MP''_2$ will appear alternatively. If the refresh rate of the SLM and the moving speed of the DL are high enough, the receptors in the human eye will have a temporal persistence due to mental processing delay and the point *M* will be observable in an enlarged viewing angle of $\angle Q''_1MP''_1+\angle Q''_2MP''_2=\angle Q''_1MQ''_2+\angle Q''_2MP''_2=\angle Q''_1MP''_2$ along the *x*-direction en route the "after image effect". Through this time-multiplexing method, more available DL positions will further enlarge the viewing angle.

Assuming a target medical object being placed in the display space virtually, iteration algorithms is used for holographic encoding which involves an iterative loop of optical field propagation between the 2D slices of the virtual object and the SLM plane [6]. One group of 2D slices of the virtual object are cut along the *z*-axis, which are source images used for holographic encoding in our proposed system. Although the virtual object is the same, the CGHs will change with DL's movement, because the phase distribution between points $O_1{}'$ and $O_2{}'$ in the FP plane changes with DL's positions and the FP plane is just in the light field propagation path of the iterative loop. In a word, different CGHs are needed to be encoded onto the SLM and corresponding 3D images are projected from the SLM when the DL translates to different positions in the proposed system. These 3D images are refracted by the DL at corresponding positions, and then through L_1 and L_2 the refracted 3D images are imaged into the same virtual target object but with different viewing regions. As discussed above, if the space intervals between adjacent positions are all set as $(f_2/f_1)D$, the adjacent viewing regions will connect end by end. Thus, the viewing angle of the displayed object can be enlarged along the *x*-direction based on the time-multiplexing method.

In the area of holographic 3D display, viewing angle's enlargement was usually implemented by projecting multiple CGHs along different viewing directions. For example, a viewing angle of 22.8° was reached in Ref [7] through a curved array of SLMs which projected CGHs along different viewing directions synchronously. In our previous work, multiple CGHs projected from one SLM were directed to different directions successively by a spinning mirror, then 360°-viewable holographic display was realized per "after image effect" [8]. A common feature of above technologies is that each CGH requires a specific group of 2D source images along corresponding viewing direction. A wide viewing angle will need many groups of 2D source images for generating multiple CGHs for different viewing directions. As a result, complicated 3D message reconstruction of the target object must be carried out in the computer for obtaining multiple groups of 2D source images.

However, in our proposed system, within the provided viewing angle (i.e. 28° in this paper as demonstrated below), the source images for all the CGHs are the same group of 2D slices of the virtual object that is cut along the *z*-axis. Such a characteristic makes the proposed technique more suitable for the 3D medical display. CT or MRI slices from the scanning device can be used directly and complicated 3D message reconstruction is not necessary when viewing is limited wthin the provided viewing angle. Although for actual medical usage, viewing from different perspectives beyond the currently provided viewing angles is required, the proposed system needs fewer groups (i.e. $360°/28° \approx 13$) of 2D slices for 360° message display. So, the quantity of the needed 2D source images is greatly reduced.

3. Analysis of the numerical aperture

The resolution in *x*-direction of a point *M* depends on its distance away from the IP_2 plane, as shown in Fig. 1. Therefore, points on a displayed 3D object will have gradient *x*-direction resolution along the *z*-direction. The inhomogeneous distribution of resolutions will deteriorate the display quality. Only when the IP_2 plane is away from the display space infinitely, a constant