3D/2D Switchable Imaging Augmented Reality System Based on Multifunctional Holographic Optical Element and Active Prism Array

Munkh-Uchral Erdenebat[1,3,4], Anar Khuderchuluun[2], Tuvshinjargal Amgalan[1], Ki-Chul Kwon[1], Nam Kim[1], Erkhembaatar Dashdavaa[3,4], Young-Min Cho[3], Hyeon-Su Jeong[3], and Hak-Rin Kim[3,5]*

[1]School of Information and Communication Engineering, Chungbuk National University, Cheongju, Republic of Korea
[2]Display Research Center, Korea Electronics Technology Institute, Seongnam, Republic of Korea
[3]School of Electronic and Electrical Engineering, Kyungpook National University, Daegu, Republic of Korea
[4]Center for Semiconductor-Specialized University, Kyungpook National University, Daegu, Republic of Korea
[5]School of Electronics Engineering, Kyungpook National University, Daegu, Republic of Korea
***rineey@knu.ac.kr**

Abstract

We propose an advanced augmented reality display system with dual-imaging modes based on the visor structure, by use of the custom-designed active prism array and a multifunctional holographic optical element. The proposed system enables switchable imaging modes while preserving the core advantages of conventional augmented reality systems, offering an innovative solution for improved visual experiences.

Author Keywords

Augmented reality, one-shot learning model, 3D/2D imaging, active prism array, multifunctional holographic optical element

1. Introduction

The augmented reality (AR) is a wearable display system like eyeglasses that enables users to observe the digital contents while simultaneously perceiving real-world environment [1]. Integrating the holographic optical element (HOE) into the AR display system provides significant advantages, including a simplified structure and reduced weight which are the biggest impacts of AR displays [2]. Most of the AR display systems are designed to support two-dimensional (2D) images. Moreover, some of the AR displays can support the three-dimensional (3D) contents [3]. For instance, a holographic micromirror array positioned as the in-coupler reconstructs 3D images from displayed elemental image arrays (EIAs) based on the principles of integral imaging. This approach allows for the straightforward recording of a micromirror array to display 3D images on the AR system. However, it is crucial to develop AR systems with the capability to switch between 3D and 2D imaging modes to accommodate varying application needs.

As liquid crystal elements continue to advance rapidly, many optical components traditionally made from standard glass or acrylic are now being replaced with active materials [4-8]. Active elements, which are created by attaching a thin liquid crystal layer onto a lightweight substrate, are well-suited for compact and lightweight devices, including cameras, microscopes, and wearable displays [5-8]. Unlike conventional optical devices with fixed functions, these active components can combine multiple functionalities such as bifocal lenses, focusing or refracting, and selectively transmitting incident beams, into a single unit. Moreover, these functions can be switched or controlled based on the polarization direction. Active components also offer significant advantages, including a high fill-factor, low driving voltage, and rapid switching [5-8].

Recently, an AR display system with 3D/2D switchable imaging modes has been proposed by M.-U. Erdenebat et al. [8]. Here, a liquid-crystalline lens array in combination with a depth camera is utilized. In 2D mode, the system directly displays a captured 2D image. In 3D mode, the depth camera simultaneously captures 2D and depth images, which are used to reconstruct a 3D model of the object. From this 3D model, an EIA is generated and displayed on the AR system, with the liquid-crystalline lens array facilitating the reconstruction of the 3D images. In particular, it has been certified that HOE and liquid crystal-based components are suitable for AR display systems. However, the 3D model accuracy and quality are poor due to the resolution of the depth camera, which significantly degrades the final 3D visualization quality.

Basically, AR displays must be lightweight and have a simple structure due to it is worn like eyeglasses, but as functions increase, additional devices should be installed, which increases the overall display weight. Therefore, this study presents an advanced AR display system built on a visor structure, incorporating dual-imaging modes. It combines a simplified optical design with efficient visualization effects to enhance the functionality and performance of context-aware 3D and 2D imaging modes.

2. Proposed method

The proposed system features a simple visor-type optical configuration, consisting of a microdisplay, an active prism array (APA) with an electrical polarizer, a multifunctional holographic optical element (HOE), and a standard camera. Two distinct visualization modes are then presented to the observer. When HOE is fabricated using holographic wavefront printing method, there is an advantage in that the desired lens profile can be digitally printed [9]. Unlike the previous method that relied on depth camera [8], the proposed system employs only a conventional camera to capture 2D images of real objects. When real-world object-based content is required, the camera captures an image of the physical object, which then serves as the input data for both imaging modes.

An APA is a liquid-crystalline polymer device with a custom-designed array with prism function [4], fabricated using the ultraviolet imprinting method. In the on-state of the electrical polarizer, the APA molecules exhibit optically anisotropic

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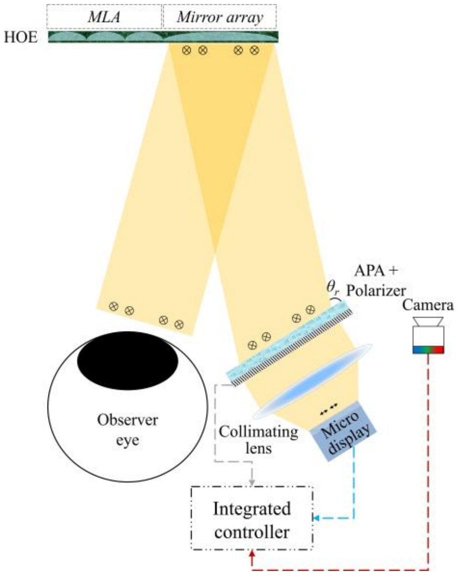


Figure 1. Schematic configuration of the 2D imaging mode in the proposed AR display system.

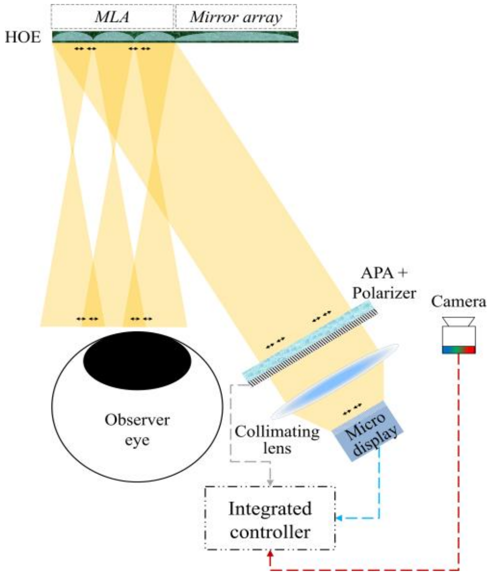


Figure 2. Schematic configuration of the 3D imaging mode in the proposed AR display system.

properties, refracting incident light beams at an angle θ_r. This refraction occurs when the light, linearly polarized by the polarizer, interacts with the APA. The angle θ_r is influenced by the refractive index of the liquid-crystalline polymer material, the minimum deviation, and the angle of the reference optical prism. Furthermore, the APA design must account for the distance between the APA and the HOE as well as the dimensions of each HOE component. In the off-state of the electrical polarizer, the APA behaves like transparent glass, allowing incident light to pass through without alteration.

The multifunctional HOE combiner is fabricated using the holographic wavefront printing technique and comprises two sections: a microlens array (MLA) and a micromirror array. The hogels in the MLA section possess a specific focal length, functioning similarly to a traditional MLA, while the hogels in the micromirror array section have an infinite focal length, reflecting incident light beams directly rather than focusing them. Unlike conventional methods that directly record the optical properties of a physical MLA or micromirror, the holographic wavefront printing technique enables the precise display of a lens profile with desired dimensions and specifications on a spatial light modulator, which is then seamlessly printed onto a holographic material. This approach significantly enhances the quality of 3D image reconstruction. Moreover, the MLA and micromirror array sections are recorded at different angles, ensuring that the diffracted beams from both sections converge at the same location (the observer's eye), to allow users to view 3D and 2D visualizations without moving their eyeballs. The overall size of the multifunctional HOE is determined by the total number of hogels across both sections.

Figures 1 and 2 illustrate the overall structure and operational procedure of the proposed AR display system for both imaging modes. The main components of the proposed AR system are interconnected and synchronized via an integrated controller, which manages the devices and oversees the entire operation. The imaging mode is determined by the state of the APA, while the multifunctional HOE guides the corresponding images to the observer. Here, the MLA section is aligned along the main

the multifunctional HOE guides the corresponding images to the observer. Here, the MLA section is aligned along the main optical axis, and the micromirror array section is positioned at an angle θ_r relative to the main axis.

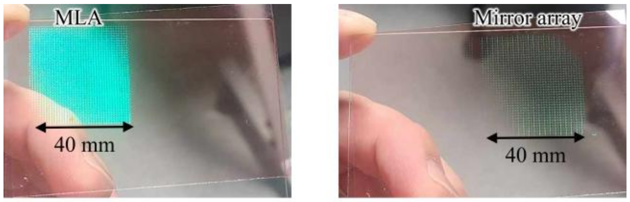
In the 2D imaging mode (Fig. 1), the electrical polarizer's switch is on-state, and the 2D image (whether captured by a camera or rendered from virtual objects) is directly displayed by the microdisplay. The APA then refracts the incident light beams at an angle θ_r, directing them to the micromirror array section of the HOE. Once the 2D image is reflected by the HOE's micromirror array section, the observer perceives it as a 2D projection of the object within the real-world environment.

As illustrated in Fig. 2, the EIA is displayed on the microdisplay instead of directly displaying the 2D image. This arrangement enables the reconstruction and observation of a 3D visualization of the object when the electrical polarizer is in its off-state, allowing the incident beam to pass through the APA as non-refracted. For a real-world object, the depth information of the captured image is first estimated using a one-shot learning model, a high-quality depth estimation algorithm based on a deep neural network. This model efficiently generates an accurate depth map from a single 2D image at high speed while preserving the resolution of the input image. Remarkably, it encodes depth data with significantly higher resolution and quality than a depth camera. Subsequently, the EIA is created by combining the depth and captured images, where the depth data encodes the 3D structure, and the color and texture information are derived from the captured image.

Thus, the proposed system surpasses existing 3D or 3D/2D AR systems by offering enhanced 2D and 3D visualization of real objects through a significantly simpler structure and more efficient operation.

3. Experimental results

In the experiment, the proposed AR display system was implemented as illustrated in Figs. 1 and 2. The system utilized a Sony α6000 digital camera with a resolution of 6000 × 4000



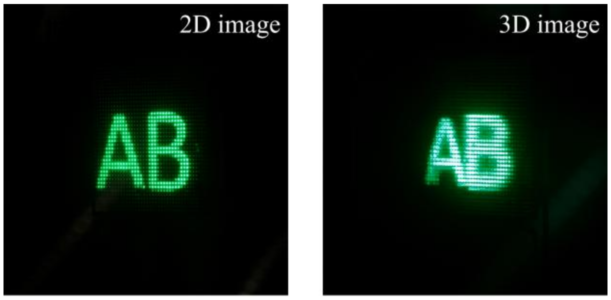
(a) (b)

Figure 3. The actual appearance of the printed multifunctional HOE consists of two sections: (a) the MLA and (b) the micromirror array.

pixels (set to capture images at the region-of-interest of 1920 ×1080 pixels), and a microdisplay with a resolution of 1920 × 1080 pixels. An APA was fabricated by using a reactive mesogen with the birefringent properties and an ultraviolet-curable resin of nano-imprinting material with an isotropic refractive index, where the electrical polarizer comprised a polarization-switching liquid crystal layer. In its on-state, the APA refracted incident light beams at a refractive angle of approximately $\theta_r \approx 7.2°$, with the distance between the APA and the multifunctional HOE set to approximately 185 mm.

The multifunctional HOE was fabricated using the holographic wavefront printing method with a Bayfol HX200 photopolymer and green coherent laser illumination at a wavelength of 532 nm, where MLA and micromirror array sections were printed sequentially due to the recording different recording angle. To ensure the accurate relay of diffracted beams to the observer's eye, the phase profile of the micromirror section was tilted along the Y-axis by 0.61 rad., where the reference beam was configured at 45°. The active area consisted of 80 × 40 hogels, with 40 × 40 hogels allocated to each of the MLA and micromirror array sections. Each hogel measured 1 mm in size, and the focal length of the MLA was set to 3.3 mm. Figure 3 depicts the real appearance of the custom-fabricated HOE. It is noteworthy that the micromirror array, lacking a focusing function, appeared slightly darker; however, its reflective functionality performed as intended.

First, we validated the operation of the custom-fabricated APA and the functionality of the HOE combiner. The 2D image and EIA for the two letters "A" and "B" were displayed in both imaging modes, with an original separation of 10 mm. Figure 4 shows the displayed and diffracted images on multifunctional HOE for each imaging mode of the proposed system. When the electrical polarizer was in the on-state, the APA refracted the incident light beams by approximately 7.2°, guiding them to the micromirror array of the HOE, where they were reflected to the observer's eye, as shown in Fig. 4(a). In contrast, when the electrical polarizer was turned off, the APA did not refract the incident light beams, allowing the 3D image to be observed while the EIA was displayed on the microdisplay, as shown in Fig. 4(b). Here, it was confirmed that the switching speed was very fast, and it was possible to observe the 3D and 2D imaging modes selectively. Also, it has been verified that 2D and 3D images were observed well when the image sensor was continuously looking in the same direction.



(a) (b)

Figure 4. Displayed images on the proposed AR display system for (a) 2D and (b) 3D imaging modes.

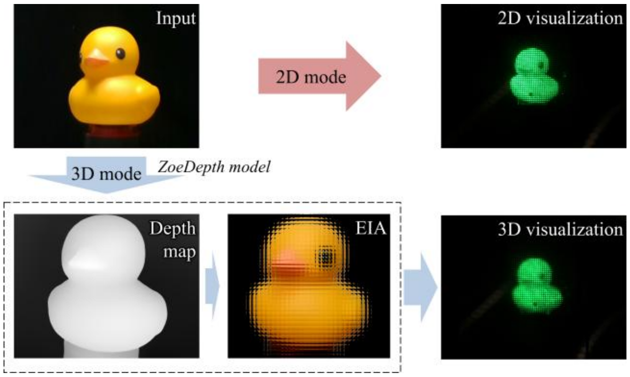


Figure 5. The appearance of the real-world object "duck", along with the 2D and 3D visualizations provided by the proposed AR system, including the generated depth map and the corresponding EIA.

The next experiment validated the display of both 3D and 2D images for a real-world object, a rubber toy duck. First, a camera captured the 2D image, and both imaging modes provided different visualizations. The captured image and diffracted visualization by the micromirror array section is shown in the top row of Fig. 5. Conversely, when the electrical polarizer was in the off-state, the EIA of the object was generated and directly displayed by the microdisplay, resulting in a 3D visualization, as presented in the bottom row of Fig. 5. To generate the EIA, the pre-trained ZoeDepth deep neural network model was employed [9]. This model, trained on a metric depth dataset, estimates depth values for pixel sets in the input image, rather than a single depth value, allowing for the capture of depth across a wide area and enhancing accuracy and robustness. Consequently, the ZoeDepth model estimates the depth of the main object in the input 2D image with high accuracy and speed, maintaining the resolution of the input image. The depth data generated by the model was then used to create the EIA, with color information for each pixel of the EIA derived from the input color image. When the generated EIA was displayed, a 3D visualization of the real-world object, the duck, was successfully reconstructed. The reconstructed 3D image confirmed that the object was visualized as a volume, verifying the system's ability to effectively render depth information.

4. Conclusion

In conclusion, we propose an advanced visor structure-type AR display system, featuring context-aware dual imaging modes enabled by an APA and a multifunctional HOE. The switching mechanism between the imaging modes is controlled by the power state of the electrical polarizer. When the electrical polarizer is in the on-state, the APA refracts incident light beams toward the micromirror array section of the HOE at specific refractive angles, resulting in the display of a 2D image. Conversely, in the off-state of the electrical polarizer, the incident light beams are directed to the MLA section of the HOE, enabling the observer to experience a 3D visualization of the object. For real object-based 3D imaging, a one-shot learning-based deep neural network model is utilized to efficiently and accurately encode 3D depth data from captured images. The depth data is then used to generate an EIA, which is displayed on the microdisplay to produce the 3D visualization. Additionally, the recording angles for each section of the HOE are carefully designed to guide the diffracted beams precisely to the observer's eyes. The proposed system combines the versatility of switchable imaging modes with the core advantages of traditional AR systems, presenting a novel solution for enhanced and dynamic visual experiences.

5. Impact of Your Research

The proposed system stands out for its simple structure while delivering impressive performance in AR display systems with 3D/2D switchable imaging modes. Lightweight and compact designs are essential for AR displays, as they are typically worn like eyeglasses. However, adding extra functionalities often requires additional components, increasing the system's weight and bulkiness, which can lead to discomfort. To address this, the proposed system integrates advanced context-aware 3D/2D switchable imaging modes by incorporating only a lightweight and thin APA and electrical polarizer into a basic setup comprising a microdisplay and a HOE combiner. Additionally, 3D and 2D contents can be visualized either selectively or simultaneously via fast switching of the electrical polarizer.

The HOE combiner serves multiple functions with a single holographic film: it not only directs images from the microdisplay to the observer's eyes, but also facilitates the visualization of both 3D and 2D images. This is achieved through its multifunctional design, consisting of an MLA and a micromirror array sections. Since the HOE is fabricated via holographic wavefront printing technology, the HOE combiner allows for easy customization of any desired lens profiles.

The APA, combined with the electrical polarizer, is pivotal for switching between imaging modes. Unlike conventional bulky prisms with fixed specifications, the APA is significantly thinner and lighter. Moreover, it can switch much faster between acting as a simple transmitter (like a glass) or a deflector (like a prism), depending on the polarization direction of the incident light. This capability enables rapid switching between 3D and 2D imaging modes. The specifications of the HOE and APA were carefully designed and fabricated to fit the system's structure, with θ_r and HOE size optimized by adjusting the gap between the APA and HOE.

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