Toward “KANDO” Creation with Immersive Visual Expression

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ABSTRACT

XR (AR/VR/MR) technology has been intensively studied in recent years. We expect they will enable an emotional experience with an unprecedented immersive expression. In this paper, we introduce and discuss our recent developments in XR display technology.

1 INTRODUCTION

Recent years have seen a growing interest in XR (Virtual Reality (VR)/Augmented Reality (AR)/Mixed Reality (MR)) display technology. They provide a new medium of visual expression that surpasses conventional flat panel displays to provide an immersive, sensory, and emotional (*“KANDO”* in Japanese) experience. In 1968, Ivan Sutherland developed the head-mounted display (HMD), which is used in VR today [1]. At present, applications of the headset to realistic games [2], entertainment, and education etc. have been advancing with its wide field of view (FOV) exceeded over 100°. Developed in 1992, Cruz-Neira *et al.*’s cave automatic virtual environment (CAVE) display system marks another milestone in the evolution of VR displays [3]. The CAVE is a surround-screen display system in which images are projected onto the walls of a room. Current applications of the CAVE include flight simulators and entertainment.

For AR applications, a see-through glass display, so-called AR glass, has been developed. It enables the superposition of display information and images in the real world. We developed AR glass using a hologram light guide plate system [4]. Recently developed headsets such as Microsoft's Hololens [5] and Magic Leap [6] enable a high degree of superimposition between real world objects and displayed images for MR. Their applications such as entertainment and design support have been actively discussed.

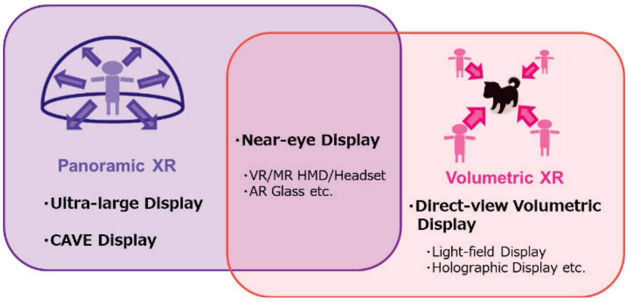

Fig. 1 Panoramic XR, volumetric XR experiences, and XR displays

Recent advances in volumetric capturing and photorealistic CG have led to 3D direct view displays such as a light field display, a holographic display, and the XR displays mentioned above.

The immersive, realistic experiences provided by these XR displays can be categorized into panoramic XR and volumetric XR experiences, as shown in Fig. 1. In this paper, we introduce and discuss our recent developments in XR displays in these categories.

2 KEY PARAMETERS OF XR DISPLAYS FOR ENHANCING IMMERSION AND SENSE OF PRESENCE

Fig. 2 shows key performance indicators for XR displays that are important for evoking the sense of presence and immersion. In the human eye, visual acuity is highest in the fovea on the retina, which corresponds to the center of the visual field at about 1° 20'. Visual acuity rapidly decreases around the fovea with a visual field of about 120° (temporal FOV). A resolution of over 8K is required to cover the field with a visual acuity of 1.0. Frame frequency becomes a parameter in the time resolution, and it affects factors such as motion blur and flicker. Kuroki *et al.* evaluated the frame frequency and dynamic response characteristics and determined that 240 Hz was the allowable limit [7].

The dynamic range of human vision is about eight digits and the present target for XR is to improve the range to six digits. Additionally, extension of the quantization of grayscale level to 10–12 bit has been discussed. Rich color is also important for an immersive experience; the current DCI-P3 standard is the standard for high-spec products and covers about 90% of Pointer’s colors in the natural color gamut, while the

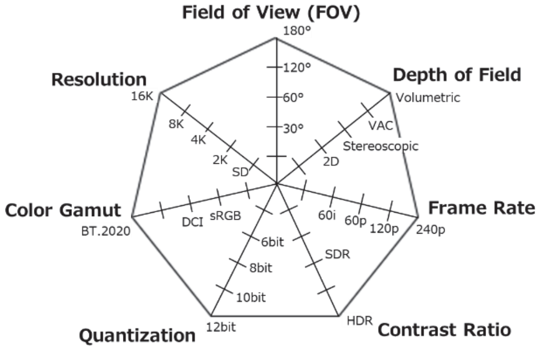

Fig. 2 Key performance indicators for XR displays

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new standard BT.2020 covers 99%. Emissive displays such as OELD and inorganic LED are suitable for these applications, and progress is being been made towards higher resolution. In order to enhance the sense of presence, stereoscopic or volumetric expression play an important role.

3 ULTRA-LARGE DISPLAY and CAVE DISPLAY

3.1 Ultra-Large Micro-LED Tiling Display System: Crystal LED Display System

Though resolution, contrast, and color gamut have been improved in LCD and OLED, a wider FOV for a direct-view experience is still in progress for these displays. It is difficult to fabricate a display larger than 130" due to constraints of mother glass size and manufacturing facilities. Though it is possible to attempt screen expansion by tiling LCD and OLED, seamless tiling is difficult because of edge sealing and bezels. The seams between the tiling panels interfere with the immersive sensation. On the other hand, an LED display is suitable for forming a seamless display larger than 100”. However, in the conventional LED display with packaged LEDs, the pixel pitch generally exceeds about 1 mm, which results in grainy images and degradation of black level due to external light reflected by the package.

To address these issues, recent advancements have been made in mini/micro LEDs and techniques for mass transfer directly onto a substrate. We introduced the Crystal LED Display, the first ever micro LED display, at the Consumer Electronics Show (CES) in 2012 [8]. Then, improvements to picture quality and tiling technology led to the recent development of the Crystal LED Display System, a scalable tiled display [9]. The features include a large, seamless screen, clear images without graininess, and high dynamic range. The use of micro LED minimizes the light emission area, so the black region covers 99% of the screen. This enables a true black display and rich gradation even at low luminance. The innovative active-matrix PWM driving circuit enables accurate color reproducibility over all gradations and a maximum luminance of 1000 cd/m^2. With a dynamic range of six digits and a large display area, the system provided an enhanced sense of presence and immersion.

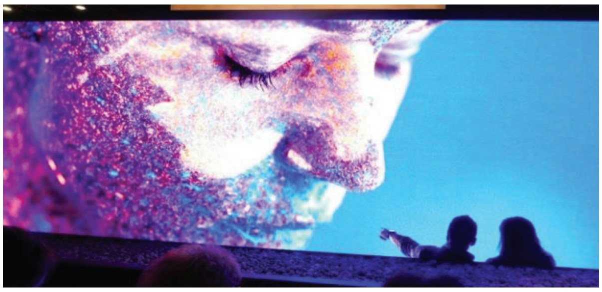

Fig. 3 Scalable tiled display system with Micro LED “Crystal LED Display System”

3.2 The CAVE Display System with 4K Ultrashort Throw Projector

As mentioned in the introduction, the CAVE is a surround-screen display system for VR. The conventional CAVE typically uses a long throw rear projector, so it requires a large space behind a screen to project images onto the screen. The resolution of the display used for the projector has not been sufficiently high, which detracts from the immersive feeling.

Sony developed an ultrashort throw projector using a 0.74” CMOS-driven reflective LCD (Silicon X-tal Reflective Display (SXRD)) with a 4K×2K resolution (8.85 million effective pixels) and 120 Hz frame rate [10]. This projector produced high-definition images and drastically reduced the space needed for projection. We also developed a laser-phosphor light source which attained high brightness as well as a wider color gamut (WCG) [11].

Fig. 4 shows our CAVE display system “Warp Square” with the 4K ultrashort throw projector. In addition to high resolution, high image contrast, WCG with 4K SXRD and our laser light source, and the ultrashort throw optical system, Sony developed the CAVE system which saves installation space and enhances the sense of presence and immersion. Various applications of this system such as entertainment, sightseeing, and education are under development.

Fig. 4 CAVE display system with 4K SXRD ultrashort throw projector “Warp Square”

4 NEAR-EYE DISPLAY

4.1 OLED Microdisplay

Most current commercialized VR HMDs use OLED displays driven by low-temperature poly-Si (LTPS) TFTs. OLED provides a heightened sense of presence due to its fast response and high image contrast. The standard resolution is around 440 ppi and 1K×1K pixels per eye, and higher-resolution products with about 800 ppi and 2K×2K pixels per eye are starting to appear in the market. Google has reportedly developed a prototype with 1443 ppi and 4.8 K×3.8 K pixels [12].

OLED microdisplays driven by CMOS transistors have been progressing in order to increase resolution. We developed a 0.5” 4032-ppi OLED microdisplay with a pixel size of 6.3 μm and 1.6 K×1.2 K pixels (see Fig. 5) [13]. A high image contrast ratio of over 100,000:1 and a 240-Hz frame rate were attained. Further development of higher definition and larger pixel number will lead to a compact and ultra-high definition VR HMD with an increased sense of presence and immersion.

Fig. 5 0.5” 4032-ppi OLED microdisplay with 6.3-μm pixel size and 1.6 K×1.2 K pixels

4.2 Waveguide AR Glass

In 2008, we demonstrated a see-through AR glass with a light waveguide [4], which was subsequently launched into the market in 2012. In 2015, a further miniaturized, lighter weight and brighter Smart Eyeglass was created for developers [14]. An LCD system with an LED light source was implemented as an optical engine, and a holographic optical element (HOE) with a high-diffraction efficiency photopolymer was developed on a glass substrate. In addition to its natural glasses design, a light waveguide thickness of 3 mm and 98% transmittance were attained.

In 2018, the first full-color AR glass with a plastic substrate was developed, as shown in Fig. 6 [15]. The weight was reduced with higher impact resistance and the degree of freedom was increased for the glass design.

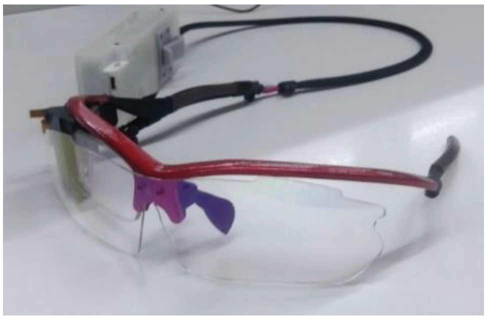

Fig. 6 Prototype of full-color AR glass with HOE waveguide on a plastic substrate

4.3 Retinal Scan Near-Eye Display

In order for a varifocal system to effectively superimpose display information and a real object at an arbitrary distance, a complex optical system that solves the vergence-accommodation conflict (VAC) is needed. Instead of the varifocal approach, we have developed a Maxwellian view near-eye display, or a retinal scan near-eye display, which always presents images in focus regardless of the focal length of the eye. Its advantages include higher brightness and low power consumption. A compact full-color retinal scan near-eye display with a laser-beam scanning (LBS) projector was developed, as shown in Fig. 7 [16]. The integration of a MEMS mirror and RGB laser light source minimizes the size of the LBS projector. The unique relay optical system uses a novel holographic grating to compensate for the color dispersion of the holographic image combiner in front of the eye. A high resolution (1280×720p), wide FOV (47° diagonal), high transparency (over 85%), and handheld miniaturization were all attained.

Fig. 7 Prototype of full-color laser beam scanning based retinal scan near-eye display and image displayed through the prototype

5 TOWARD DIRECT-VIEW VOLUMETRIC DISPLAY

5.1 Eye-Sensing Light Field Display

The co-existence of a wide-viewing angle and high resolution is one of the main issues in a light field display, because, in a conventional approach, multiple display pixels need to be consumed for a single image pixel to increase the number of viewpoints, lowering the image resolution as a result. One possible solution is eye-tracking the delivery of a light field image with respect to the position of a user. We have developed eye-sensing technology with a high-speed vision sensor, real-time light field rendering technology, and a 15” display glass-free volumetric monitor with a 4K HDR LCD panel and micro optical lens. By integrating these components, we successfully developed a prototype of the eye-sensing light field display revealed at CES 2020 and InfoComm 2020, as shown in Fig. 8 [17]. The prototype shows a high-resolution stereoscopic image with precise motion parallax, from which the user can feel a sense of presence of the displayed objects.

Fig. 8 Prototype of the eye-sensing light field display

6 360-degree Transparent Holographic Screen Display

In order to maximize the display's FOV and enhance the sense of presence of virtual objects in a real environment, we have developed a 360-degree transparent holographic screen display, real-time sensing of an observer's position using multiple high-speed cameras, and real-time image rendering to express a motion parallax effect [18]. The display consists of a transparent cylindrical HOE screen and a projector that shows 2D images on the screen from the inside of the cylinder. The fusion of the real-space background and the virtual image on the cylindrical transparent screen enhances the floating sensation of the image. Integrating this feature with real-time motion parallax results in a visual illusion that enhances the sense of presence in the cylinder (see Fig. 9).

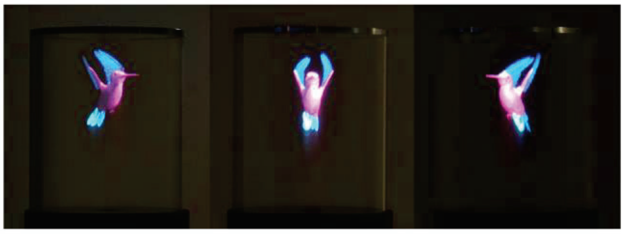

Fig. 9 Prototype of 360-degree transparent holographic screen display

7 SUMMARY

In this paper, we discussed categorization and key performance parameters of XR displays and introduced our recent developments in XR displays. Though VR/AR displays have been thoroughly investigated over the years, it was not until recently that they became popularized. XR technology has been rapidly evolving, with improvements in image quality, FOV and volumetric displays, sensing technology with high speed vision sensors, revolutionary image processing by GPU/DNN, and 5G high-speed data transmission. The popularization of XR is imminent, with growing demand for immersive experiences and various new applications of XR technology, including entertainment, design, education, sports, healthcare, medical treatment, architecture and automatic operation.

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