

Super Multi-View Near-Eye Display with Adjustable Point Light Source Array

Minseong Kim, and Jae-Hyeung Park

Department of Electrical & Computer Engineering, Seoul National University, Seoul, South Korea

Abstract

In this paper, we propose a compact near-eye display using lenslet array and adjustable point light source array. The proposed system reduces vergence-accommodation conflict by providing depth information using a super multi-view technique. It also achieves a compact form factor by generating the virtual image of the display panel using a lenslet array. We verify the feasibility of the proposed system by optical experiments.

Author Keywords

Virtual Reality; Near-eye display; Super Multi-view.

1. Introduction

The growing demand for the metaverse has led to increasing interest in near-eye display (NED) as a key technology for its implementation and has encouraged active research both in academia and industry [1]. A NED is a device composed of a display panel and an optical system which is designed to enable augmented reality (AR) and virtual reality (VR) experiences. A typical configuration of the VR NEDS includes a display panel and an eyepiece lens. By positioning the display panel near the focal length of the eyepiece lens, a virtual image is created at a distant location, enabling users to experience virtual scene. However, the eyepiece lens used in the conventional NEDs has a focal length of tens of millimeters, resulting in optical thickness of similar dimension, which contributes to a bulky form factor. This bulky form factor can lead to physical discomfort for users during prolonged wear. In addition to the physical discomfort induced by the form factor, conventional NEDs have another issue known as the vergence-accommodation conflict (VAC), which also creates difficulties for prolonged use [2]. The VAC arises because the conventional NEDs only rely on stereoscopy, leading to a mismatch between the vergence distance, at which depth is perceived, and the accommodation distance, where the eye focus. This mismatch can cause discomfort for users, often resulting in symptoms like motion sickness. Previous studies have been actively conducted to address these issues. First, to reduce the bulky form factor, studies have been conducted using pancake optics, where folding optics is applied to the eyepiece lens to maintain the optical path while reducing the physical gap created by the eyepiece lens's focal length [3]. Additionally, studies have been conducted using a lenslet array to position an intermediate virtual image of the display panel at the focal length of the eyepiece lens, thereby reducing the physical gap [4]. Studies aimed at reducing the VAC have explored methods such as holographic [5], light field [6] and varifocal displays [7], which provide monocular 3D depth information. A holographic display provides depth information by reconstructing light wavefronts of 3D objects using a spatial light modulator. A light field display provides depth information by providing multiple perspective views of a 3D object from different angles. Additionally, approaches like the Maxwellian display have been developed, which restrict the exit pupil to deliver all-in-focus images [8].

In this paper, we propose a compact, VAC-free super multi-view NED for VR. The proposed system reduces thickness by positioning the intermediate virtual image of the display panel at the focal length of the eyepiece lens using a lenslet array. It also employs an adjustable point light source array (PLSA) as a light source for the display panel. The light from the PLSA is integrated by the lenslet array, forming a real spot image in the eye pupil plane, which works as an exit pupil or the viewpoint of the system. The spot size is smaller than the eye pupil, enhancing the depth of focus of each view. The transverse position of the spot is controlled by the adjustable PLSA. By synchronizing the PLSA and the display panel, multiple views can be projected to the eye through slightly different transverse positions within the eye pupil, providing super multi-view (SMV) 3D images without the VAC issue.

2. Background of the proposed system

Optical configuration of conventional VR NED: Figure 1 shows a schematic diagram of conventional VR NED. The optical configuration of a VR NED consists of a display panel and an eyepiece lens where the display panel is positioned near the focal length of the eyepiece lens. The virtual image of display panel is created at an optically distant location through the eyepiece lens, allowing the user to experience a virtual environment.

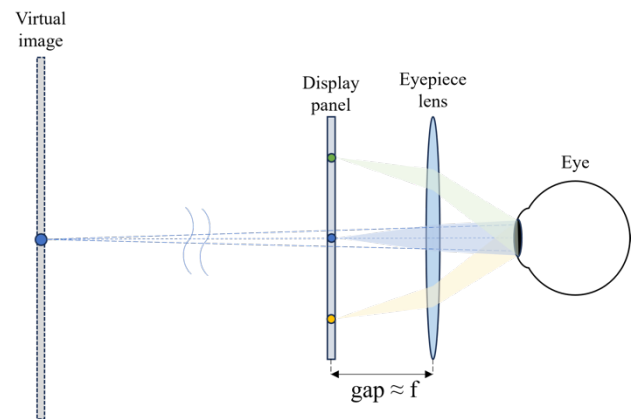


Figure 1. A Schematic diagram of conventional VR NED.

Lenslet array imaging: A lenslet array is an optical component composed of multiple convex lenses with a small aperture arranged in an array form. The lenslet array is primarily used in light field technology to record and reconstruct 3D images [6]. It reconstructs the light field through elemental images, which are calculated based on the pitch and focal length of the lenslet array. These elemental images contain angular and spatial information of the 3D object. By integrating the elemental images using the lenslet array, the light field display can present 3D images. Recently, another use of the lenslet array has also been reported. In this case, the lenslet array creates an intermediate virtual image of the display panel at the focal

length of the eyepiece, reducing the form factor of VR NEDs [4]. The proposed system in this paper uses the lenslet array in a way that it serves two roles simultaneously as illustrated in Fig. 2. The first role is to reduce the optical thickness by generating the intermediate virtual image of the display panel at the focal length of the eyepiece lens. The distance between the display panel and the lenslet array is shorter than the focal length of the lenslet array, resulting in the creation of a virtual image. The elemental images are displayed on the display panel and integrated at the intermediate virtual image plane. The second role is to form the real image of the adjustable PLSA onto the eye pupil. The distance between the adjustable PLSA and the lenslet array is longer than the focal length of the lenslet array, generating a real image. This real image functions as the exit pupil of the system, providing enhanced depth of focus for each view presented by the system.

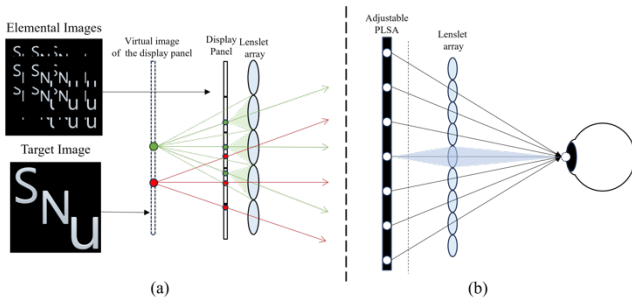


Figure 2. (a) A Schematic diagram of generating virtual image of the display panel (b) A schematic diagram of generating real image of the adjustable PLSA.

Principle of super multi-view: SMV is a technique that present VAC-free 3D images [9]. As shown in Fig. 3, in natural viewing condition, individual point on the object emits a spherical wave which is then captured by the eye pupil and focused onto the retina by the eye lens. A SMV display imitates this by sampling the spherical wavefront into discrete rays passing through different positions, i.e., viewpoints within the eye pupil. The rays at each viewpoint provide a perspective view of the object. By forming multiple viewpoints within the eye pupil and projecting corresponding perspective images, 3D images that drive the proper accommodation response can be displayed. Time-multiplexing is a way for implementing the SMV display where the perspective images are projected to the corresponding viewpoints sequentially. The proposed system in this paper achieves the time-multiplexing SMV display by synchronizing the adjustable PLSA and the display panel.

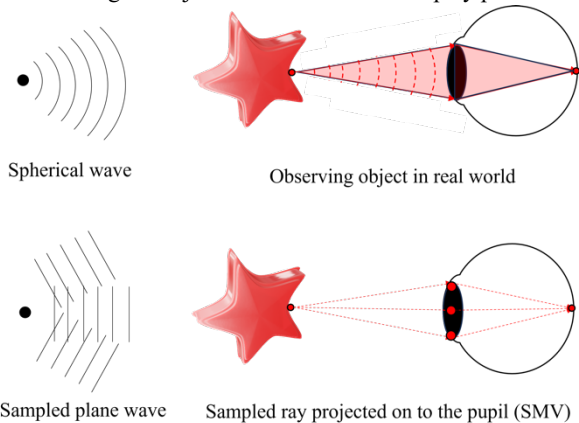


Figure 3. Principle of the SMV technique.

3. Proposed System

Figure 4 is a schematic diagram of the proposed system. The proposed system is a direct-view type configuration like a conventional VR NED structure, consisting of an adjustable PLSA, a display panel for elemental image, a lenslet array, and an eyepiece lens. The adjustable PLSA which works as a backlight for the display panel is designed to control the global transverse shift of the PLSA in its plane. The display panel is a liquid crystal (LC) panel without a backlight working as a transmission type amplitude modulator.

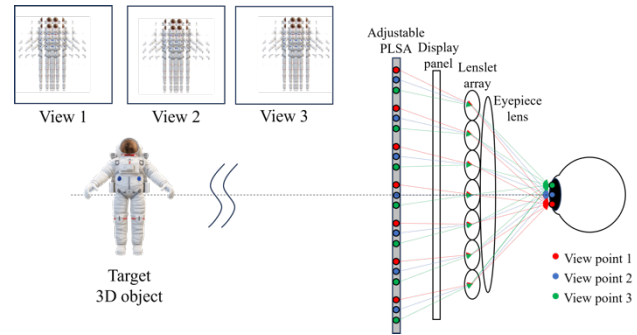


Figure 4. A schematic diagram of the proposed system.

The display panel presents perspective images with appropriate disparity for each view, and the transverse position of the PLSA is shifted to form the viewpoint at the corresponding position in the eye pupil plane. Each view projected through the viewpoint onto a pupil has long depth of focus due to the small viewpoint size which works as the exit pupil through which light is projected. By projecting multiple views through the corresponding viewpoints within the eye pupil, the system allows the user to focus on the intended 3D depth, while other planes appear blurred, providing accurate 3D depth information. The adjustable PLSA and display are synchronized to ensure that the corresponding image for each view is displayed precisely, and time multiplexing is employed to project multiple views onto the pupil simultaneously.

The proposed system not only addresses the VAC by providing 3D depth information but also significantly reduces the thickness compared to conventional VR NED. Figure 5 shows a schematic diagram of the conventional VR NED system and the proposed system. In the conventional system, the gap between the display panel and the eyepiece lens is approximately the focal length of the eyepiece lens, generating the virtual image of the display panel at a distant plane. In the proposed system, a lenslet array is employed to generate the intermediate virtual image of the display panel near the focal length of the eyepiece lens, which then magnifies the image for immersive virtual images at a distant location. The gap between the display panel and the lenslet array is designed to be shorter than the focal length of the lenslet array, ensuring the formation of the intermediate virtual image behind the display panel.

The final optical thickness of the proposed system is determined by the gap between the adjustable PLSA and the lenslet array. This gap is slightly larger than the focal length of the lenslet array to generate the real image of the PLSA in the eye pupil plane working as the viewpoint. However, since the focal length of the lenslet array is very short, the increased thickness due to the PLSA is not significant, and the proposed system is still much thinner than the conventional NEDs as shown in Fig. 5.

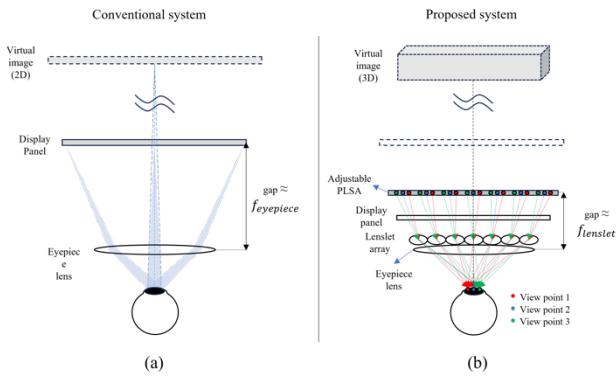


Figure 5. Comparison of the schematic diagrams. (a) conventional VR NED system. (b) proposed system.

4. Experimental result

Figure 6 is the experimental setup for the proposed system. In the experiment, an LCD with a pixel pitch of 25 μm was used as the adjustable PLSA and another LCD with the same pixel pitch but the backlight removed was used as the transmission-type display panel. The lenslet array consists of Fresnel lenses with a 5 mm pitch and a 10 mm focal length. The eyepiece lens is another Fresnel lens with a 40 mm focal length. Figure 7 shows the PLSA images displayed on the adjustable PLSA, which were designed such that the corresponding viewpoints are formed in the pupil plane with a 1.5mm spacing.

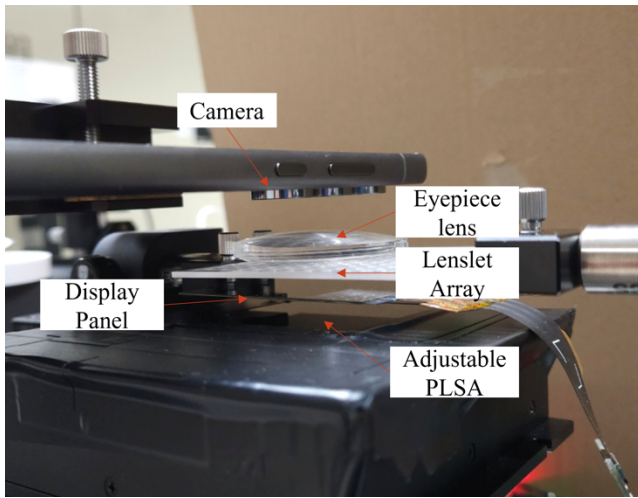


Figure 6. Experimental setup for proposed system.

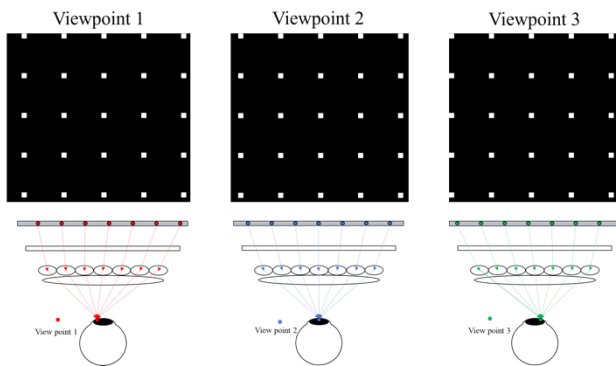


Figure 7. PLSA images for corresponding viewpoints

Figure 8 shows the real image of the PLSA captured on the pupil plane. After displaying the PLSA images shown in Fig. 7 on the adjustable PLSA, their real images, i.e., the corresponding viewpoint was captured at the pupil plane. In Fig. 8, it is seen that each PLSA forms an array of the real image spots in the eye pupil plane. All these spots convey the same image, allowing the eye to view the perspective virtual image through any of the array elements, and thus working as the eyebox expander. In Fig. 8, it is also confirmed that the spot array in the eye pupil plane shifts as the PLSA moves in the adjustable PLSA plane. This result verifies that the viewpoint position can be controlled by adjusting the PLSA in the proposed system.

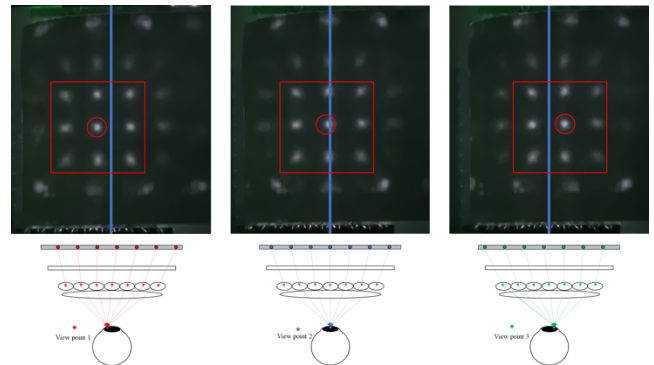


Figure 8. Captured images of each viewpoint at the pupil plane.

Figure 9 shows the experimental result for a single depth image at a disparity-controlled distance. In this setup, 1 \times 3 viewpoints are projected within the lens pupil of the camera. The disparity between the viewpoint images was adjusted to form the target SMV single-depth image at 0.33m. Figure 9 clearly shows that the captured image is sharp when the camera is focused at 0.33m while it is much blurred when the camera focus is moved to 0.2m or optical infinity.

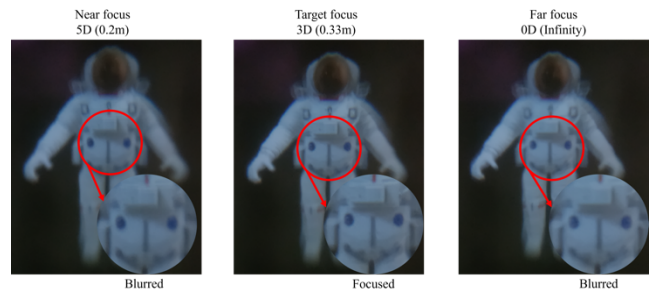


Figure 9. Experimental result of a single-depth image.

Figure 10 shows another experimental result with a two-depth 3D image. The depth of the rook object is designed to be 0.2m while that of the knight object is 5m. As shown in Fig. 10, when the camera focus is set to 0.2 m, the rook object appears sharply in focus, while the knight object is blurred. Similarly, when the camera focus is set to 5 m, the rook object becomes blurred, and the knight object becomes clear. These experimental results verifies that the proposed system can effectively provide accurate depth information using the SMV technique.

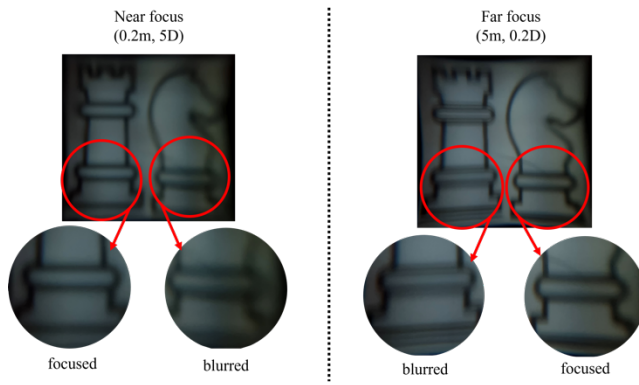


Figure 10. Experimental result of a two-depth image.

5. Conclusion

In this study, we proposed a compact, VAC-free SMV NED for VR. The proposed system integrates a lenslet array and an adjustable PLSA to address the challenges of conventional VR NEDs, including bulky form factors and VAC. By employing a lenslet array, the optical thickness is significantly reduced and the adjustable PLSA enables the projection of multiple viewpoints using time multiplexing, allowing the system to deliver accurate 3D depth information.

Experimental results demonstrated the system's feasibility to provide precise 3D depth information. The system successfully projected images with appropriate disparity onto the pupil plane, enabling the user to focus on the intended depth while other planes appeared blurred. Additional experiments validated the system's capability to display multiple objects at different depths. The implementation and experimental results showed that the proposed system not only mitigates the VAC by accurately presenting 3D depth information but also achieves a more compact form factor compared to conventional NEDs.

6. Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea

(NRF) funded by the Ministry of Education (RS-2024-00464162, 50%) and by Samsung Display Co., Ltd. (50%).

7. References

1. Dincelli E, Yayla A. Immersive virtual reality in the age of the Metaverse: A hybrid-narrative review based on the technology affordance perspective. *J Strategic Inf Syst.* 2022 jun;31(2):101717.
2. Hoffman D.M, Girshick A.R, Akeley K, Banks M.S. Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *J Vis.* 2008 Mar;8(3):33-33
3. Hou Q, et al. Stray light analysis and suppression method of a pancake virtual reality head-mounted display. *Opt Express.* 2022;30(25):44918-44932
4. Bang K, Jo Y, Chae M, Lee B. Lenslet VR: thin, flat and wide-FOV virtual reality display using Fresnel lens and lenslet array. *IEEE Trans Vis Comput Graph.* 2021;27(5):2545–2554.
5. Maimone A, Georgiou A, Kollin JS. Holographic near-eye displays for virtual and augmented reality. *ACM Trans Graph.* 2017;36(4):1–16.
6. Lanman D, Luebke D. Near-eye light field displays. *ACM Trans Graph.* 2013;32(6):1–10.
7. Stevens R.E, Rhodes D.P, Hasnain A, Laffont P.Y. Varifocal technologies providing prescription and VAC mitigation in HMDs using Alvarez lenses. In: *Digital Optics for Immersive Displays.* SPIE; 2018. Vol. 10676, p. 142–58.
8. Lin T, Zhan T, Zou J, Fan F, Wu S.T. Maxwellian near-eye display with an expanded eyebox. *Opt Express.* 2020;28(26):38616–38625.
9. Ueno T, Takaki Y. Super multi-view near-eye display to solve vergence–accommodation conflict. *Opt Express.* 2018;26(23):30703–30715.