Color holographic display method based on a single-spatial light modulator

Di Wang
Qiong-Hua Wang
Jun Wang
Xin Zhou
Da-Hai Li
Color holographic display method based on a single-spatial light modulator

Di Wang, Qiong-Hua Wang,* Jun Wang, Xin Zhou, and Da-Hai Li
Sichuan University, School of Electronics and Information Engineering, Chengdu 610065, China

Abstract. A color holographic display method is proposed. It uses a spatial light modulator with a synthetic computer-generated hologram, which includes red, green, and blue three monochromatic scenes’ information. We calculate three holograms corresponding to red, green, and blue, and then generate a color hologram according to the law of sampling. A filter owning the pixel structure is designed so that white light emitting diode can be used as reconstructed light. We numerically evaluate the image quality of color-reconstructed images and compare the quality of color-reconstructed images with that of reconstructed color images using another color holographic projection method. The experimental results verify the feasibility of the method.

Keywords: color reconstruction; computer-generated holography; spatial light modulator.

Paper 131855 received Dec. 8, 2013; revised manuscript received Mar. 7, 2014; accepted for publication Mar. 17, 2014; published online Apr. 9, 2014.

1 Introduction

Holographic display is an ideal three-dimensional display technology, and it records and reproduces all light field information, which includes the amplitude and phase in the form of a fringe pattern generated by interfering light with a reference beam. There are two methods to achieve color holographic display: one is using three spatial light modulators (SLMs) to reconstruct the image. For example, Japanese scholars use three liquid crystal display (LCD) panels to display holograms, upon which they record the red, green, and blue components of a color image. The reconstructed image could be seen by compounding the diffracted lights from each LCD. However, this method has three color holography space synthetic registrations, and the system is large and complicated. The other is to use one SLM such as a phase-modulated LCD. Time-division method uses red, green, and blue lights to illuminate SLM in turns. It records three color components holograms of the image individually, the SLM displays one of the holograms in sequence and outputs synchronized signals. Three reference lights are switched by the synchronized signals and color-reconstructed image could be seen due to the afterimage effect on human eyes. However, the use of synchronous control circuit increases the complexity of the system. In addition, spatial-division method is also used to reconstruct a color image by one hologram. In this method, a color image is divided into RGB components, and each component is distributed on one third of the hologram. The method also needs three filters to adjust the direction of three laser beams, which can ensure the lasers illuminates one third of the SLM, respectively.

In order to realize full-color holographic display by using a simple optic system, we propose a method to achieve full-color display based on one SLM in this article. Using this method, we generate a synthetic computer-generated hologram according to the law of sampling. Furthermore, a filter with the pixel structure is designed so that white light emitting diode (LED) can be used as the reconstructed light, which makes holographic display more practical.

2 Method

The hologram design procedure begins with a separation of a color input bitmap into three primary color components, as shown in Fig. 1. The wavelength of recording light is \( \lambda_r = 632.8 \text{ nm} \), \( \lambda_g = 532 \text{ nm} \), and \( \lambda_b = 488 \text{ nm} \), respectively, and the sampling interval of the object on the hologram in the horizontal and vertical direction are \( \Delta x \), \( \Delta y \). According to the law of sampling, \( \Delta x \), \( \Delta y \) satisfy the following formulas:

\[
\Delta x \leq \frac{1}{4B_x},
\]

\[
\Delta y \leq \frac{1}{4B_y},
\]

where \( 2B_x \) and \( 2B_y \) are the frequency bandwidth of the object light. Owing to the wavelength-dependence of the size of reconstructed images, the green and red input bitmaps are adequately prescaled by factors of 532 nm/488 nm = 1.09 and 632.8 nm/488 nm = 1.27, respectively. Hence, the three reconstructed images are matched in size. The hologram of each color component is then calculated separately using an iterative Fourier transform algorithm (IFTA) in 60 iterations. The information is stored in the corresponding matrix—\( r(m, n) \), \( g(m, n) \), and \( b(m, n) \).

The block of IFTA is shown in Fig. 2. First, we initialize the amplitude and phase of the object wave filed, and set the frequency domain amplitude \( B \). The amplitude \( a \) and random phase \( \phi \) constitute an original complex amplitude function \( f \). Then, the complex amplitude function \( f \) is Fourier transformed into the frequency domain, yielding the complex amplitude function \( F \). At last, the error values \( e \) is calculated. If \( e \) is less than the threshold \( \varepsilon \), \( \phi \) is the
desired phase, or continue the calculations. Here, the error value \( e \) is defined by

\[
e = \sqrt{\frac{\sum_{x,y} (|A| - |B|)^2}{M \times N}},
\]

where \( M \times N \) is the pixel resolution of the target image. Then, remaining the previous phase \( \varphi \) unchanged we can construct a new complex amplitude function \( G \) with the given amplitude \( |B| \). A new phase \( \varphi' \) on the hologram can be obtained by the inverse Fourier transformation of \( G \). At last we use the new function which is constituted by the phase \( \varphi' \) and the amplitude \( A \) to repeat the above operations until the error value meets the set value.

Then we make a synthetic hologram to record three monochromatic scenes’ information. The information is stored in the matrix \( c(m, n) \). The part structure of the synthetic hologram is shown in Fig. 3. Here, \( r, g, \) and \( b \) represent the sampling units of the red, green, and blue components on the hologram, respectively.

In order to guarantee that the synthetic hologram includes the information of red, green, and blue scene, each sampled color component hologram records the object’s information at the specific location. So, the information \( c(m, n) \) of synthetic hologram needs to satisfy the following relationships:

\[
c(m, 3k - 2) = r(m, 3k - 2),
\]

\[
c(m, 3k - 1) = g(m, 3k - 1),
\]

\[
c(m, 3k) = b(m, 3k),
\]

where \( k \) and \( m \) are positive integers.

The horizontal and vertical sampling intervals of the synthetic hologram are \( \Delta x \) and \( \Delta y \), respectively. In order to make sure the information is not lost on the synthetic hologram, the sampling interval needs to satisfy the law of sampling. According to Eqs. (1)–(2), we can get the following equations:

\[
\Delta x \leq \frac{1}{4B_x},
\]

\[
\Delta y \leq \frac{1}{6B_y}.
\]

Each sampling line on the synthetic hologram records one particular color information, and every adjacent three lines of the hologram record information of different color component, respectively, which can avoid crosstalk caused by different hologram superposition. This method can achieve uniform light intensity and stereo watching continuity of tricolor-reconstructed images.

Plane light is used as the reference light and reconstructed light. In order to get the color reconstruct image, we need to keep the wavelengths of the reference light and the reconstructed light same. Here, we designed a filter with pixel structure so that white LED can be used as reconstructed light. Figure 4 illustrates the part structure of the filter, where \( r, g, \) and \( b \) represent the red, green, and blue filter part, respectively. The filter has the unit structure of micrometers, and it can be produced by lithography process. The filter is placed between the reconstructed light and the hologram. The pixel interval is equal to the sampling interval on the hologram.
3 Result and Analysis

Figure 5 is the schematic layout using the proposed method. The optical system for the holographic display comprises a LED light source, a pinhole, a collimator lens, a filter, a positive lens, a driving board, a PC, a display screen, and a SLM. The computer sends holograms instead of typical images to the SLM via SLM driver circuit for generating the desired redistributing light in a predefined manner.

We process color separation of the color scene for red, green, and blue components using computer graphics. The pixel resolution of the picture is $512 \times 512$, then three holograms which separately record the information of red, green, and blue components of the color scene are developed by IFTA, and the information is stored in the corresponding matrix—$r(m, n)$, $g(m, n)$, and $b(m, n)$. In the iterative process, we set the frequency domain amplitude $A = 1$, take the iterations 100 times. With the increase of the iteration number, the absolute error decreases, and we can see the error curve in Fig. 6. The horizontal axis represents the iteration number, and the vertical axis represents the error value $e$. When the iteration number is greater than 60, the error value remains to be constant. Then, the synthetic hologram is generated according to Eqs. (4)–(6), where the information is stored in the matrix—$c(m, n)$.

White LED light can improve its spatial coherence through a pinhole. Load the synthetic hologram on the SLM. We choose three original objects, as shown in Fig. 7. The reconstructed images by our method are shown in Fig. 8(a). At the same time we contrast another way—spatial division method. We scale the object to one third of the original, then three color holograms are generated and each color scene occupies one third area of the SLM. A full-color flat image can be formed because of color mixing. We get the reconstruction image by computer simulation as shown in Fig. 8(b). Figure 9 shows the peak signal-to-noise ratio (PSNR) between the original objects (Fig. 7) and reconstructed images by our method and spatial division method. The green and red charts are the PSNR values of reconstructed images using our method and spatial division method, respectively. From the picture, we can see that the PSNR values by our method are higher. Using one third of the information, the quality of the reconstruction image is decreased, while the propose method satisfies the law of sampling, which ensures the information on the hologram, and the result shows that the proposed method has certain advantages.

Besides, compared with the method of pixel by pixel, the proposed method does not need to treat each pixel as...
a sampling unit, which makes the process simpler. Unlike the method of time sequential color effect, which uses the synchronize control circuit to switch the hologram and the three reference lights in turns, our method designs a filter to realize the LED illumination. In short, the proposed method has certain advantages and potential applications.

4 Conclusions

We propose a color holographic display method, which could record color information on one hologram. Compared with other methods, it only uses one SLM without synchronous control circuit, which can reduce the cost of the system. A filter owning pixel structure is designed so that laser illumination is replaced by LED illumination to assume safety for naked eye observation. In short, the proposed method makes the color holographic display simple and flexible, which makes it possible to realize the holographic TV.

Acknowledgments

This work was supported by the NSFC under Grant Nos. 61320106015 and 61377018, and the RPSPC under Grant Nos. 2013TD0002 and 2013GZX0165.

References

1. Y. J. Pan et al., “Fast polygon-based method for calculating computer-generated holograms in three-dimensional display,” Appl. Opt. 52(1), A290–A299 (2013).
2. J. Jia et al., “Reducing the memory usage for effective computer-generated hologram calculation using compressed look-up table in full-color holographic display,” Appl. Opt. 52(7), 1404–1412 (2013).
3. B. J. Jackin and T. Yatagai, “Fast calculation of spherical computer generated hologram using spherical wave spectrum method,” Opt. Express 21(1), 935–948 (2013).
4. Y. Sando, M. Itoh, and T. Yatagai, “Holographic three-dimensional display synthesized from three-dimensional Fourier spectra of real existing objects,” Opt. Lett. 28(24), 2518–2520 (2003).
5. M. Kim et al., “Hologram generation of 3D objects using multiple orthographic view images,” J. Opt. Soc. Korea 12(4), 269–274 (2008).
6. Y. Sando, M. Itoh, and T. Yatagai, “Color computer-generated holograms from projection images,” Opt. Express 12(11), 2487–2493 (2004).
7. T. Kozacki et al., “Wide angle holographic display system with spatiotemporal multiplexing,” Opt. Express 20(25), 27473–27481 (2012).
8. A. Shiraki et al., “Simplified electroholographic color reconstruction system using graphics processing unit and liquid crystal display projector,” Opt. Express 17(18), 16038–16045 (2009).
9. P. A. Blanche et al., “Holographic three-dimensional telepresence using large-area photorefractive polymer,” Nature 468(7320), 80–83 (2010).
10. K. Takano and K. Sato, “Color electro-holographic display using a single white light source and a focal adjustment method,” Opt. Eng. 41(10), 2427–2433 (2002).
11. F. Xu, Y. Li, H. Jin, and H. Wang, “Study on reconstruction of the kinoform with white-light illumination,” Acta Photonica Sin. 39(2), 271–274 (2010).
12. K. Takano, N. Minami, and K. Sato, “A simple method of color electro-holographic display system using a white source and three LCD panels,” in Proc. IEEE Int. Conf. Multimedia Expo., pp. 105–108 (2001).
13. T. Shimobaba and T. Itoh, “Color holographic reconstruction system by time division multiplexing with reference lights of laser,” Opt. Rev. 10(5), 339–341 (2003).
14. M. Makowski et al., “Color image projection based on Fourier holograms,” Opt. Lett. 35(8), 1227–1229 (2010).

Fig. 8 Reconstructed images by the (a) proposed method and (b) spatial division.

Fig. 9 Peak signal-to-noise ratio (PSNR) values of the reconstructed images.
Di Wang is working toward her PhD degree in optics from the School of Electronics and Information Engineering, Sichuan University, China. Her recent research interest is information display technologies.

Qiong-Hua Wang is a professor of optics at the School of Electronics and Information Engineering, Sichuan University, China. She was a postdoctoral research fellow at the School of Optics/CREOL, University of Central Florida, from 2001 to 2004. She has published more than 190 papers on display devices and systems. She is an associate editor of Journal of the Society for Information Display. Her recent research interests include optics and optoelectronics, especially display technologies.

Jun Wang received his PhD degree from the Department of Electronic and Computer Engineering, Hanyang University, Republic of Korea, in 2011. He had a postdoctoral fellowship at the University of Wisconsin-Madison, USA, from 2011 to 2012. He has been an associate professor since 2012 at the School of Electronics and Information Engineering, Sichuan University, China. His current research interests are computer-generated-hologram 3D display, GPU-based parallel computing, and real-time image and video processing.

Xin Zhou is a professor of optics at the School of Electronics and Information Engineering, Sichuan University. He received his MS degree from the China Academy of Engineering Physics in 1991 and his PhD degree from Sichuan University in 2006, respectively. He has published more than 40 papers. His recent research interests include laser and optical communications and optical encryption.

Da-Hai Li is a professor of optics at the School of Electronics and Information Engineering, Sichuan University. He received his MS degree from the University of Electronic Science and Technology of China in 1996 and his PhD degree from Sichuan University in 2002, respectively. He has published more than 60 papers. His recent research interests include optics and optoelectronics, especially display technologies and optical measurements.