3 3D-Image Technology

3-1 Electronic Holography System Using 4K Video System

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This paper presents the problems encountered when holography is converted to electronic form and describes a system prototyped to combat those problems. More specifically, this paper addresses the problems of hologram data acquisition, the viewing zone angle being narrowed down due to the inadequate resolution of electronic devices that display hologram data, and unnecessary beams causing interruption. The paper also describes a color electronic holography system prototyped based on a 4K video system. This system is designed so that an integral photography camera is used to take ray information, with the data obtained being used to calculate hologram data. The system is therefore characterized by the fact that it can take real ray information under a natural light without using a laser beam. Moreover, a display unit configured with a 4K display device enables a wider viewing zone angle than in conventional practice.

1 Introduction

The technology to realistically reconstruct an event occurring in a remote place or something happening in the past would prove to be very useful. TV is one example. Viewers can enjoy splendid sights of a location abroad without going there, and need only watch a news program to know what happened in the past. Three-dimensional TV, only recently commercialized, displays objects in a three-dimensional manner with a two-view system capable of presenting an image for the right eye and another image for the left eye, while ordinary TV systems can only present two-dimensional images. Viewers can therefore perceive objects as being protruded. One could say that TV is becoming better able to reproduce something realistic, while two-view systems remain unnatural. Consequently, there are high expectations for the further development of three-dimensional display technology.

Many systems are being considered to enhance the quality of three-dimensional display, thereby increasing realistic effects. One example is a system called the multi-view system that presents images from more viewpoints than the two viewpoints afforded by the two-view system. Multiple screens are overlapped depth-wise to display images on a screen that matches the depth of the subject, and such a system is called a depth sampling system. Among the various three-dimensional image systems is the holography system[1], which is considered the ultimate system.

Holography is a technology capable of reconstructing the state of the same beam produced in case of an actually existing object.

Therefore, when one views a three-dimensional image reconstructed by holography, all physiological factors necessary for humans to perceive the three-dimensional quality of an object can be reproduced, such as binocular disparity, vergence, accommodation, and motion parallax. Because TV and other devices used in various environments by countless people should employ three-dimensional display which is the least burdensome on the human eye, holography is considered to be an idealistic system. Holography used to center around systems that handle still images by using photography, printing or similar applications, but in recent years, studies have been conducted on electronic holography that makes holography a reality by using an electronic means[2]-[9].

This paper describes electronic holography and related studies undertaken by NICT. First, the paper outlines three-dimensional display by holography. Then it describes the challenges to be addressed in converting holography to electronic form, and the approach taken to address those challenges through photographic technology and then display technology. The paper finally presents a color electronic holography system that was prototyped based on a 4K video system to address those challenges.

2 Three-dimensional display by holography

Holography is a technology that records and reconstructs a beam that propagates through space by using interference and diffraction phenomena. When used in three-dimensional display, holography records a beam scattered at the subject and then reconstructs it, thereby reproducing a three-dimensional image of the subject.

In recording, a coherent beam (laser beam) is divided into two as shown in Fig. 1 (a). Then one beam is applied to the subject, while the other (called a reference beam) is irradiated on the recording medium. The beam irradiated on the subject is scattered the subject, and reaches the recording medium (called an object beam). This reference beam and object beam interfere with each other on the recording medium, thereby forming a stripe pattern of white and black (called a fringe pattern). Recording this fringe pattern captures the state of the object beam. When the subject remains still, the fringe pattern becomes a certain stripe pattern, but if the subject moves, the fringe
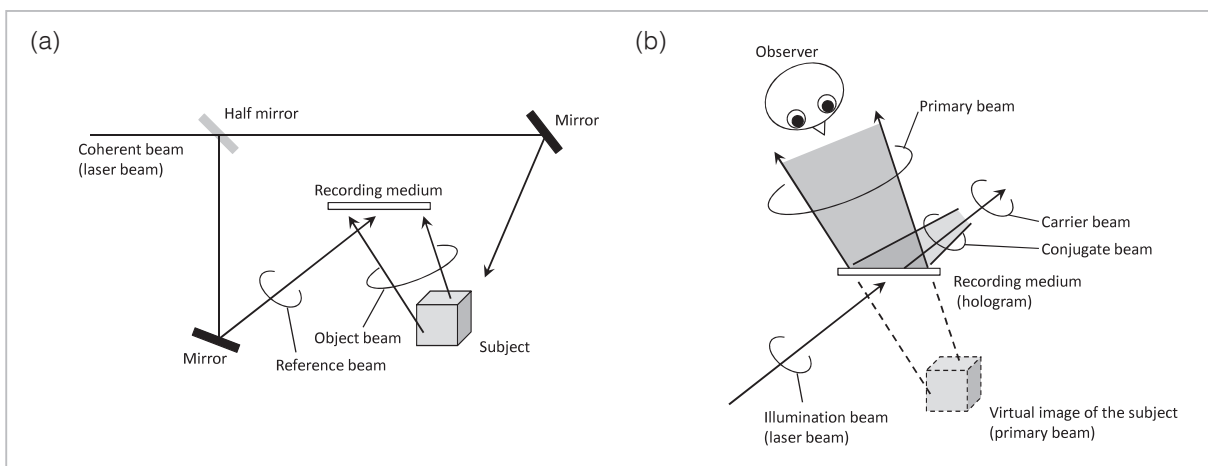
(a) Recording
    The fringe pattern between the object beam and reference beam is recorded on a recording medium. The medium that records the fringe pattern is called a hologram.
(b) Reconstruction
    Irradiating an illumination beam on a hologram enables the recorded object beam to be reconstructed, so that a virtual image is produced at the location where the subject existed.

pattern changes. For that reason, an electronic imaging device is used as a recording medium to record changes in the fringe pattern, thereby making it possible to record movement of the subject. On the recording medium, let the complex amplitude distribution of the object beam be $O(x, y)$ and the complex amplitude distribution of the reference beam be $R(x, y)$, and thus the fringe pattern to be recorded $H(x, y)$ can be expressed by the following equation:

$$H(x,y) = |O(x,y) + R(x,y)|^2$$
$$= |O(x,y)|^2 + |R(x,y)|^2 + O(x,y)R^*(x,y) + O^*(x,y)R(x,y) \quad (1)$$

where, $O^*(x, y)$ and $R^*(x, y)$ denote the complex conjugates of $O(x, y)$ and $R(x, y)$. The medium recording this fringe pattern is called a hologram. Moreover, this paper refers to electronic information about the fringe pattern as hologram data. In electronic holography, an electronic imaging device can be considered as a device for obtaining hologram data.

In reconstruction, a hologram is given the same beam (called an illumination beam) as the reference beam as shown in Fig. 1 (b). The illumination beam is diffracted by the fringe pattern of the hologram and becomes a beam including the same beam (called a reconstructed beam) as the object beam. Expressing this process with an equation yields the reconstructed beam $U(x, y)$ in the following equation:

$$
\begin{aligned}
U(x,y) &= H(x,y)R(x,y) \\
&= (|O(x,y)|^2 + |R(x,y)|^2)R(x,y) \\
&\quad + O(x,y)|R(x,y)|^2 + O^*(x,y)R^2(x,y)
\end{aligned} \quad (2)
$$

where, the second term on the right side of Equation (2) becomes a beam proportionate with the object beam $O(x, y)$, assuming a constant intensity of the reference beam $|R(x, y)|$, and is thus called a primary beam. Although overall intensity varies with the intensity of the reference beam, this indicates that the beam from the subject can be reproduced as is. In other words, since a beam that produces the virtual image of the subject is reconstructed at the location where the subject existed, the observer perceives the subject as existing at that location.

The right side of Equation (2) includes other terms as well. The first term is a beam proportionate to the illumination beam $R(x, y)$. This beam can be regarded as one that passes through the hologram, and is thus called a carrier beam. The third term is a beam phase-conjugate with the primary beam, and thus called a conjugate beam. These beams are different from the primary beam, making both unnecessary, though the beams occur as a matter of principle. It is therefore necessary to remove or otherwise dispose of these beams to prevent both from interrupting the observation of the primary beam.

3 Challenges with electronic holography

In electronic holography, hologram data is displayed on an electronic display device for conversion into a hologram. For that reason, the first challenge is to find an effective way to obtain hologram data. One method of direct imaging is to use a Charge Coupled Device (CCD) or other image sensor as a recording medium (electronic imaging device) as shown in Fig. 1 (a). This method (called digital holography) entails a technology inherent in holography and enables idealistic hologram data to be obtained. As a laser beam must be irradiated onto the subject in a darkroom, however, this method is problematic in being unsuited for capturing scenery and other large objects, as well as human facial expressions that should desirably be imaged in a natural environment. Another problem is that this method cannot take the light information of objects that emit light on their own. In order to apply electronic holography in broadcasting and communication, one could say that research and development should be pursued on methods of obtaining hologram data, without limitations on the type of subject or being confined to darkrooms.

The second problem stems from the large pixel interval (pixel pitch) of devices used to display hologram data. The pixel interval in the display device determines the upper limit

in the space frequency of fringe patterns that can be displayed, and the space frequency in a fringe pattern rises as the angles between the object beam and reference beam increase. Therefore, the pixel interval in the display device determines the maximum angle formed between the object beam and reference beam. The pixel interval (p) and the maximum angle (ϕ_M) formed between the object beam and reference beam can be expressed by using wavelength λ of the beams as follows:

$$\phi_M = \sin^{-1}(\frac{\lambda}{2p}) \qquad (3)$$

Equation (3) indicates that a display device with pixel interval p records and reconstructs an object beam in the direction of travel with an angle within $2\phi_M$ centering around the reference light's direction of travel. Placing the viewpoint within the zone where the object beam is reconstructed allows the reconstructed image of the subject to be observed. The angle to create this zone is thus called the viewing zone angle. The viewing zone angle becomes $2\phi_M$ on a display plane with pixel interval p. For example, let beam wavelength λ be 632.8 mm, and with a pixel interval of 1 μm corresponding to that of a hologram-use photographic plate with a resolution of 500 lines/mm, the angle is 36 degrees. At 10 μm (corresponding to that of existing projector-use display devices), the angle is 3.6 degrees. For a pixel interval with a narrow pitch as in the former case, the viewing zone angle can be widened as shown in Fig. 2 (a), so that images can be easily seen in a three-dimensional manner on a two-view system. Moreover, an angle difference can be applied to the direction of travel between the primary beam on one hand, and the conjugate beam and carrier beam on the other. And this facilitates the arrangement of equipment so that the conjugate and carrier beams do not enter the eyes of an observer who is observing the reconstructed image.

For a pixel interval with a wide pitch as in the latter case, a narrow viewing zone angle as in the case of Fig. 2 (b) will conversely make it difficult to obtain three-dimensional sight with both eyes. Moreover, failure to apply an angle difference to the direction of travel for the primary beam, conjugate beam and carrier beam causes the conjugate beam and carrier beam to enter the eyes of an observer who is observing the primary image, thereby becoming interrupting beams. Existing electronic devices used to display hologram data correspond to that status under present conditions. For that reason, how to remove the interrupting beams and enlarge the visible bream are presented as the second challenge facing electronic holography.

4 Technology of electronic holography

4.1 Technology for obtaining hologram data

The two representative methods of obtaining hologram data are digital holography and the method of generation by calculation. Digital holography is a method of obtaining the fringe pattern as image signals by using an electronic imaging device as a recording medium in the conventional ordinary hologram generation processes illustrated in Fig. 1 (a). This method is characterized by recording the fringe pattern that records an actual object beam as is, thereby making it possible to obtain high-quality hologram data. Hashimoto et al. obtained hologram data by using a CCD as an imaging device, and displayed the data on a liquid crystal panel to reconstruct images on a real-time basis[3]. Among the numerous studies conducted on microscopic applications, Sato et al. successfully obtained hologram data from a die only a few centimeters in size[10]. Awatsuji et al. employed an imaging device used in high-speed cameras and successfully obtained hologram data at high speed[11]. While direct acquisition is advantageous in enabling high-quality acquisition, it is also disadvantageous in that the space frequency of the recordable fringe pattern and the hologram size are limited by the pixel interval of the electronic imaging device and the number of pixels. For that reason, the performance of
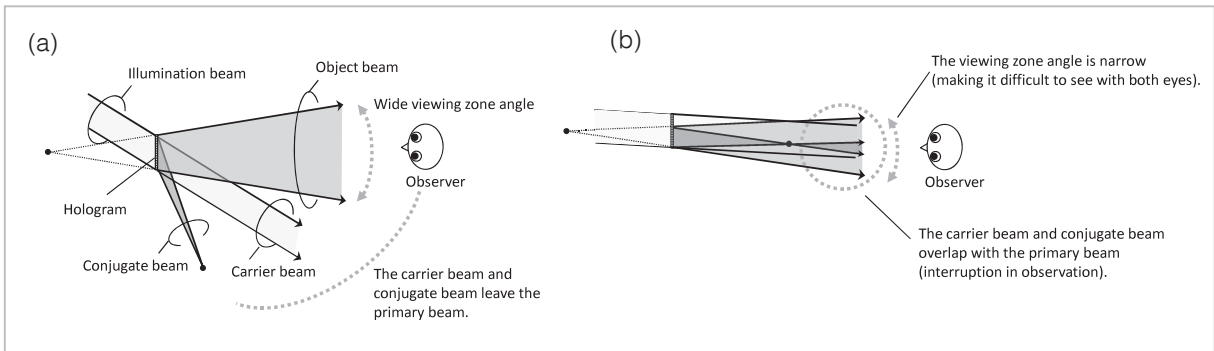
Fig.2 *Holography reconstruction*

(a) For display devices having a narrow-pitch pixel interval
  The viewing zone angle is wide. Since an angle difference can be applied between the direction of travel by the carrier beam, conjugate beam and primary beam, the observer can see the primary beam alone.
(b) For display devices with a wide-pitch pixel interval
  The viewing zone angle is narrow. Since no angle difference can be applied between the direction of travel by the carrier beam, conjugate beam and primary beam, the primary beam becomes overlapped with the carrier beam and conjugate beam. For that reason, both the carrier beam and conjugate beam will become interrupting beams.

existing electronic imaging devices makes it difficult to acquire large holograms. Moreover, since natural light become noise for direct acquisition, this method is also problematic in that it requires imaging in a darkroom. Expectations therefore run high for future research on those matters.

The method of generation by calculation is called Computer-Generated Hologram (CGH). This is a method of generating holograms by calculation from space location information about the subject, for which various methods have been considered. One representative method consists of treating the subject as a set of point sources of light. In this method, the first step is to calculate the distribution of light waves generated on a hologram plane as a beam emitted from each point source of light propagation; the next step is to add all those distributions of light waves; the last step is to calculate the interference with the reference beam, thereby obtaining hologram data. Since calculating beam propagation at that time entails huge amounts of calculations, reports have been made on considerations to shorten the calculation time, such as by using a parallel computer, special-purpose hardware[12][13], and an enhanced algorithm[14][15] to speed up calculations. Although CGH imposes no limi-

tations on the subject as a matter of principle, it is not easy to acquire space information about the real thing. Consequently, Computer Graphics (CG) data is often used.

In addition to the methods described above, another method being considered involves calculating a hologram from images photographed using the Integral Photography (IP) system[16][17], that is, converting IP images into a hologram[18]-[20]. IP is a technology for photographing and displaying a subject by using an array of many very small lenses arranged on a plane, and as a three-dimensional image technology, IP is capable of reconstructing space images. This IP capturing and conversion technology will be described in detail in the article[21] in this special issue.

4.2 Display technology

In electronic holography, the devices used to display hologram data have inadequate resolution, so that removing interrupting beams and expanding the viewing zone angle become important challenges. Off-axis holography is a well-known means of addressing these challenges. This method avoids interruption by directing the conjugate beam and carrier beam away from the eyes of the observer as shown in Fig. 2 (a), by increasing the angle between

the object beam and reference beam. Since the space frequency of the fringe pattern increases, this method is used for a hologram plane having a resolution as high as that of a film for holography.

For hologram planes with low resolution (i.e., a large pixel interval), the well-known method combines half-zone plate processing[22] for recording with the single side band holography[23] for reconstruction. As shown in Fig. 3 (a), half-zone plate processing is a method of processing that involves dividing the spread of beams from the point source of light constituting the subject with a plane that passes the point source of light, and includes the direction of travel by the reference beam and only uses one of the beams to record the fringe pattern. In other words, this can be considered a method of processing that entails limiting the spread of the original object beam to half. As shown in Fig. 3 (b), the single side band holography removes the reconstructed beam generated by applying an illumination beam (i.e., carrier and conjugate beams—the interrupting beams) onto a hologram processed on a half-zone plate by means of a spatial filter.

In order to address the challenge of an en-larged viewing zone angle, it is also important to reduce the pitch of pixels on the display device. However, various other methods are being considered, including a method whereby the longitudinal viewing zone angle is converted to transverse, thereby expanding the transverse viewing zone angle[24][25], switching the viewing zone angle in time series[26], and using more than one display device[27].

Paper[28] in this special issue describes the removal of interrupting beams and the expansion of the viewing zone angle in more detail.

5 Electronic holography system prototyped

To address these challenges, a 4K video system of 8 million pixels (3840 × 2160 pixels) was used to prototype an electronic holography system as shown in Fig. 4. The system consists of a hologram data acquisition block and a display block, both of which operate at 30 fps (frames per second).

Figure 5 (a) shows the hologram data acquisition block. This block is used for imaging the subject by IP and calculating a hologram based on that imaging. A field lens (L_1) and an aperture (A_2) were set between lens array
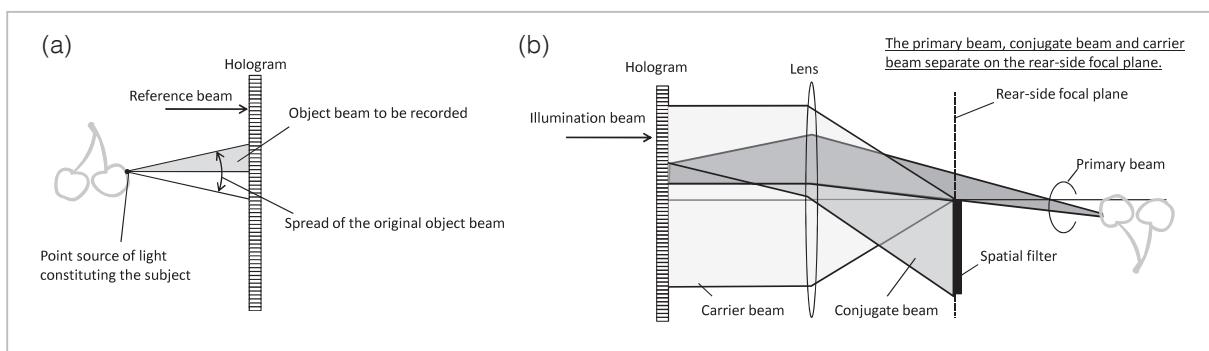

Fig.3   *Removing the interrupting beams*

    (a) Half-zone plate processing in recording
       This method of processing involves dividing the spread of beams from the point source of light with a plane that passes the point source of light, and includes the direction of travel by the reference beam and only uses one of the beams to record the fringe pattern.
    (b) Single side band holography in reconstruction
       For holograms subjected to half-zone plate processing, the reconstructed beam can be passed through a lens to separate the passage region of the primary beam, conjugate beam and carrier beam on the rear-side focal plane. Placing a spatial filter on the rear-side focal plane removes both the conjugate beam and carrier beam.
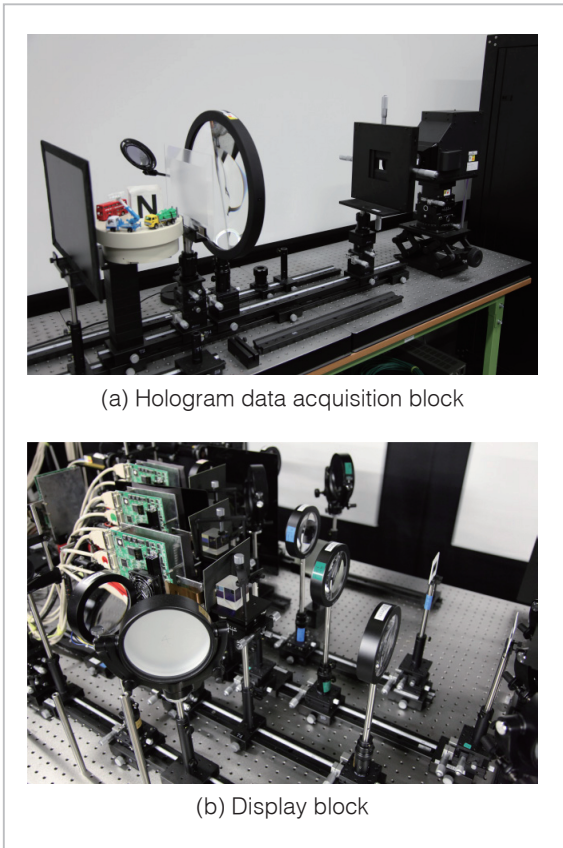
(a) Hologram data acquisition block

(b) Display block

Fig.4 *External view of an electronic holography system based on a 4K video system*

L_0 and the 4K video camera. The size and focal point distance of each lens constituting the lens array are designed to enable imaging of only the viewing zone angle at which images can be displayed in the display block. The lens array consists of 240 × 135 elemental lenses, and a provision was made to enable imaging 16 × 16 pixels of elemental images with each elemental lens. Hologram calculations generate 30 holograms per second in reconstructing each of the RGB colors for color display. In other words, 90 holograms are calculated per second.

In IP, the important challenge is to avoid overlapped recording between elemental images. This refers to a beam that passed through an elemental lens, reaches the portion corresponding to the light-receiving device, and is only supposed to be reflected on the corresponding elemental image, but the beam actually reaches the neighboring portion and is erroneously reflected on the neighboring elemental image. To address the problem, this device is equipped with aperture A_2 as the method described in papers[29] and[30].

Figure 5 (b) shows the display block. Three 4K liquid crystal panels (LCDs) are used as the display devices. For coloring in
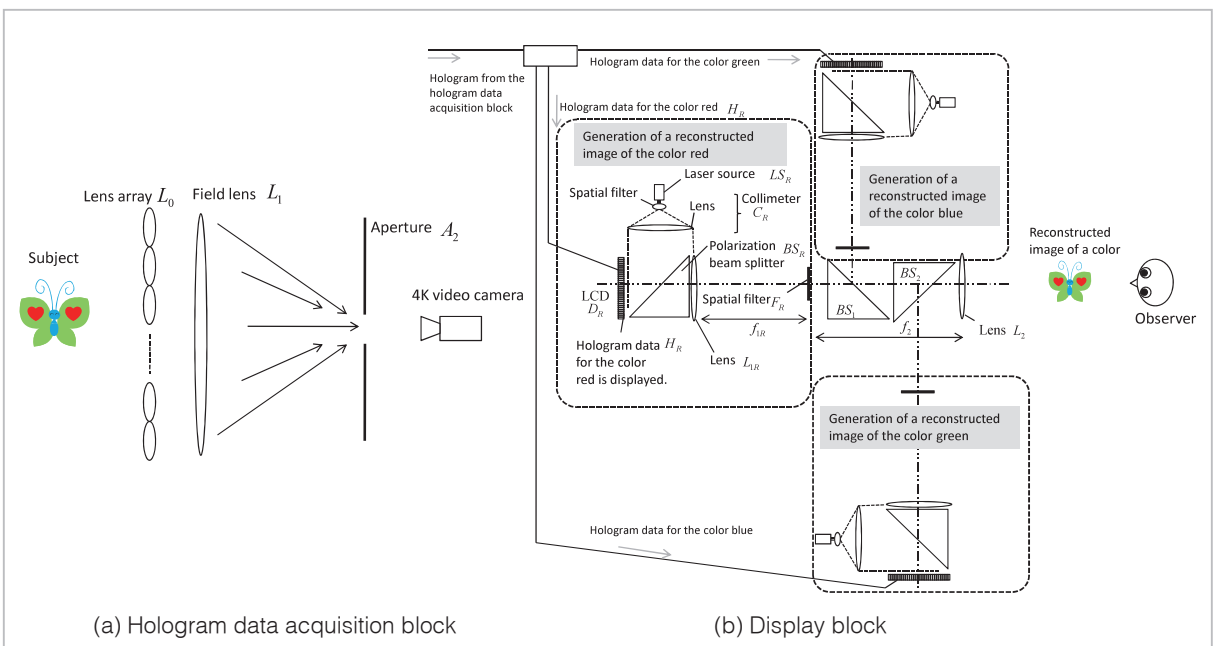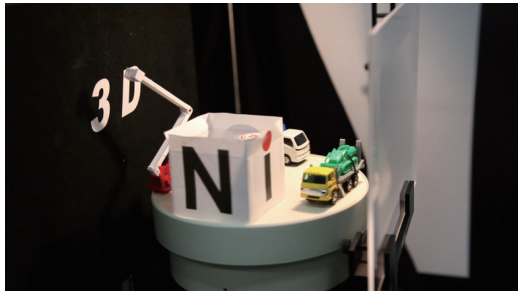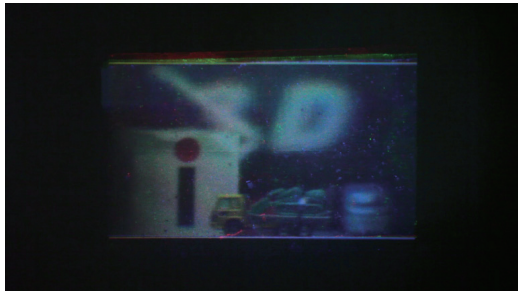

(a) Hologram data acquisition block

(b) Display block

Fig.5 *Electronic holography system based on a 4K video system*

(a) Subject

(b) A miniature car placed in the foreground is focused on, and a reconstructed image of it is taken.

(c) The alphanumeric string "3D" in the background is focused on, and a reconstructed image of it is taken.

Fig.6   *Experimental results*

the three mutually similar portions for each of the RGB colors and the latter stage, the RGB reconstructed image is compiled with a beam splitter to synthesize a colored reconstructed image. A device for the color red is drawn to the left of Fig. 5 (b). This device operates as follows: First, a beam emitted from the laser source is placed into a parallel beam with the required width by means of a collimeter (C_R). Next, the beam passes through a polarization beam splitter (BS_R) and is applied to the LCD (D_R). D_R displays hologram data (H_R) for the color red, so that the laser beam reflected by D_R will be included in the primary beam, car-

rier beam and conjugate beam. All the beams are directed to pass through the polarization beam splitter (BS_R) and a lens (L_{1R}) before reaching the space filter (F_R). F_R is placed at the focal point distance (f_{1R}) of L_{1R} so as to block beams of the optical axis and beams above or below the optical axis. For that reason, the primary beam passes through F_R, but the unnecessary conjugate beam and carrier beam do not. Another lens (L_2) is placed at a focal point distance (f_2) away from F_R. Since f_{1R} and f_2 are set to be the same, L_{1R} and L_2 are used to constitute a 4-f optical system. As a result, the primary beam from the LCD (D_R) moves by $4f_2$ without any strain as a matter of principle. As shown in Fig. 5, a reconstructed image will appear as if floating to the right of L_2. The reconstructed images other than that of the color red will also be generated similarly to the color red. The beam splitters (BS_1 and BS_2) synthesize the reconstructed images. As a result, a reconstructed image of a color with no interrupting beams will appear as if floating to the right of L_2.

Figure 6 shows the experimental results. As the subject, three miniature cars and a block marked "N", "I", "C" and "T" on its four sides were placed on the table immediately after the lens array. Moreover, a plane marked "3D" was placed at a location about 250 mm from the lens array.

Two images were taken with a video camera. The first photo was taken with forward focus; the second one was taken with rearward focus. If a three-dimensional image is reconstructed, the first one should clearly show the miniature car in the foreground, with "3D" in the background as being unclear. The second photo is inverted, with the miniature car taken as unclear and "3D" seen as clear. Figure 6 (b) and (c) show these experiment results. Since the results are as predicted as seen here, we concluded that a three-dimensional image had indeed been reconstructed.

This system makes it possible to generate a hologram based on the image of a subject taken under a natural light without using a laser beam, thereby displaying a reconstructed

image to be displayed in holography on a real-time basis. Moreover, a pixel pitch of 6.8 μm for the 4K display device has achieved a viewing zone angle of 4.0 degrees.

6 Conclusion

This paper described the typical challenges facing electronic holography and the related studies being conducted today. And with regard to electronic holography capable of recording and displaying real bodies, it also described an electronic holography system based on a 4K video system that takes IP images into a hologram to be presented to an observer. This device demonstrated that it achieved real-time real image input and a wider viewing zone angle than conventional models.

Studies on electronic holography remain in the initial stages. In addition to the challenges presented here, many other challenges remain to be addressed, such as the need to develop large screens, the problem of speckle noise, and size reduction of the device. We also intend to address these challenges in the future.

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