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Compact near-eye display for firefighter's self-contained breathing apparatus

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Abstract
We introduce a display for virtual-reality (VR) fire training. Firefighters prefer to wear and operate a real breathing apparatus while experiencing full visual immersion in a VR fire space. Thus, we used a thin head-mounted display (HMD) with a light field and folded optical system, aiming to both minimize the volume for integration in front of the face into a breathing apparatus and maintain adequate visibility, including a wide viewing angle and resolution similar to that of commercial displays. We developed the optical system testing modules and prototypes of the integrated breathing apparatus. Through iterative testing, the thickness of the output optical module in front of the eyes was reduced from 50 mm to 60 mm to less than 20 mm while maintaining a viewing angle of 103°. In addition, the resolution and image quality degradation of the light field in the display was mitigated. Hence, we obtained a display with a structure consistent with the needs of firefighters in the field. In future work, we will conduct user evaluation regarding fire scene reproducibility by combining immersive VR fire training and real firefighting equipment.

KEYWORDS
consistent user experience, firefighter interface, immersive wearable display, slim optics, virtual-reality training

1 | INTRODUCTION

In recent years, the use of virtual reality (VR) in education and training systems has grown rapidly. This is largely due to the advancement of real-time visualization and physical simulation technologies, which have allowed us to simulate disaster scenarios with a high level of realism. The primary goal of education and training services is to provide trainees with knowledge and experience through the exchange of information, with VR technology serving as the medium for this exchange. However, it is essential that the medium used does not distort the user experience when simulating a real-world scenario.

In this study, we aimed to develop a technology that can improve user experience and satisfaction for interfaces that simulate multiple senses involved in a particular scenario [1]. Our goal was to achieve an ideal virtual presence by minimizing the factors that may interfere with the immersive experience and recognition of the scenario in a VR environment.

Specifically, from 2019 to early 2022, we developed a VR firefighter training system for instructors at firefighting training centers to train both newly inducted and frontline firefighters. Existing systems use commercial head-mounted displays (HMDs). During an assessment of requirements, firefighters expressed that training systems that utilize traditional HMDs do not provide an immersive experience when recreating a fire scene. Therefore, the issue with current consumer HMDs is that they are not suitable for use with a full-face respirator* because of their bulky design. This paper details the development process and results of a slim optical-system-based immersive display technology designed to be worn comfortably with a full-face respirator without interfering with its use. We aim to provide firefighters with a more realistic and immersive VR training experience to improve their overall preparedness and ability to respond to real-world scenarios.

The development process of the proposed slim optical-system-based immersive display technology involves several steps, including the analysis of current VR technology and the identification of the limitations of existing HMDs. We addressed these limitations by designing a slim optical system that can be worn comfortably with a full-face respirator while delivering a high-quality visual experience. The results of this research fulfill the physical requirements for VR training wearing a real self-constrained breathing apparatus (SCBA), allowing for the implementation of a training experience that provides firefighters with a more realistic experience and enhanced immersion.

This research highlights the importance of developing technology that can improve user experiences and satisfaction with VR environments and the potential benefits that this technology can bring to the field of education and training for disaster scenarios. The development of a slim optical-system-based immersive display technology that can be worn comfortably with a full-face respirator is a step toward improving the overall preparedness and response capabilities of firefighters in real-world scenarios. We look forward to continuing this research and exploring further developments in VR technology that can enhance the educational and training experiences of individuals for disaster response.

1.1 | Contributions

This study makes the following contributions to HMD research for VR applications:

1. We address problems of VR HMDs noted by firefighters in fire training. A conceptual framework is introduced to demonstrate the development of a display technology for a specific purpose.
2. Key elements for the development of a full-face SCBA-integrated display are established. The requirements and challenges of interfaces for realistic training are analyzed.
3. We develop a slim optical-system-based HMD using a pinhole array and folded optics. The technological approach and experience for designing display devices are detailed, demonstrating the seamless integration of field equipment for realistic training.
4. A practical solution is devised by integrating an HMD with real-world equipment to validate the usefulness of the proposed technology. We present a prototype of positive-pressure SCBA integrated into firefighting equipment and validate its feasibility.

2 | RELATED WORK

Early VR-based training systems were developed using a combination of boarding simulators and immersive screens, particularly in the aerospace and military industries [2, 3]. These systems are effective in delivering a high level of VR presence based on the use of isolated VR environments and interactions with the simulated world beyond a screen through realistic human–machine interfaces. Consequently, the experience gained from these training systems can be easily transferred to real-world scenarios. However, fire scenes are extreme environments that require full-body movement and the use of all physical senses. In cases where direct interaction and experiential training are crucial, existing visualization interfaces are limited in terms of providing sensory feedback that accurately reflects the target scenario. Hence, VR training systems running on desktop computers are being developed to focus on indirect experiences, such as theoretical operational procedures, instead of providing full immersion.

The implementation of an immersive VR application system relies on HMDs, which can help overcome the narrow field of view (FOV) of traditional computer monitors. However, many limitations remain in terms of usability and continuous user engagement regarding factors such as the volume and weight of HMDs. The form factors of HMDs are significantly influenced by their optical modules, which evolve over time. Prior to the 2000s, commercial HMDs utilized lens optics to expand microdisplay panel images to approximately 1 in. in size with an FOV of 30°–40°. This was when performance was prioritized over usability, resulting in HMDs that were bulky and weighed as much as a few kilograms. In the 2010s, advancements in optics, such as large expanse, extra perspective optics, and the mass production of high-resolution display panels with more than 300 pixels

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*In the Republic of Korea, most firefighters use a specific model of firefighting breathing apparatus, and the space available in front of the face is very narrow, as shown in Figures 1 and 9.

per inch (PPI), led to the wider adoption of VR technology [4–6]. The advancement of graphics processing units and real-time 3D game engines has facilitated the development of commercial VR systems for both consumer and educational purposes [7, 8]. In the 2020s, the display panel resolution was improved to over 2K, and real-time human factor optimization using eye trackers was introduced to enhance image quality and performance [9, 10].

In the 2010s, the optical systems of immersive HMDs were generally thick (approximately 50 mm–60 mm) based on the volume of optical modules using single lenses, as is the case of the Oculus RIFT and HTC VIVE devices. However, in the 2020s, various VR/augmented reality (AR) display technologies have been introduced to reduce the thickness of optical modules, including catadioptric lenses and polarization-based reflective-folded lenses. For example, Panasonic VR Glass and HTC FLOW have thicknesses of approximately 30 mm with catadioptric lenses [11] and polarized-based reflective folded lenses [12, 13]. Some systems, such as the ThinVR system proposed by Ratcliff and others [14], have implemented curved 2D compound lens arrays with an approximate thickness of 20 mm. Lanman and others [15] proposed a microlens array to reduce the thickness of the optical module to approximately 10 mm. Light-field technology has also been used to reduce the thickness and improve the FOV, as demonstrated by Maimone and others [16]. A holographic reflective optical-system-based AR glass [17] demonstrated that the thickness of the front part of the eyepiece can be reduced to less than 10 mm while providing an FOV of up to 80°. These technologies use a combination of lenses and optical filters to reduce physical thickness. However, they also have limitations such as reduced resolution and brightness, nonuniform images, and increased wear based on additional requirements for projection optics around the eyes.

3 | REQUIREMENTS FOR FULLY IMMERSIVE SCBA DISPLAY

During the user requirement survey in the planning phase and in several simultaneous technical hands-on live demonstrations, we identified a consistent demand for an HMD that can be used along with a working SCBA. To provide a high-quality, realistic experience, the following functional requirements should be satisfied:

1. Development of a device that enables wearing a positive-pressure air respirator face mask after putting it on an HMD or by attaching it inside the face mask to make operations easier.
2. The HMD must not physically alter (modify) the existing SCBA or interfere with its operation.
3. The user's perceived FOV should be greater than 100°, which is similar to that of a normal air respirator facial mask and should be experienced when wearing the VR interface.

The developed display must be compact and positioned in front of the face when wearing an SCBA. We aimed to design a slim display based on the most widely used SCA 550 model air respirator face mask developed by a major company in the domestic firefighting sector. The average head size of a 40-year-old adult man and the wearable respirator model were established using the Size Korea database (the government's population measurement standards project) [18] (Figure 1). Using computer-aided design, allowable dimensions of 130 mm in the horizontal direction, 70 mm in length, and 30 mm in depth were confirmed. To account for the human factor characteristic [19–21] of the optical axis of the eye not being aligned with the visual axis, the binocular module could be designed as a separate monocular module that rotated the optical module outward to provide additional design space. However, previous data on the extrusion of free space were used to derive a rough estimate for the design of the thin optical system because the dimensions may vary depending on individual facial measurements and the pressure of the air respirator.

The issues related to wide FOV, high-resolution video output, lightweight, and miniaturization to comply with user requirements are typical requirements for HMDs (or smart glasses) in general and not just for firefighting training, and they are constantly improved. In the study period, various lightweight/slim standalone commercial smart glasses were available, but most of them had drawbacks such as a narrow FOV of 30–40°, low video resolution, and clarity issues under external illumination. Although some HMDs met the requirements of wide FOV and high resolution, they could not be embedded in a tight space without

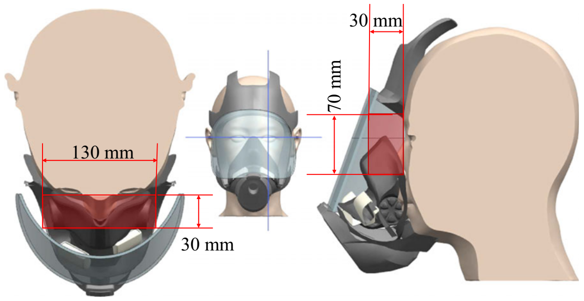


FIGURE 1 Allowable space measured based on male standard head model wearing facial mask.

structural modifications to the mask depicted in Figure 1. In camera-enabled see-through HMDs, quality issues such as video lag, camera–eye mismatch, color mismatch with natural scenes, and video distortion have not yet been completely resolved. To overcome these drawbacks, we developed an HMD for an SCBA, as detailed in Sections 4 and 5.

4 | PINHOLE APERTURE ARRAY-BASED SLIM NEAR-EYE DISPLAY

4.1 | Optical design of pinhole aperture array

The use of light-field display technology based on a pinhole array mask (PAM) is a straightforward approach for implementing a slim near-eye display (NED). This approach involves positioning the image output panel in front of the user's face. Our previous study [22] was aimed to investigate the relations between various design parameters, including the overlap ratio of multiple pinhole projection images (α), diameter of each pinhole (d_p), distance between pinholes (g_pp), distance between the PAM and the user's face (D_dp), angular resolution (AR), and size of the user's pupil (d_pupil). The study results are shown in Figure 2.

$$\alpha = \frac{d-\beta}{d}. \tag{1}$$

According to the simulation examples presented in Figure 3, if the actual pupil size (d'_pupil) becomes smaller than the d_pupil used to generate the basic image, the actual overlap ratio (α') decreases, leading to empty spaces in the retinal projection image. This highlights the importance of properly accounting for the size of the user's pupil when designing a light-field display system using a PAM.

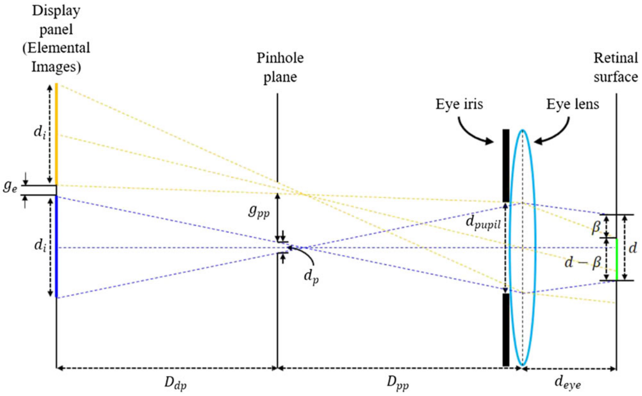


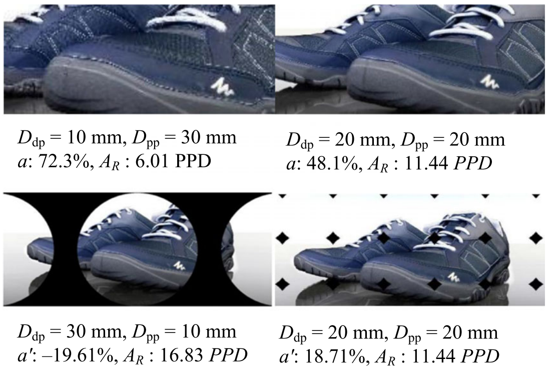
FIGURE 2 Basic principles and parameters of pinhole array mask (PAM)-based near-eye display (NED) reprint from [22].

It is necessary to consider the potential impact of variations in pupil size on the overall display performance.

4.2 | First prototype using PAM-based slim NED

We developed a prototype of a PAM and cardboard HMD based on the simulation results of various parameter combinations described in Section 4.1, as shown in Figure 4. By comparing the image quality experiences, we developed the following design guidelines for pinhole-array-based NED:

1. Overlap ratio (α) between retinal images: The overlap ratio is inversely proportional to the retinal images. Hence, it should be minimized for any empty spaces not to be visible to the user.
2. Adjusting overlap ratio and image quality: The overlap ratio and image quality can be adjusted by adjusting the distance (D_pp) between eye pinholes.


$D_\mathrm{dp} = 10$ mm, $D_\mathrm{pp} = 30$ mm
a: 72.3%, A_R : 6.01 PPD

$D_\mathrm{dp} = 20$ mm, $D_\mathrm{pp} = 20$ mm
a: 48.1%, A_R : 11.44 PPD

$D_\mathrm{dp} = 30$ mm, $D_\mathrm{pp} = 10$ mm
a': –19.61%, A_R : 16.83 PPD

$D_\mathrm{dp} = 20$ mm, $D_\mathrm{pp} = 20$ mm
a': 18.71%, A_R : 11.44 PPD

FIGURE 3 Comparison of reconstructed views from pinhole-array-based near-eye display (NED).

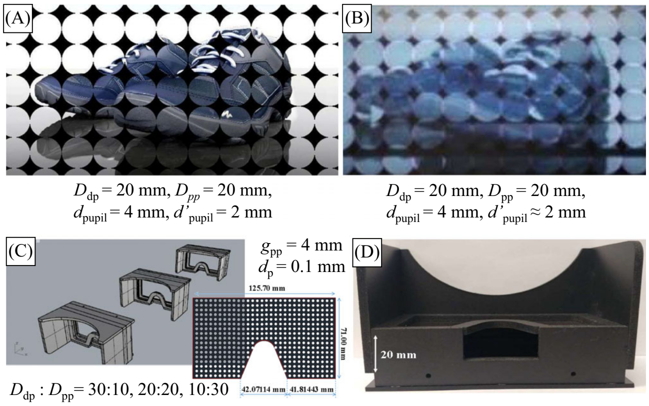


FIGURE 4 (A) Simulated image, (B) camera-captured image, (C) three types of frame prototypes and pinhole array mask (PAM), and (D) head-mounted display (HMD) prototype.

3. Consideration of pupil size: According to a previous study [23], the average adult pupil size is 2–4 mm in well-lit environments and 4–8 mm in low-light environments. Because PAM and fully immersive HMD environments block external light, it is important to design the pupil size to be as large as possible. The system should be designed with an overlap ratio above a certain threshold to ensure a clear view. Nevertheless, changes in pupil size can result in a flipped view or empty spaces.
4. Eye-pinhole distance (D_{pp}) and image quality: The eye-pinhole distance and image quality are inversely proportional, meaning that if D_{pp} is exceedingly large, the image quality will be negatively impacted. In contrast, if D_{pp} is very small, it can interfere with the actual wearing of the HMD. To balance these factors, although the image quality may be compromised, the overlap ratio should be designed to be high with a D_{pp} value that increases user versatility.

4.3 | Analysis of pinhole aperture array-based slim NED

The pinhole aperture array-based slim NED (PAM-type NED) is a promising technology owing to its ease of production and economic feasibility. However, the design of the PAM-type NED has a major drawback, specifically, a considerable reduction in image brightness caused by pinhole masks. As shown in Figure 4, less than 5% of the brightness of the panel passes through the pinhole masks and reaches the user's eye. Furthermore, a change in the size of the user's pupil compared with the simulated reference value of the output image can disrupt the continuity of the image, further reducing the overall image quality. To address these issues, microlens-array-based light-field display technology [14, 15] may be a potential solution because it offers brighter and more consistent image quality. However, this solution requires a more complex production process and higher cost. Therefore, the tradeoff between cost and image quality should be considered in the NED design.

5 | POLARIZATION-BASED FOLDED OPTICS FOR SLIM NED

5.1 | Polarized catadioptric folded optics

The light-field display technology described in the previous section suffers from a basic image-quality degradation problem depending on the overlap ratio of the retinal projection image. To overcome this problem, polarized catadioptric optics have been used in recent years to reduce the thickness of HMDs while preserving the resolution and wide viewing angle of the image output panel. The concept of overlapping optical paths and reducing the volume of optical systems was introduced by La Russa in 1966 [24]. Since then, several polarization catadioptric folded-optics technologies have been developed and applied to commercial products [25–30].

We aimed to develop a slim NED that considers the requirements mentioned in Section 1, availability of lens materials, and ease of manufacturing process. We explored the application of polarized catadioptric folded optics in the design of slim NED and examined their potential as a solution to image-quality degradation of conventional light-field displays.

5.2 | Second prototype with polarization-based folded optics

To develop a slim NED, a folded optical system comprising two lenses was designed, as shown in Figure 5. The lens diameter was 45 mm (Figure 5A) to support a screen of approximately 3 in. compatible with the size of the monocular image panels in commercial HMDs. The FOV was designed to reach a minimum angle of 100°. The optical module was designed to provide an image with a diagonal FOV of up to 102.06° between the pupil and screen (Figure 5A) using two spherical lenses (L1 and L2) made of glass with refractive indices of 1.74 and 1.53, respectively. Simulation results indicated that the optical distortions were less than 10% but would require reverse compensation (barrel distortion) when generating the rendered image. We developed a prototype for the second slim HMD with an optical module that was approximately 38% thinner (21 mm; Figure 5B) than a commercial product (55 mm; Figure 5C).

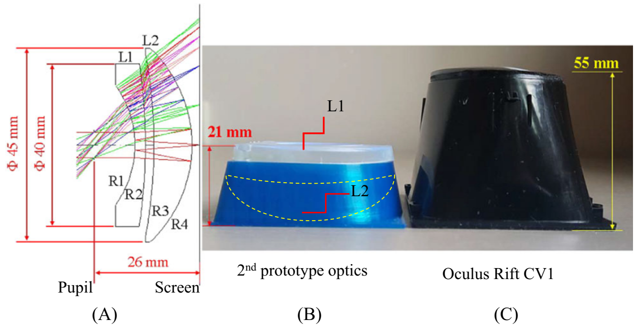


FIGURE 5 (A) Optical path simulation of second prototype and (B) thickness comparison with optical module of (C) commercial head-mounted display (HMD).

To evaluate the sensory performance of the optical module, a binocular prototype was fabricated to facilitate the simultaneous close-up observation of both eyes using a foldable smartphone, as shown in Figure 6A. The prototype was tested by capturing photographs (Figure 6B) and viewing the enlarged images on an AMOLED smartphone screen with a resolution of 425 PPI using an Apple iPhone 13™ camera. The results revealed that images exceeded the FOV of the camera.

5.3 | Third prototype with polarization-based folded optics

To further reduce the volume of the slim NED, the design of the lenses was modified, as shown in Figure 7, and the refractive indices of the two glass materials were changed to 1.74 and 1.57. The maximum diameter of the lens remained at 44 mm, similar to that of the second prototype. However, the screen size of the image output area was reduced to 2.5 in. This modification resulted in a reduced optical distortion rate of less than 5%, an increased viewing angle of 103°, and a thinner optical module with a thickness of 18 mm. Therefore, we developed a prototype for the second slim HMD with an optical module that was approximately 32.7% thinner (18 mm; Figure 7C) than a commercial product (55 mm; Figure 5C).

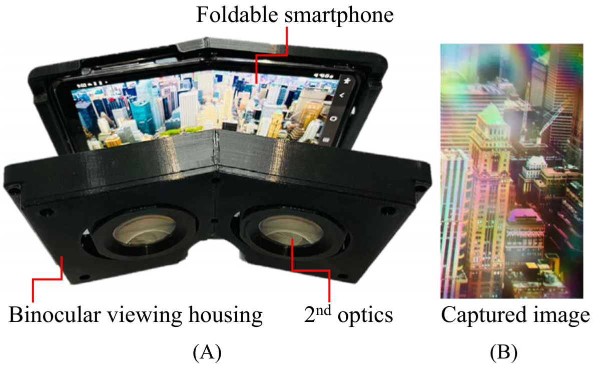


FIGURE 6 (A) Second prototype slim optics over a smartphone display mockup and (B) image captured using the prototype.

To address varying visual sensory human factors, such as optical axis alignment (Figure 8B,C) and interpupillary distance, a binocular display prototype was fabricated with an adjustable folding angle and interpupillary distance adjustment function, as shown in Figure 8A. This allowed the slim NED to be worn in close contact with the user's face and accommodated a variety of users. The performance of the optical module was tested by photographing and viewing an enlarged image of an AMOLED smartphone screen with a resolution of 426 PPI using an Apple iPhone 13 camera.

The linear polarization filter (between pupil and lens L1) and circular polarization filters (1/4λ waveplate) for catadioptric optics, which are shown in Figures 5A and 7A, were removed to improve clarity. However, for prototype production, these optical filters were inserted with a half-mirror reflective coating (R1 and R4 in Figure 5A) and a retarder between the lens (L1 and L2 in Figure 5A) and panel (L2 and screen in Figure 5A). The addition of these filters allowed the prototypes to provide clearer and higher-quality image outputs. In addition, these refractive lenses had a broadband antireflective coating (400–700 nm) to reduce surface reflections.

6 | SLIM AND IMMERSIVE NED FOR A FIREFIGHTER SCBA

To evaluate the practicality of the developed optical modules, prototypes were created and incorporated into an SCBA commonly used by firefighters as shown in Figure 9. First, we dismantled a commercial HMD to update the

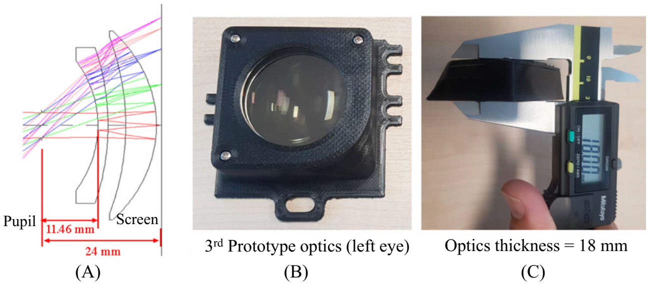


FIGURE 7 (A) Optical path simulation of third prototype, (B) its optics, and (C) thickness measurement.

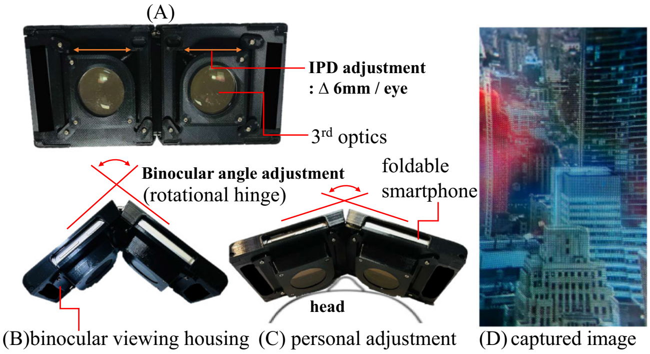


FIGURE 8 (A) Third prototype with slim optics over (B, C) smartphone display mockup and (D) captured image.

optical and external designs and make modifications to better fit the SCBA form factor. However, the PAM optical system used in this design has a lower perceived resolution. To address this issue, the PiMax 4K HMD, which has a built-in resolution of 3480 × 2160 pixels, was modified to improve the image output quality. The thickness of the optical system was reduced to 73% of its original value (from 55 to 40 mm) by incorporating the first optics prototype. (Figure 9A).

Although this slim design made it difficult to mount the housing case inside the SCBA, we 3D-printed a housing and assembled it with a wearable respiratory component to form a single unit. An image-quality experience test revealed that the prototype was difficult to use under normal conditions because of its low light transmission level (only 2% of the original light passed through it).

Several commercial HMDs were dismantled and remodeled for the second slim NED prototype. The Oculus RIFT CV1 model was selected because of its relatively small logic board and monocular image panel (3.54 in.). The optical module was replaced with a second optics prototype, reducing its thickness to 38.2% of the original value (Figure 5). However, an integrated plane frame with logic boards prevented the prototype from being fully embedded in the internal curved surface.(Figure 9B) During an image quality experience test, immersive images with an FOV of 100°, similar to the FOV of commercial HMDs, were obtained.

Finally, a separate binocular NED module was developed with a 2.89-in. image panel containing 1440 × 1440-pixel components (24 μm pixels) found in commercial HMDs, and a linear polarization film was added between lens L2 and the screen. The third optics prototype reduced the thickness of the optical section to 32.7% of the original value (Figure 7). To install it inside the SCBA, the angle of the binocular module was modified to 26°, similar to that of commercial HMDs that provide a binocular FOV greater than 180°. This modification improved the wearability of the binocular module and allowed it to be fully installed in the SCBA (Figure 9C). During the experiment, immersion images with a diagonal FOV of 103°, which is similar to the FOV of a commercial HMD, were obtained.

7 | LIMITATIONS

Because this study prioritized the technological needs of firefighters for VR training, it had the following limitations. Empirical studies are still required to confirm our findings through user testing. When this study was conceived in 2018, slim optics had not been fully deployed in

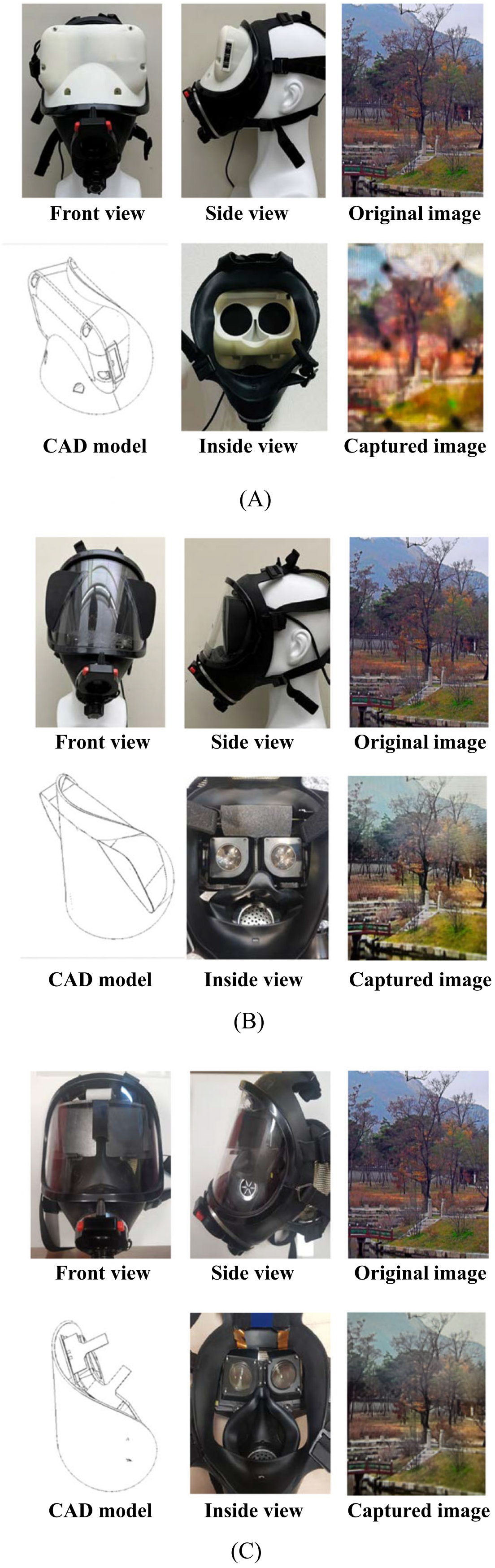


FIGURE 9 Legend on next page.

FIGURE 9 Developments of built-in near-eye display (NED) for firefighting self-constrained breathing apparatus (SCBA) (CAD, computer-aided design): (A) 1st NED, (B) 2nd NED, and (C) 3rd NED.

products for fully immersive HMDs. Currently, folded optics is the preferred technology for delivering wide viewing angles and high-resolution video (above 2K) experiences with slim HMDs, such as those in this study and in new commercial products by various companies (for example, HTC and META). This study aimed to share the research procedure that led to the stepwise improvement of PAMs and folded optics to solve functional problems faced by firefighters engaged in VR training. Although efforts have been made to obtain physical parameters that satisfy the functional demands of firefighters, we believe that user evaluation experiments must be conducted to compare and verify whether VR fire training content using the resulting technology is superior to available commercial HMDs (which cannot be used while wearing SCBAs) in reproducing the feeling of improved fire scene activity (for example, tension/discomfort after wearing a respirator). It also remains necessary to conduct experiments to compare and measure user satisfaction regarding the realistic reproduction of fire scenes by using commercial products with similar optical systems and the results of this research as an interface for VR fire training.

8 | CONCLUSIONS AND FUTURE WORK

We present a novel development in the field of slim-optical-system-based NED technology. We aimed to develop a device that can be operated simultaneously with a positive pressure-type respiratory system when necessary. The experimental results demonstrated that it can be used effectively in VR training scenarios. This NED technology has the advantage of being easily mass-produced based on the use of a polarization-based compound folding lens structure, which provides an appropriate form factor and image quality while maintaining a suitable viewing angle.

Various issues must be addressed in future work:

1. Research is needed to improve the manufacturing and human factor elements, including the use of lighter polymers to reduce the thickness and weight of the device, fusion of aspheric design, and Fresnel optics [31] to reduce the thickness of the optics, improve the viewing angle, and increase the resolution of the image panel. Follow-up research should be conducted to develop a visualization system that considers human factors, such as eye tracking and focus control [32, 33]. These improvements will further enhance the effectiveness and usability of the proposed slim-optical-system-based NED technology in various applications.
2. Multimodal immersive interface-based presence enhancements should be investigated. Many factors may affect the firefighter's ability to recreate a sense of activity in a fire scene. In terms of interfaces, we are developing an interface that supports free movements in a virtual fire scene and wearing real firefighting equipment (for example, a haptic pistol nozzle that provides firewater spraying forward and a fire suit that provides the sensation of cold water and heat of fire to the whole body in real time). Thus, we aim to replace general-purpose VR hand controllers with real equipment to verify the overall effectiveness of immersive VR fire training.

Overall, the developed slim optical system-based NED seems promising for VR training that allows firefighters to experience realistic fire scenes in a limited simulation environment. This environment uses only a fraction of the capabilities of traditional desktop computers and HMDs. We expect that our development will pave the way for research and development in firefighter VR training using our framework.

CONFLICT OF INTEREST STATEMENT

The author declares that there are no conflicts of interest.

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