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Interactive color electroholography using the FPGA technology and time division switching method

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Abstract:

In this paper, we report an interactive color electroholography system using the field-programmable gate array (FPGA) technology and the time division switching method for color reconstruction. We implemented 30 dedicated-processors for a computer-generated hologram (CGH) into an FPGA chip, and the FPGA chip can generate full-parallax CGHs, on which we record color information for a color 3D object, faster than a personal computer. The time division switching method can reconstruct a color 3D object from the CGHs, to make use of the afterimage effect on human eyes. The system allows us to perform interactive operations for a reconstructed color 3D object using a keyboard, while viewing the reconstructed color 3D object.

Keywords: three-dimensional display, computer generated hologram, CGH, field programmable gate array, hologram, holography

Classification: Science and engineering for electronics

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1 Introduction

In recent years, electroholography has been attracted much attention as a three-dimensional (3D) display technology since it can optically reconstruct a 3D object from a computer-generated-hologram (CGH) on which are recorded the 3D object data [1, 2]. In order to realize a practical 3D display using electroholography, however, we must overcome significant problems: the enormous computational time for a CGH, the small size, narrow viewing zone and color reconstruction for a reconstructed 3D object. Therefore, so far, it has been difficult for electroholography to perform interactive operations for a reconstructed color 3D object by user interface, while viewing the reconstructed color 3D object.

THe electroholographic display unit we developed has a special-purpose computational chip (SPC) for CGH calculation and a reflective liquid-crystal display (LCD) panel on a small printed circuit board. We used an FPGA chip as the SPC. The SPC has 30 dedicated-processors for CGH calculation and can generate CGHs faster than recent personal computers. The unit allows us to perform interactive operations for a reconstructed monochrome 3D object [3].

In this paper, we report an interactive color electroholography using the electroholographic display unit based on the FPGA technology, and the time division switching method for color reconstruction.

A color 3D object data is divided into red, green and blue components in order to compute three CGHs corresponding to each component by the FPGA chip. The CGHs are sequentially displayed on the reflective LCD panel with a high refresh rate. The LCD panel also simultaneously outputs synchronized signals, indicating that one of the CGHs is currently displayed on the LCD panel. In the time division switching method, red, green and blue light emitting diodes (LEDs) as used for reference lights, are switched by the synchronized signals. As a result of the afterimage effect on human eyes, we can obtain a color 3D animation of about 7 frames per second from a color 3D object of about 400 points. In this system, we can perform interactive

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operations for the reconstructed color 3D object using a keyboard, while viewing the reconstructed color 3D object.

2 Interactive color electroholography

In order to solve the enormous computational time for a CGH, for instance, some software approaches perform fast computation of a full-parallax CGH by translating the expression of CGH into recurrence formulas [4, 5, 6]. These approaches can compute CGHs at high speed; however, even for a general computer on which these approaches are implemented it is difficult for CGHs to compute in real time. Other excellent approach based on a computer-generated image hologram can develop an interactive color electroholography system only using a personal computer [7]. However, the approach is restricted for the reconstruction along the depth direction, because the approach is based on a computer-generated image hologram.

In order to obtain more computational speed, we need to use a hardware approach together with software approaches, such as the recurrence formulas algorithm. Fortunately, CGH calculation is suitable for implementation into hardware. We have proposed a hardware approach using the FPGA technology for rapid CGH calculation [3, 6].

Figure 1 shows the photograph of the electroholographic display unit and the outline of the SPC, respectively. The electroholographic display unit, which is approximately $28\,cm \times 13\,cm$ in size, consists of four modules, namely, a universal serial bus (USB) controller, the SPC, an LCD controller, and the reflective LCD panel. The reflective LCD has a resolution of 800 × 600, a pixel pitch of $12\,\mu m$, an active area of $9.6\,mm \times 7.2\,mm$, and a maximum refresh rate of $360\,Hz$. The USB controller is used for communication of the coordinate datum of 3D objects between a host computer and the unit. The datum is stored in static RAM chips.

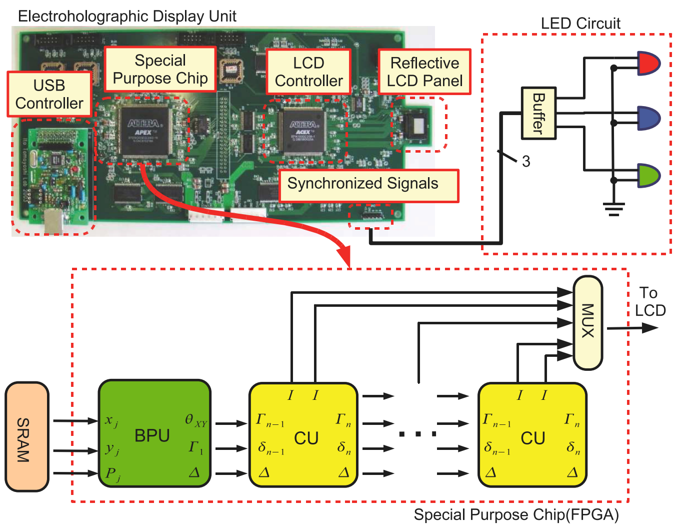

Fig. 1. The photograph of the electroholographic display unit and the outline of the special-purpose chip

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The SPC automatically starts the computation of a CGH after receiving the datum. The SPC implemented by pipeline architecture, can perform CGH computation using our recurrence formulas algorithm [3, 6] faster than a personal computer. After finishing the computation, the SPC sends the CGH data to the LCD controller. The LCD controller controls the reflective LCD panel, and the fringe pattern of the CGH is displayed on the reflective LCD panel. When we illuminate a reference light onto the reflective LCD panel, we can observe a reconstructed 3D animation [3].

2.1 Outline of Special-Purpose Chip for Computer-Generated-Hologram

The SPC can compute a CGH using the following equations:

$$\theta_{XY} = P_j((x_\alpha - x_j)^2 + (y_\alpha - y_j)^2),\ \ \Gamma_1 = P_j(2(x_\alpha - x_j)+1),\ \ \Delta = P_j \times 2, \quad (1)$$

$$\Gamma_n = \Gamma_{n-1} + \delta_{n-1},\ \ \delta_n = \delta_{n-1} + \Delta,\ \ I(x_\alpha + n,\ y_\alpha) = \sum_j^N A_j \cos(2\pi(\Gamma_n + \delta_n)), \quad (2)$$

where $P_j = \frac{p^2}{2\lambda_t z_j}$ is pre-computed by a host computer.

Here, A_j is the intensity of the 3D object, N is the total number of points of the 3D object, and p is the sampling spacing on the CGH and the 3D object. Note that we set a constant value of 1 in A_j to simplify the design of the SPC. The x_α and y_α are the horizontal and vertical coordinates on the CGH, and x_j , y_j and z_j are the horizontal, vertical and depth coordinates of the 3D object, respectively. All the parameters are integer values normalized by p. λ_t is the wavelength of the reference light. The wavelength is generally constant with regard to monochrome reconstruction; however, in the time division switching method λ_t becomes variable for a time, since we need to switch the red, green and blue reference lights at certain intervals.

The SPC consists of two modules: the BPU (Basic Phase Unit) and the CU (Cascade Unit). We implemented one BPU and 30 CUs into the FPGA chip. The BPU is used to compute three parameters, θ_{XY}, Γ_1 and Δ. The CU can compute two recurrence formulas and two light intensities $I(x_\alpha + n,\ y_\alpha)$ and $I(x_\alpha + 30 + n,\ y_\alpha)$ on a CGH. For example, the first CU ($n = 1$) can calculate two intensities $I(x_\alpha + 1,\ y_\alpha)$ and $I(x_\alpha + 31,\ y_\alpha)$. Similarly, the second CU ($n = 2$) can calculate two intensities $I(x_\alpha + 2,\ y_\alpha)$ and $I(x_\alpha + 32,\ y_\alpha)$, and the last CU ($n = 30$) can calculate two intensities $I(x_\alpha + 30,\ y_\alpha)$ and $I(x_\alpha + 60,\ y_\alpha)$. Therefore, the SPC can calculate 60 light intensities on a CGH in parallel.

After finishing CGH calculation, "MUX" in Fig. 1 selects sequentially one of the 60 light intensities in order to display the CGH on the reflective LCD panel. After sending the 60 light intensities to the reflective LCD panel, the SPC updates automatically new coordinates (x_α, y_α) to add x_α to 60, then, the SPC automatically starts calculating the next 60 light intensities on a CGH.

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2.2 Interactive Electroholography System

The problems of the small size and the narrow viewing zone for a reconstructed 3D object are essentially caused by the rough pixel pitch and the low resolution of an LCD panel. In order to enlarge the viewing angle and the size, an LCD panel for a CGH must have a large displaying area and a minute pixel pitch, because the viewing angle is proportional to the displaying area and the size is inversely proportional to the pixel pitch, respectively. For instance, a method solving the problems can equivalently enlarge the resolution and miniaturize the pixel pitch by tiling some LCDs and using lenses [2].

So far, electroholography has been studied primarily for monochrome reconstruction, while several pieces of research have also studied color reconstruction. For example, in 1994, a pioneer method for color reconstruction used three LCD panels to display CGHs, upon which we recorded the red, green and blue components of a 3D object [8]. When illuminating red, green and blue laser lights onto each LCD, the method can reconstruct a color 3D object by compounding the diffracted light from each LCD, using half mirrors.

If we develop a wide-viewing color electroholography by the color reconstruction method as mentioned above, we will need three times the number of LCD panels than a monochrome system. This causes the increase of the cost and the scale of the system. Therefore, a color reconstruction method is desirable to allow reconstruction of a color 3D object by using only an LCD panel. We developed a new color reconstruction method, “the time division switching method”, which can reconstruct a color 3D object by using only an LCD panel [9, 10].

Despite the simplicity of the time division switching method, it can reconstruct a color 3D object clearly with one LCD panel which has a high refresh rate.

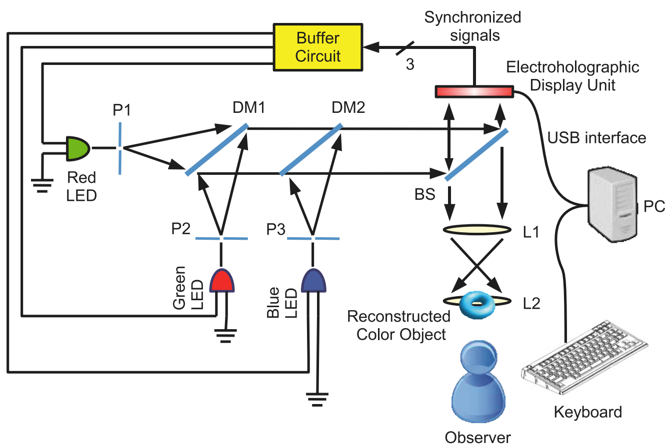

Fig. 2. Outline of interactive electroholography system

Figure 2 shows an interactive electroholography system using the electroholographic display unit and the time division switching method. The

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pinholes P1, P2 and P3, with a diameter of about 0.8 mm, are used for making reference waves from the LEDs, respectively. The dichroic mirrors DM1, DM2 are used for combining the lights from three LEDs. The beam splitter BS channels the reference waves onto the reflective LCD panel and then channels the diffracted light to lens L1 and L2 via the reflective LCD panel. L1 and L2 are convex lenses. L1 is used to shorten the viewing distance of a reconstructed color 3D object, while L2 is used to expand the viewing size of the reconstructed color 3D object.

The host computer ("PC" in Fig. 2) generates a color 3D object and divides the red, green and blue components. Each component has the coordinates x_j, y_j and P_j including z_j and λ_t.

The host computer sends the red components with $\lambda_{t1} = 633\,nm$ to the electroholographic display unit. The unit automatically starts calculating the CGH corresponding to the red component. After the calculation, the host computer sends the blue components with $\lambda_{t1} = 432\,nm$ to the unit. The unit automatically starts calculating the CGH corresponding to the blue component. Likewise, the CGH corresponding to the green component is computed. After calculating three CGHs, these CGHs are sequentially displayed on the LCD panel at intervals of 100 Hz. In order to perform interactive operations, such as rotation and movement, for the reconstructed color 3D object, the host computer generates the next color 3D object corresponding to the user operation, and we repeat the above process.

The electroholographic display unit outputs three synchronized signals, indicating that one of the red, green and blue CGHs is currently displayed on the LCD panel. The synchronized signals are connected to each LED via the buffer circuit in order to amplify the drive capacity of the LEDs. Red, green and blue LEDs are switched via the synchronized signals in order to illuminate the CGHs. As a result of the afterimage effect on human eyes, we can clearly observe a colored 3D animation.

2.3 Experimental Result

In the interactive electroholography system, we can obtain CGHs, whose size is 800 × 600 grids, corresponding to each color from a color 3D object composed of about 400 points in about 0.15 seconds. We can perform interactive operations for the reconstructed color 3D object using a keyboard, while viewing the reconstructed color 3D object. Figure 3 shows an example of the observer's operations on reconstructed 3D animations which consists of a red torus, blue circle and green corn. This photograph shows the scene in which the 3D object is rotating from (a) to (h) by the observer's operations.

3 Conclusion

We developed the interactive color electroholography system using the electroholographic display unit, which has the FPGA-based special-purpose computational chip and the reflective LCD panel, and the time division switching method. The electroholographic display unit is implemented on a small

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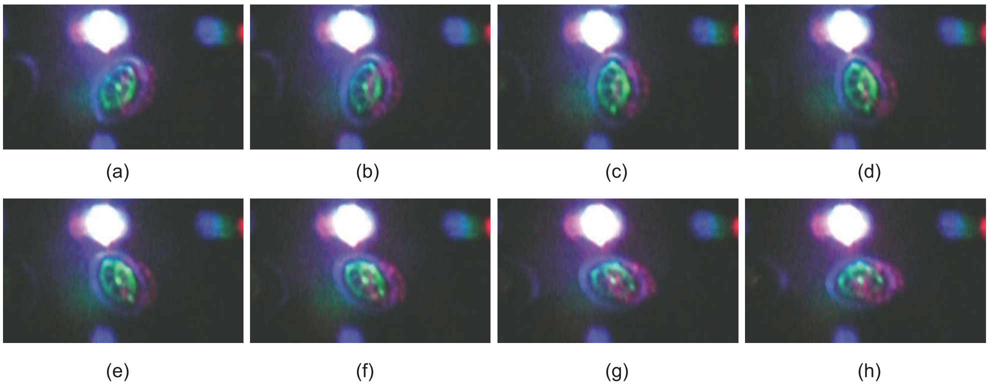

Fig. 3. Experimental Result

printed circuit board, so that the size of the color interactive 3D display system could also be small. If we develop an interactive color electroholography system with a wide-viewing area, we will be able to comparatively easily realize such a system by placing several electroholographic display units in an optical system.

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