

# Mixed Display Platform to Expand Comfortable Zone of Stereoscopic 3D Viewing

Ungyeon Yang, Namkyu Kim, Jinseok Seo, Ki-Hong Kim, and Gil-Haeng Lee

*Common stereoscopic three-dimensional (3D) display has a convergence and accommodation conflict that violates the natural human cognitive process of viewing. This weakness exposes the challenge in supporting fun factors while eliminating safety problems in the 3D viewing experience. Thus, human factors have become a major research topic. In this letter, we propose a 3D stereoscopic visualization platform that can expand the sense of a 3D space by fusing organically mixed stereoscopic displays to provide a continuous feeling of 3D depth. In addition, we present pilot test results to show the possibility of the technical implementation of the proposed platform and note ongoing research issues to be addressed.*

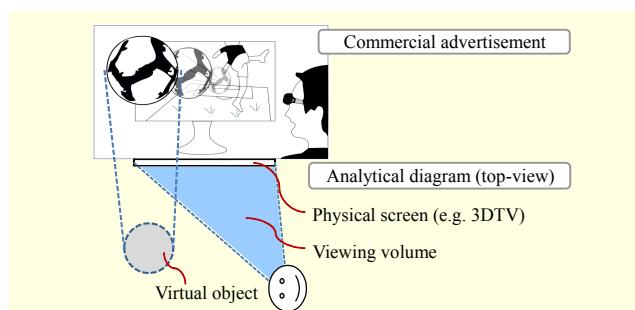
**Keywords:** 3D stereoscopic display, mixed display platform, 3D depth feeling, human factors.

## I. Introduction

Many commercials advertise three-dimensional (3D) technology while showing an object seemingly protrude beyond the screen, claiming that this visual sensation can be sustained even when the screen is out of view. Figure 1 describes the viewer's constraints in seeing general 3D displays. With current display technologies, out-of-screen visualization schemes for virtual objects are not possible outside of the view volume, which is defined by the user's eye and a physical screen. On the other hand, providing 3D effects using extreme depth information for 3D imaging content causes such negative

issues for the viewer as fatigue, headache, and dizziness. A typical cause of such safety problems is the principle of popular 3D visualization technology, which makes use of binocular disparity stimulus in human 3D perception. Thus, the mismatch between the convergence and accommodation of two eyes is a fundamental defect. To overcome this weakness, a proposed visualization platform must provide rendered 3D stereoscopic images to viewers in a comfortable 3D physical space.

Most 3D displays have a restricted viewing area for natural 3D stereoscopic visualization. In this study, we propose the use of the expanded 3D (E3D) technology, which suggests a new platform that can naturally visualize and interact with virtual 3D objects around users even within a touchable distance. Using a mixed display platform, our technology expands a single experience-space of 3D display, which has a limited comfortable 3D viewing range [1]. To realize this goal, in previous studies [2], [3], we proposed a layered multidisplay architecture that fuses the visualization areas from homogeneous and heterogeneous displays into one connected space, divides this space into various service areas from the perspective of a user-centered viewpoint, and shares the space to obtain a seamless experience.



**Fig. 1.** Excessive 3D viewing volume in space of a general stereoscopic display.

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## II. Mutually Complementary Mixed Display Platform

There is no ultimate display technology yet available, and each display device has its own advantages and disadvantages. In our layered multidisplay concept, we can group various displays into the following categories based on the distance from the user's eye, as shown in Fig. 2 (the left right arrows indicate possible virtual viewing ranges that are perceived by the human eye in each candidate stereoscopic display): ① a retinal display (RD) in the human eye system, consistently presenting vivid images; ② a head-attached display (HAD), in which the distance of the virtual screen to each device depends on the optical characteristics; ③ a handheld display (HHD) on a mobile device, for example, a smartphone or tablet device; ④ a near-body display (NBD) or devices that users can easily touch, for example, a desktop monitor; ⑤ a spatial display (SD) located in the surrounding area relatively close to the user, for example, a television; and ⑥ a far/distant display (FDD), which provides images in the background or surrounding environment, for example, a cinema screen. In addition, according to the previous studies [1]-[3], if we assume a visual 3D comfortable range, we can also calculate the comfortable range of each display using the view frustum form shown in Fig. 2, by considering the comfortable range not as restricted discrete space but as a scalable continuous space.

By connecting the comfortable ranges of the displays, we can split and control visualization space to preserve the natural 3D stereoscopic viewing experience around the user's performance area. Therefore, it can naturally provide an expanded perception of 3D space that accommodates the user's gaze. If the virtual object,  $O_a$ , is presented on the SD,  $S_s$ , viewers will experience a feeling of 3D depth that is excessive and uncomfortable. Therefore, in this case, if  $O_a$  is rendering on the NBD,  $S_n$ , through a seamless transition from  $S_s$  to  $S_n$ , viewers will be able to experience a more natural 3D feeling. In some cases, the virtual object,  $O_b$ , should be presented only on an RD or HAD because the object is not included in any comfortable ranges of other displays. We must also consider a more robust virtual objects rendering scenario.

Figure 3 shows various visual ranges consisting of viewers, virtual objects, and various displays in the multidisplay platform. Based on the ownership of the viewing frustum, a visually comfortable range can be classified as a public visual range (for example, NDB, SD, and FDD, shown in Fig. 2), a personal visual range (for example, RD and HAD), or a mobile visual range (for example, HHD), based on the criterion of the movement and sharing of the visual content.

Figure 3(a) shows a depth-directional space expansion scenario. In the overlapping area, the platform must select the display device to draw the given virtual object,  $O_1$ , between

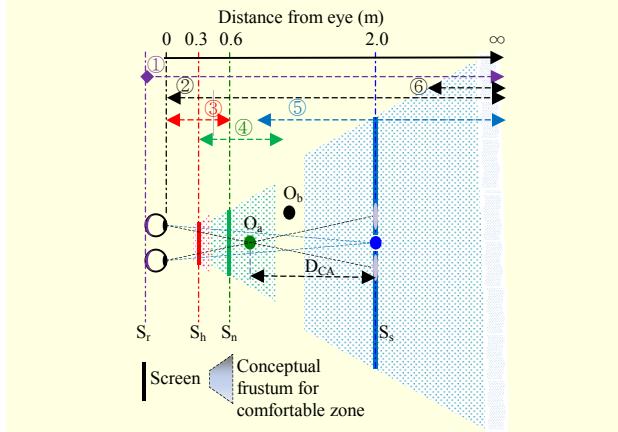


Fig. 2. Conceptual layered multidisplay platform.

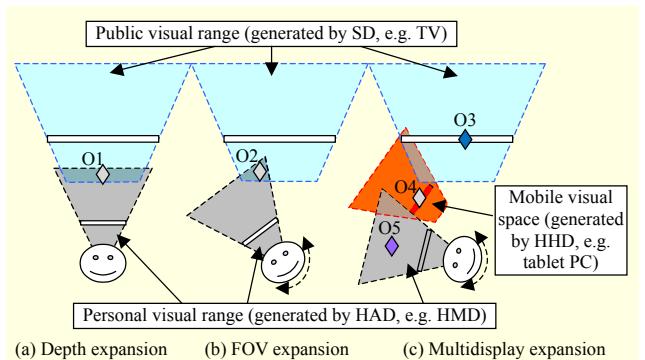


Fig. 3. Visual scenarios of multidisplay platform.

each display's comfortable ranges. Figure 3(b) represents the field-of-view (FOV) expansion of the horizontal dimension of the space, which can compensate for the limitations of two displays. As in the depth expansion scenario, the system considers a proper rendering choice for the overlapped virtual object,  $O_2$ . Finally, Fig. 3(c) indicates the expansion of the comfortable range by connecting three or more homogeneous and heterogeneous devices to create a seamless space that visualizes the virtual objects,  $O_3$ ,  $O_4$ , and  $O_5$  on each display.

## III. Experimental Implementation and Discussion

The following features are required to implement the E3D platform. First, to synthesize multiple stereoscopic images, the position and orientation information of the displays and users must be tracked precisely. Second, to mix various stereoscopic images, a display located in the middle of the layered multidisplay structure must support the see-through functionality. Third, for a shared display, the individual viewpoints of the users must be simultaneously supported. Fourth, RDs and HADs must have a unified function to synchronously receive all visual images from outside the

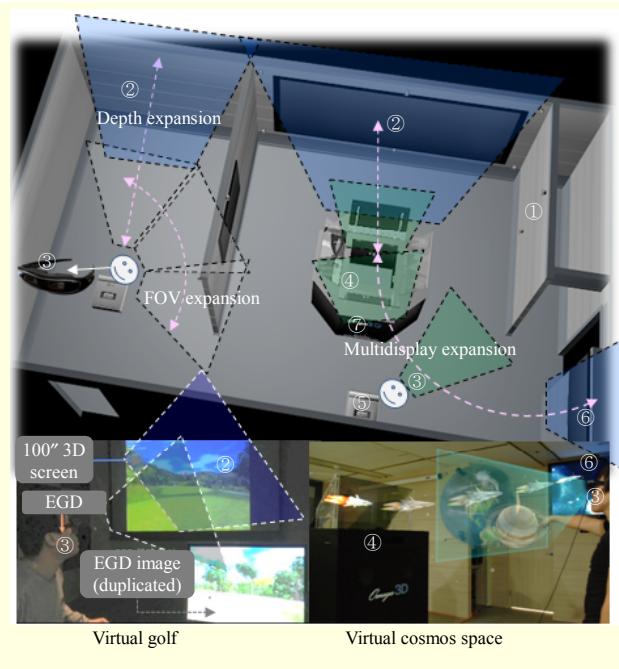


Fig. 4. Overview of pilot testing system.

display.

Figure 4 shows an overview of the pilot testing system to verify its feasibility. The entire demonstration space is tracked by a motion capture system (1). A virtual golf system is on the left side of the room, and the user can experience the expansion of the virtual fields in all directions over a limited region on the front projection screen (2) using an eyeglass display (EGD) (3). For example, in the case of short distance virtual golf putting, a player cannot see a virtual golf ball on the putting green with access only to a front projection screen display because the putting posture leads to a change in viewing direction. To overcome the viewing volume limitation, we duplicate the putting green scene for the user wearing an EGD. In addition, we build a mixed display environment with three or more homogeneous and heterogeneous display devices on the right side of the room, including auto-stereoscopic displays (4), for example, Omega3D quad-view [5] for concurrently participating users, an FDD with a 3D projector (for example, LG CF3D (5)), SDs (for example, 65'' LG 3DTVs (6)), a multimodal interaction system using Microsoft's Kinect (7) for a gesture interface, and a 24-channel-based real-time 3D sound effect system. In this scenario, there is a spaceship control that the user can use to move among visual volumes from various displays using natural gestures.

Figure 5 shows the first prototype of the EGD, which realizes view expansion scenarios in the E3D platform. The EGD is equipped with IR-LEDs for marker-based tracking, paired film-type patterned retarders (FPR) for stereoscopic viewing, a see-through optical system, a 34° FOV optical

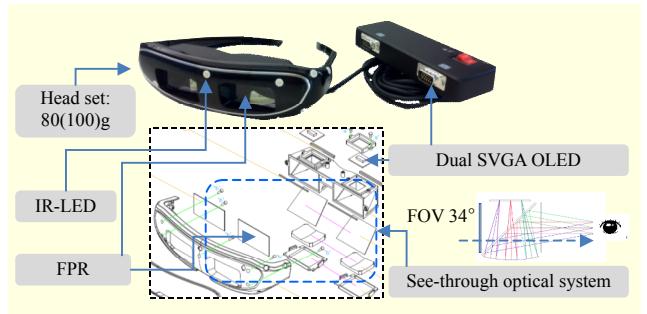


Fig. 5. EGD hardware for the E3D platform.

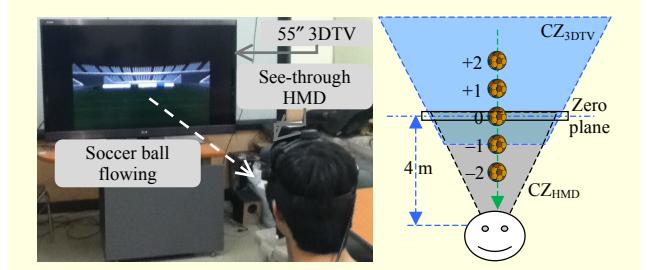


Fig. 6. Overview of pilot experimental environment.

system, and an SVGA OLED optical system for combining outside views.

We design a pilot test to verify a depth expansion scenario. The objective of the experiment is to verify how naturally the proposed system creates an expanded depth perception in a 3D stereoscopic environment.

To execute our experiment, we implement a virtual soccer stadium, as shown in Fig. 6. At the start of the experiment, a soccer ball flies in from the distance. Because the proposed E3D platform including the EGD is undergoing an upgrade (as shown in Fig. 5), we make use of a 55'' passive 3D HDTV and an optical see-through head-mounted display (HMD) with an FPR with an SVGA (800×600) resolution. At the beginning of the experiment, the ball is displayed only on a 55'' 3DTV (LG 55LW5700), and the display device for the ball switches to an optical see-through HMD (Trivisio LCD29) at a specific distance. The independent variable is the distance (-2 m, -1 m, 0 m, 1 m, and 2 m) based on the zero parallax plane, at which the display devices for the ball are switched.

When two or more stereoscopic devices are connected, their 3D stereo content should be systematically connected for visual expansion. To provide the viewer with a more natural stereoscopic perception, calibration processes between the 3D display devices and the viewer are required. Such calibration includes stereo rendering methods for each display device, and a visual adaptation process based on the relative position between viewers and the display devices. In general, toe-in and off-axis stereo rendering schemes have been widely applied to

**Algorithm** Multiple\_Devices\_Stereo\_Rendering.

**Input.** Physical position both an EGD-wearing viewer and a 3DTV  
**Output.** Projection matrix for EGD objects rendering

**Calibration Steps.**

- 1) Set the viewer and 3DTV on given distance (e.g. 4 meters).
- 2) Display pattern on HMD and 3DTV with the given distance (initially, the distance is zero).
- 3) Perform SPAAM calibration process and compute the projection matrix corresponding the distance value.
- 4) Repeat steps 2 and 3 with other distance values (e.g. -2, -1, 1, and 2).

**Rendering Steps.**

- 1) Render the virtual environment with zero distance on 3DTV.
- 2) Find the projection matrix for rendering a moving object on EGD.
- 2-1) Find the nearest two matrices corresponding to distances including the object's position.
- 2-2) Compute the adjusting matrix by distance weighted average.
- 3) Render HMD virtual objects with the computed adjusting matrix.
- 4) If object's position is changed, repeat steps 1, 2 and 3.

**Fig. 7.** Calibration and stereo rendering steps for EGD and 3DTV mixed display environment.

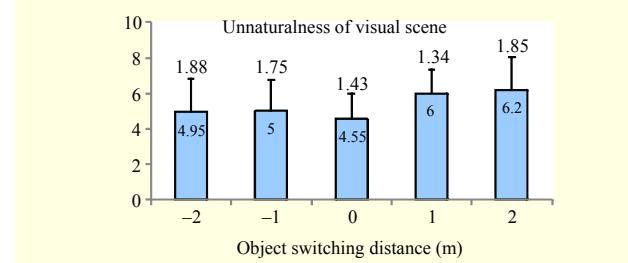
## 3D display devices.

The toe-in method is suitable for the stereo rendering of near-focused objects, and an off-axis method is applied to far and wide space stereo rendering. Taking advantage of each method, the toe-in method is used for the EGD, and the off-axis method is used for the 3DTV. The use of these heterogeneous rendering methods results in a matching error between the virtual objects on the EGD and 3DTV. To minimize this error, a modified visual calibration process from the conventional method, the single point active alignment method (SPAAM) [5], is used for our E3D system.

Figure 7 shows the calibration and rendering steps for the given EGD and 3DTV. All steps assume that the 3D physical location of the viewer and the display device are known through sensing. In the pilot environment, the calibration steps are also performed for only these five distance levels. By using the SPAAM algorithm, we can obtain computed projection matrices for each disparity level.

Seventeen males and three females participate in the pilot test. The average age of the subjects is 25. After the calibration process, the subjects watch five different visual pieces. The pieces are presented in random order to combat any bias that a participant might have from interacting with a subject who has already completed the experiment. After each viewing, the subject rates the unnaturalness of the visual piece on a scale of zero to 10, the rating being the dependent variable for each subject's analysis.

Figure 8 shows the average and standard deviation of the unnaturalness of the visual scene for the viewer at various distances. Through the statistical analysis, the ANOVA test shows that the unnaturalness of each of the five visual scenes is significantly different ( $F = 3.732, p < 0.007$ ), and the Tukey test results differ between group A (-2 m, -1 m, 0 m) and



**Fig. 8.** Unnaturalness of visual scene in pilot test.

group B (-2 m, -1 m, 1 m, 2 m). Considering the analysis results, we ascertain that the subjects experience the 3D content as being unnatural when switching devices at 1-m and 2-m distances much more than when doing so at the zero plane.

Although we conduct the pilot experiment without the complete platform environment proposed in our research, we can say that the results show the feasibility of our proposed technology and the necessity for the method to optimize the perception in an expanded 3D display platform based on a depth expansion scenario.

## IV. Conclusion

In this letter, to address the 3D visual space limitation of popular 3D display systems, we proposed an expanded 3D display platform using mixed devices and generated a feasibility test to verify the possibility of its realization. We have a plan to develop an upgraded EGD to satisfy our requirements and to study ergonomics to find the optimized parameter control methods to obtain natural viewing in our E3D platform.

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