

360-degree tabletop electronic holographic display

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Abstract: We demonstrate a tabletop holographic display system for simultaneously serving continuous parallax 3.2-inch 360-degree three-dimensional holographic image content to multiple observers at 45-degree oblique viewing circumference. To achieve this, localized viewing windows are to be seamlessly generated on the 360-degree viewing circumference. In the proposed system, synchronized four high-speed digital micro-mirror displays are optically configured to comprise a single 2 by 2 multi-vision panel that enables size enlargement and time-division-multiplexing of holographic image content. Also, a specially designed optical image delivery sub-system that is composed of confocal parabolic mirrors and an aspheric lens is designed as an essential part for achieving enlarged 3.2-inch holographic image and large 45-degree oblique viewing angle without visual distortion.

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OCIS Codes: (090.0090) Holography; (090.1995) Digital holography; (090.2870) Holographic display.

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1. Introduction

Tabletop 360-degree three-dimensional (3D) display system is one of the most interesting and simultaneously challenging 3D display system configurations [1-3]. Its full 360-degree viewing zone range, consequential novel visual 3D experience, and necessary huge content data amount contrast it against conventional flat-panel based 3D displays with narrow viewing zone [4,5]. Because of its uniqueness and ultimacy, many researchers have actively investigated the possibility of the systematic realization of tabletop 360-degree 3D display.

In the research of tabletop 3D display, the use of electronic holographic display technology is encouraging [6-8] since, in principle, the holographic image synthesis provides continuous parallax, deep depth perception cue, and resolves the fundamental problems of non-holographic 3D display techniques such as accommodation-vergence conflict [9]. A previous multiview-based tabletop displays have discretized views even with a support of hundreds of projectors [1], but the holographic display creates continuous parallax view within the viewing window. Hence, holographic tabletop display is a promising candidate for the tabletop 3D display.

In order to construct practical tabletop holographic 3D display, countermeasures for several technological issues should be devised. First, a large view volume is a requisite for commercial success. For this issue, ultrahigh resolution and high speed display panel accommodating full color R/G/B is an essential theme [10-16]. A previous tabletop system that used a digital micromirror device (DMD) showed a very limited small active display area [6], though it exploited high speed operation capability. The simple scaling of this configuration by the form of multiple array, i.e. multi-vision, can be a candidate for extending the active display area, but it makes the optical system highly complicated. Regarding this, we should additionally consider the management of large aperture optical aberration inducing distortion of large size holographic image. The design of aberration-compensated optical system is issued. Second, highly off-axis viewing circumference should be created for practicality of tabletop vision system. The previous holographic tabletop display system has a technological limitation in this point since the decentered Fresnel lens cannot cover 45-degree off-axis viewing zone due to noisy stray light generation and light field distortion by aberration, thus the viewing angle of the previous system is restricted within maximum 15 degrees [2,6]. In practice, the system configuration of refractive optical elements gets bulky and multi-elemental for achieving such highly off-axis oblique imaging condition, which is difficult in alignment and weak in chromatic dispersion, while the system based on smooth reflective optical elements such as parabolic mirror is more suitable for the same objective and has advantage of free chromatic dispersion. Third, considering the first and second points, we encounter special design and high degree of engineering of aspheric element to manage rotational symmetric large-aperture 45-degree off-axis imaging system.

In this paper, based on the above considerations, we design and demonstrate a tabletop holographic 3D display system that can serve 3.2-inch continuous parallax 360-degree

holographic 3D image content to multiple observers at 45-degree oblique viewing circumference in real time. Synchronized four high-speed DMDs are used to comprise 3.2-inch 2 by 2 multi-vision holographic panel and a specially designed aspheric optical imaging system is constructed for 45-degree off-axis holographic 3D imaging without aberration-induced visual distortion. The 2 by 2 DMD multi-vision is operated in the time-multiplexing mode to create dense 628 views on the viewing circumference at 20 frame per second, which is synchronized with a hollow-shaft motor.

2. Working principles and system design

The schematic regarding the design concept of the proposed tabletop holographic 3D display system is illustrated in Fig. 1. The aim of design is the construction of tabletop holographic 3D display system that allows an observer or multiple observers to be able to watch seamlessly-arranged 3.2-inch 360-degree electronic holographic 3D images while walking around the tabletop display. One of the key design factors is the viewing window size, which is closely related to the effective pixel size of the rotating image of virtual hologram. In operation-mode, observers watch the rotating tilted virtual hologram plane through the corresponding viewing window (VW), the rotation axis of which is on the center of the top surface of the display system. The VWs are positioned on the viewing circumference, where the observer's eyes are put to accept holographic image light field [6]. The virtual hologram plane is a filtered optical image of DMD array as shown in Fig. 1.

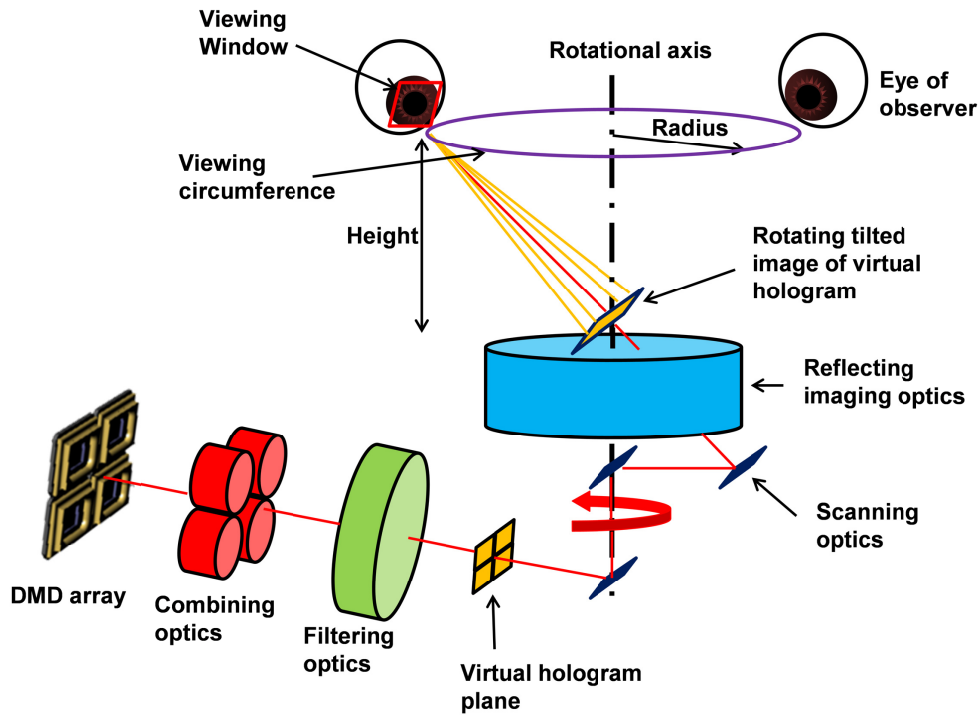


Fig.1. Schematic of the design of 360-degree tabletop electronic holographic display, the design concept of which allows several persons to enjoy the hologram contents simultaneously.

In the proposed 360-degree tabletop electronic holographic display system, 2 by 2 DMD multi-vision is considered. A practical optical configuration for constructing 2 by 2 seamless DMD array is designed as shown in Fig. 2.

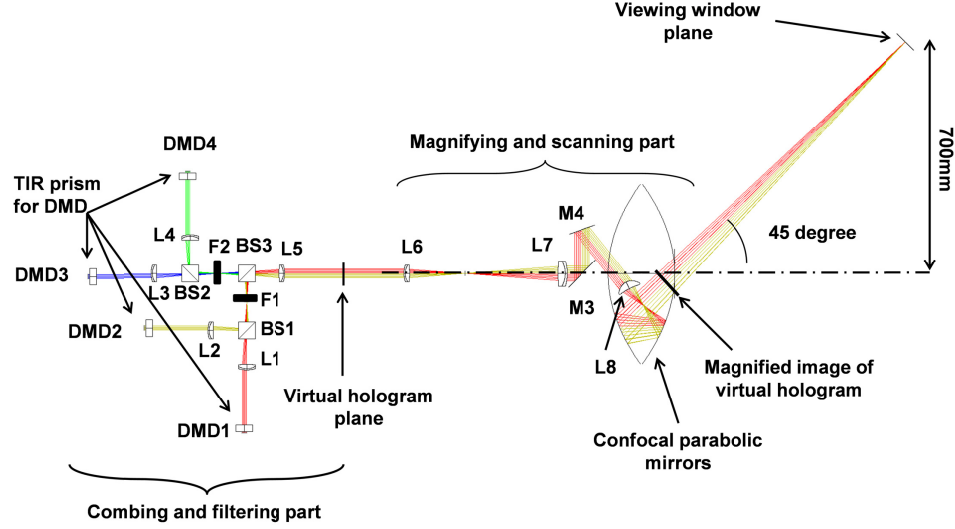


Fig. 2. Optical layout and system configuration where the system is divided into two parts, combing and filtering part and magnifying and scanning part. L: lens; BS: beamsplitter; F: optical filter; M: mirror; C: collimator. The colors of the rays are chosen according to the DMD.

The 3.2-inch seamless DMD multi-vision panel is interknitted by aligning the beam lines of four DMDs and filtering the light wave of the DMD array. Four DMDs, DMD1-4, are slightly decentered and their images are combined seamlessly by three beam splitters, BS1-3 to comprise a single large aperture panel. Four respective $4-f$ optical single sideband filter systems are installed to selectively pass the holographic signal and reject direct current (DC), conjugate noise, and higher-order diffraction [17]. In the system, a single-side band filter is placed in the Fourier domain created by the $4-f$ optics, since the DMD modulates only the binary amplitude of the light field [17,18]. Its dimensions of the filtering domain, $W_{horizontal} \times W_{vertical}$, are given by,

$$W_{horizontal} = f \tan \left[\sin^{-1} \left(\lambda / 2p \right) \right], \quad (1a)$$

$$W_{vertical} = 2f \tan \left[\sin^{-1} \left(\lambda / 2p \right) \right]. \quad (1b)$$

Here, λ is the optical wavelength, and p and f are the pixel pitch of the DMD and the focal length of the $4-f$ optics lens respectively. The plane where the optical filter is located is the angular spectrum domain, and the viewing windows are positioned in the same domain. The viewing window is the image of the optical filter image.

The effective pixel size of the tilted hologram plane can be adjusted by the magnification factor of the optical relay system. In the system, L1, L2, L3, and L4 are the first Fourier transform lenses for DMD1-4, respectively, and after filtering with F1 and F2, the filtered signal is reconstructed at the 'virtual hologram plane' through the lens L5 and forms a seamless 2 by 2 multi-vision here. At this stage, the effective pixel size of the virtual hologram is effectively doubled by comparison of the DMD pixel size [17,18]. In this study, the pixel size, resolution, and panel size of the 2 by 2 DMD array are $13.68 \mu\text{m} \times 13.68 \mu\text{m}$, $1,536 \times 1,536$, and 1.17 inch, respectively. But those of the filtered virtual hologram were tuned to $27.36 \mu\text{m} \times 27.36 \mu\text{m}$, $768 \times 1,536$, and 1.17 inch. In order to satisfy our design goal

of 3.2-inch holographic image, it is necessary to magnify the virtual hologram plane with the magnification factor of 2.76 times. The rotational scanning parts should be followed up after the magnification. After magnification, the pixel size of the 3.2-inch holographic panel with effective $768 \times 1,536$ resolution is $37.6 \mu\text{m} \times 75.2 \mu\text{m}$. This pixel size specifies the rectangular VW size.

In the system design, the exploitation of high-speed operation of DMD is intended to be maximized. The desired viewing position is the circular circumference band with 700 mm radius and 700 mm height above the tilted image of virtual hologram. Therefore, the VW is created 990 mm away from the center of the image of virtual hologram. In this study, the size of the VW is designed to be $14 \text{ mm} \times 7 \text{ mm}$ on the band for 532 nm operating light wavelength. The VW size is given by

$$VW = 2d \tan \left[\sin^{-1} (\lambda/2s) \right], \quad (2)$$

where s is the interval of the sampling points on the magnified image plane, and d is the distance of the viewing window from the magnified image plane. So, the demanded value of the sampling interval in the horizontal direction is $37.6 \mu\text{m}$ and that in the vertical direction is $75.2 \mu\text{m}$. It means that 2.76 times magnification is necessary after virtual hologram with 1.17 inch diagonal. The necessary 2.76 times magnification is obtained by two steps. First, through the magnification optics with L6 and L7, the ratio of their focal lengths results in 1.66 times magnification. Second, the following off-axis scanning part composed of mirrors M3 and M4, aspherical field lens L8, and confocal parabolic mirrors provides 1.65 times magnification. Here, the use of aspherical field lens is essential not only for the magnification but also for the formation of the VW.

In the off-axis configuration with the confocal parabolic mirrors, the aspherical field lens is mandatory for electronic holographic application. With traditional confocal parabolic mirrors as depicted in Fig. 3(a), two mirrors are spaced by their focal length and they image the input plane at the bottom of the mirrors on the output plane at the top of the mirrors. Since the space between them is only their focal length, the diverging phase is produced on the output plane. Therefore, the traditional geometry does not properly form a viewing window because the diffraction angle of the hologram is too small to cover a large area. The spherically converging carrier wave is necessary to synthesize the VW as indicated in Fig. 2. Also it is significant for the off-axis distorted diverging optical field as shown in Fig. 3(a) to be compensated. In Fig. 3(b), the effect of the aspheric lens inserted between the confocal parabolic mirrors in the proposed system is illustrated with ray tracing analysis.

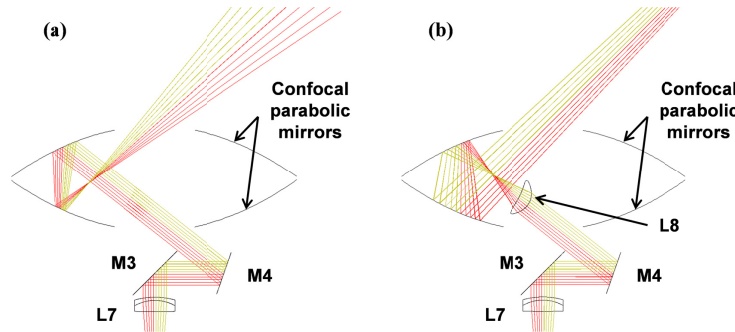


Fig. 3. (a), Traditional structure of the confocal parabolic mirrors where the optical rays at the opening of the top are diverging. (b), Proposed structure with the confocal parabolic mirrors and the aspheric lens. Here, the optical rays at the opening of the top are converging into the position of the viewing window.

In addition, three kinds of lenses were designed for our system. Two achromatic lenses with different focal lengths are used for the Fourier transform. The lenses with a focal length of 180 mm are used for the 4- f optics, and the lens with a focal length of 300 mm is used for

magnification. The aspheric lens in the confocal parabolic mirrors is designed to make the collimated incident light converge onto the viewing window after sequentially passing through the aspheric lens and the confocal parabolic mirrors. Their prescriptions are listed in Table 1.

Table 1 Lens prescriptions

Achromatic lens with 180 mm EFL		Aspheric lens	
D(mm)	50.80	D (mm)	66.00
CT1(mm)	3.60	CT(mm)	22.00
CT2(mm)	13.00	R1(mm)	34.9062 CX
R1(mm)	81.594 CX	K1	-0.562455
R2(mm)	45.587	A1	0.1243957e-07
R3(mm)	612.142 CX	B1	0.4122396e-10
Substrate	E-F3/H-QK3L	C1	0.14952993-13
Achromatic lens with 300 mm EFL		R2(mm)	174.6608 CC
D (mm)	76.20	Substrate	PMMA
CT1(mm)	6.00		
CT2(mm)	21.60		
R1(mm)	135.987 CX		
R2(mm)	75.978		
R3(mm)	1020.237 CX		
Substrate	E-F3/H-QK3L		

D: diameter; CT: center thickness; R: radius; K: conic constant; A, B, C: coefficients of 4th, 6th, and 8th order terms in even aspheric surface. System demonstration for 360-degree electronic holographic display system

3. System implementation

As is described in Fig. 2, the proposed system can be functionally divided into two parts, (i) 2 by 2 DMD combining and filtering part and (ii) magnifying and scanning part. The system prototype is presented in Fig. 4(a) with design drawings of the two parts. The design drawing and practical implementation of the magnification and scanning part are shown in Figs. 4(a) and 4(b), respectively. Figs. 4(c) and 4(d) show the design drawing and practical implementation of the DMD combining and filtering part. Much effort was devoted to align the two optical parts to match the center of the rotating tilted image of virtual hologram to the cross point of the rotation axis and the top surface of the confocal parabolic mirrors. The combining and filtering stage presents the feasibility of the scalable system, and the magnifying and scanning part renders the tabletop display comfortable for use by getting rid of any obstacles above it.

In the system layout, the lens L7, and mirrors M3 and M4, are grouped and this group is mechanically rotated under the confocal parabolic mirror as indicated in Fig. 4(a). Therefore, the 3.2-inch holographic plane rotates as the viewing window revolves along the viewing circumference band. Here, the VW is set to 14 mm × 7 mm for the operating wavelength of 532 nm and the perimeter of the circumference band is 4.4 m.

With a single revolution, the VW rotates a complete 360-degree as clarified in Ref. 6. Taking account of this periodic rotation of the rectangular VW, we count the necessary number of VWs, at least 628 to compactly distribute the VW on the viewing circumference band. Fortunately, each DMD (ViALUX GmbH, VIS-7000) has the operating speed of 22,727 Hz for binary images, so it is enough to broadcast more than 1,136 shots of 1,024 × 768 resolution images per one revolution at real time speed of 20 frame/sec. In the implemented system, 628 viewing windows are densely planted along a 700 mm radius

circular circumference band with a 700 mm height from the top surface of the confocal parabolic mirror which is shown in Fig. 4(a). Consequently, the system is implemented so that observers can see 3.2-inch holographic 3D contents by 20 frames per second, which is floating on the surface of confocal parabolic mirror system.

In this system, a continuous-wave diode-pumped solid-state laser with a wavelength of 532 nm (Cobolt Samba™, Cobolt AB) is used as a light source; its maximum output power is 300 mW. The light source is evenly divided into quarter by the use of a fiber-type beam divider (Thorlabs Inc.), and the fiber-coupled laser light is expanded uniformly after passing through a collimator (OZ Optics Ltd.). Four high-speed DMD modules (ViALUX GmbH, VIS-7000) are used as spatial light modulators (SLMs), and the lenses were designed and fabricated for this display. The DMD has a pixel pitch of 13.68 μm.

A Giant Mirage (Opti-Gone International, Inc.) is used as the confocal parabolic mirrors, and a hollow-shaft direct drive motor was manufactured to our specifications by Justek Corp. on our demand. The motor is placed inside the scanner and rotates two folding mirrors (M3 and M4) and one aspheric lens (L8), as is shown in Fig. 4(a). The folding mirrors determine the propagation direction of the optical field from the scanner. The motor rotates at the speed of 20 revolutions per second, and more than 628 viewing windows can be formed during one turn. Consequently, a 39.5 Gbps data transfer rate is necessary for this system. Currently, the internal memory of the high-speed DMD modules is used and thus only a limited length of movie play is possible.

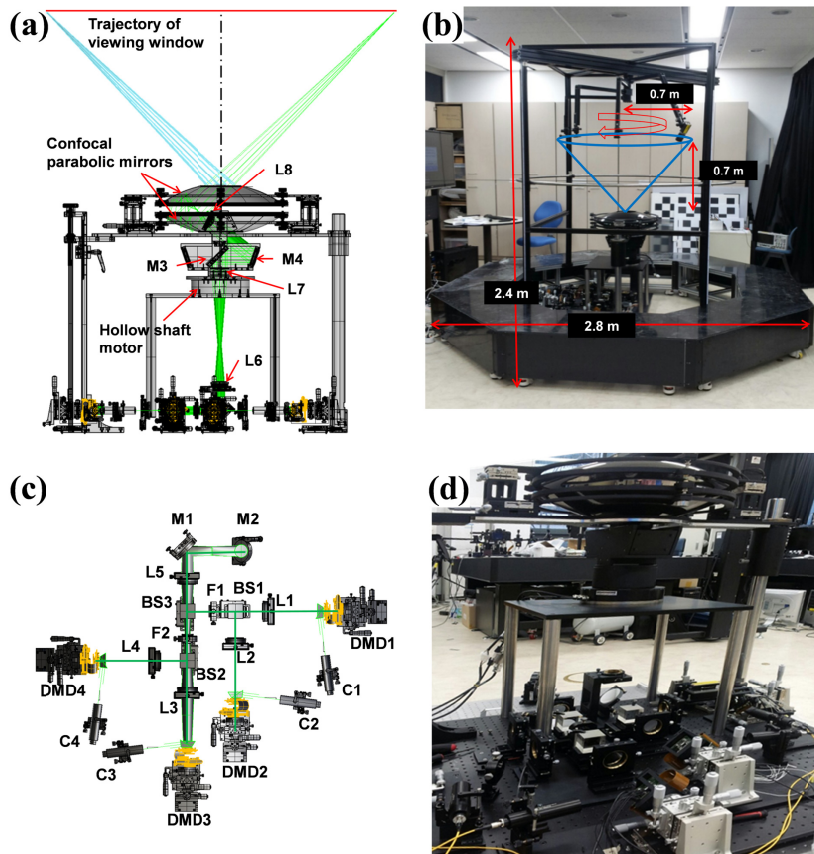


Fig. 4. Design and implementation of 360-degree tabletop electronic holographic display. (a), System design drawing. (b), Prototype implementation, (c), Optics layout of the combining and filtering part. (d), Optical parts in the implementation. L: lens; BS: beamsplitter; F: optical filter; M: mirror; C: collimator.

4. Experimental results

The observation of computer-generated holograms (CGHs) loaded in the system was tested. The CGH was designed using the point-cloud CGH synthesis method. The target 3D model and the CGH pattern were shown in Figs. 5(a) and 5(b), respectively. The total area of the CGH pattern is split into four sections that are seamlessly displayed on four DMDs. The object is modeled as a point cloud, and the size of the hologram is set to $1,536 \times 1,536$ points, the maximum size of the square that can be encoded by four DMDs. When the scanner rotates, the encoded hologram also rotates on the plane of the arrayed DMDs. Therefore, the object needs to be contained inside the circle within a diameter of 1,536 points, and only the square-shaped hologram is computed and encoded on the arrayed DMDs. In particular, CGH content was calculated to uniformly distribute light energy on the VW to sustain continuous parallax. The corresponding reconstructed image is shown in Fig. 5(c).

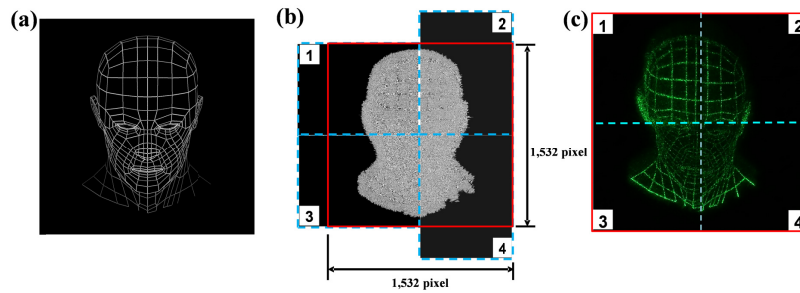


Fig. 5. Computer generated hologram and reconstruction image. (a), Target image expected to appear at the tabletop. (b), Computer generated hologram encoded on four DMDs. (c), Reconstruction image captured by the camera focusing on the center of the tabletop. The number at each corner in (b) and (c) means the order of the assigned DMD.

The hologram images captured by four cameras at four different positions, i.e. front, rear, right, and left indicated in Fig. 6(a) are respectively shown in Figs. 6(b), 6(c), 6(d), and 6(e). These are four sides of the wire frame of a human head with 90-degree intervals. Since the proposed tabletop holographic display uses time-multiplexing technique of VWs, thus CGH is assigned to a specific VW. Therefore, the occlusion between objects is naturally displayed. In the photos of CGHs, the occlusion effect such that the wire on the front is displayed and the wire at the back is screened by the front surface is confirmed.

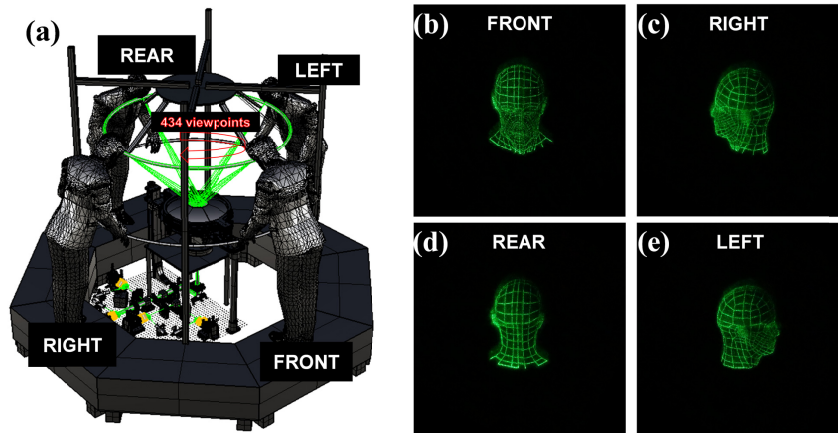


Fig. 6. (a), Observation experiment setup. (b),(c),(d),(e), Captured images at four different positions with 90-degree interval.

5. Conclusion

In conclusion, we have investigated technological innovation in the development of 360-degree holographic tabletop 3D display with highly oblique observation viewing circumference. As indicated in the introductory part, the issues of the enlargement of virtual hologram and the seamless continuous parallax holographic 3D image generation at the 45-degree off axis viewing circumference were addressed. This study has remained many research issues and one of them is the scale reduction or minimization of the system. The integration of red, green, and blue color components for full-color holographic display in the scale-downed tabletop system will be a very challenging topic. In addition, the active area of the confocal parabolic mirror system is only less than 10% of the parabolic mirror area. The waste of the space is a serious problem. Introduction of advanced freeform optic technology is considered as a prospected solution. Besides the system design issues, the CGH for DMD is binary CGH and it results in the degradation of the image quality severely. The binary CGH optimization problem is still an open problem in the CGH research field [19, 20]. Basically, the tabletop display generates 360-degree continuous horizontal parallax. However, the small vertical length of VW restricts the vertical viewing angle tightly. The enhancement of vertical viewing angle is also a pending issue in the development of holographic tabletop display.

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