HDR VR

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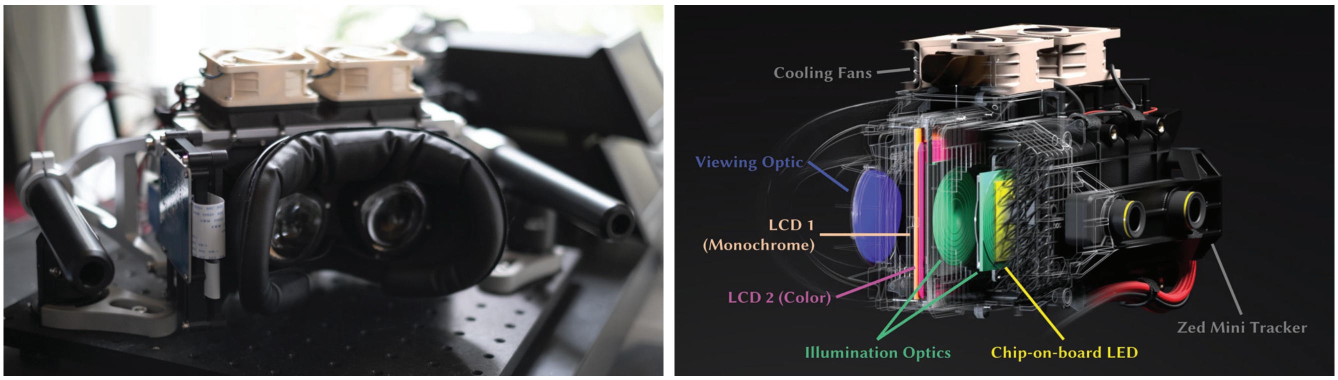


Figure 1: *Left:* Our prototype high-dynamic-range VR demonstrator. *Right:* A cutaway view showing the display stack. A chip-on-board LED's emission cone is shaped by a pair of Fresnel lenses to illuminate color and monochrome LCDs stacked in series, which are imaged by the eyepiece.

ABSTRACT

The human visual system operating in natural conditions can resolve luminance values that range from over a million candelas per meter squared (nits) to near zero, and is able to simultaneously resolve over 4 orders of magnitude without adaptation [Kunkel and Reinhard 2010]. While most traditional displays can only replicate a fraction of the smaller simultaneous range, high-dynamic-range (HDR) displays aim to support luminance and contrast ranges closer to perceptual limits [Reinhard et al. 2010]. HDR displays have achieved widespread commercial success across cinema, home theater, and personal use devices, but this popular technique remains largely unexplored in the context of Virtual Reality (VR) displays, typically limited to peak luminance values near 100 nits [Mehrfard et al. 2019]. The perceptual impact of HDR on the unique mix of controlled ambient, wide field-of-view, viewing optics, and immersive presentation typical of VR displays is largely unexplored.

To address this, we present a high-dynamic-range virtual reality demonstrator with a display system comprised entirely of off-the-shelf parts, capable of peak luminances over 16,000 nits. We achieve this without reducing the field of view (FOV) or simultaneous contrast relative to commercially-available VR headsets. Furthermore, HDR demos in excess of 1,000 nits that support binocular and motion parallax depth cues have not been widely seen by our community. Consequently, our prototype has the potential to achieve a higher degree of perceptual realism than existing direct-view devices like HDR televisions and other high-luminance prototypes.

1 DISPLAY ASSEMBLY

We designed our display with the following targets in mind:

- Exceed 10,000 nits peak luminance
- Match existing VR FOV, resolution, contrast, and framerate
- Support interactive stereoscopic content with 6 degree-of-freedom tracking

We followed existing VR architectures while relaxing power, thermal, and weight limits. See Figure 1 for a photograph and cutaway view of the key headset components, which include:

Backlight: We use one Lighten Phoenix LTHX1212-060-005 chip-on-board phosphor LED for each eye, driven by a Thorlabs DC2200 LED power supply. Each LED is followed by an Edmund Optics 13-457 f=10mm Fresnel lens, a 28mm air gap, and finally an Edmund Optics 43-024 f=38.1mm Fresnel lens to steer the emission cone toward the display eyebox.

Modulation: Following the work of Seetzen et al. [2004], we employ a dual-modulation approach using liquid crystal displays (LCD). Due to the low efficiency and potential for color moiré patterns when using two color LCDs, we use one color and one monochrome LCD. Until recently, transmissive LCDs were uncommon, requiring the disassembly of displays with integrated backlights [Rhodes et al. 2019]. The rise in popularity of desktop resin 3D printers has led to the widespread availability of high resolution, high contrast transmissive displays. We use a Wisecoco 6" 1620×2560 monochrome display, and a Sharp LS060R1SX02 6" 1440×2560 transmissive color display.

Viewing Optics: We used viewing optics from a commercially available Meta Quest 2 headset to achieve a ~90 degree field of view. The monochrome LCD is placed at the eyepiece's focal length, with a virtual image conjugate at infinity. The color display is imaged beyond infinity to help reduce moiré effects induced by the two pixel grids.

Thermal Management: The primary challenge for such a configuration is heat. Both LCDs have an operating temperature below 60 degrees Celsius, above which the liquid crystals remain in an isotropic state regardless of the electric field and cannot display an image. We employ a pair of 60mm fans to draw cool air from below the headset across the front and back of the LCD stack and a sintered metal heat sink for the LED backlights before exiting the top of the headset.

Tracking: A Zed Mini tracking camera is affixed to the front of the headset to provide tracking.

2 SOFTWARE

Dual-layer HDR decompositions often require a deconvolution step to correct the mismatch in optical resolutions of the two layers, which is particularly important for the local dimming arrays commonly found in HDR televisions. In our case, the circle of confusion for a point on the rear color LCD has a footprint of 1.75 pixels on the front monochrome LCD. Because of this small size and the lower sensitivity of the human visual system to color contrast [Kim et al. 2013], we use a simple factorization without deconvolution. The target color image $\left[I_r^*, I_g^*, I_b^*\right]$ is normalized to the floating point intensity range [0,1]. A square-root monochrome image I_m is calculated using Rec709 color coefficients C_r, C_g, and C_b:

$$I_m = \sqrt{C_r I_r^* + C_g I_g^* + C_b I_b^*} \tag{1}$$

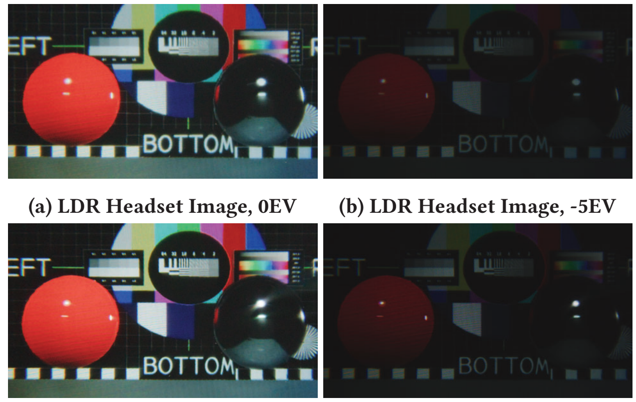
Then, the color component I_c is extracted using a naive factorization:

$$I_c = \begin{cases} \left[\frac{I_r^*}{I_m}, \frac{I_g^*}{I_m}, \frac{I_b^*}{I_m}\right], & \text{if } I_m > 0 \\ \left[0, 0, 0, \right], & \text{otherwise} \end{cases} \tag{2}$$

This process is implemented as a post-processing shader in Unity. The Zed tracking Unity integration provides 6 degree-of-freedom tracking. The headset is connected via two HDMI cables to an NVIDIA RTX 3090 GPU in a desktop PC. The headset runs in real time at the 50Hz native refresh rate of the two LCDs.

3 RESULTS

We measured the peak brightness and dynamic range of the headset using a Konica Minolta CS-2000A spectroradiometer with a VR lens attachment. The peak brightness, sampled in the center, was measured at 16632 nits. The dark state was measured at 0.05 nits, for a sequential contrast ratio of 332640:1. Instantaneous contrast was estimated by capturing a checkerboard pattern and its complement, with the pattern aligned and scaled so that the integration region of the luminance meter was closely circumscribed by one of the checker squares. This contrast ratio was measured at 39:1, and is limited by the Fresnel viewing optic.



(a) LDR Headset Image, 0EV **(b) LDR Headset Image, -5EV**

(c) HDR Headset Image, 0EV **(d) HDR Headset Image, -5EV**

Figure 2: Through-the-lens captures of our prototype headset showing a synthetic scene illuminated with a captured HDR light probe. *Top Row:* The headset operating in low dynamic range mode. Luminance values are clipped to 100 nits. *Bottom Row:* An equivalent capture when operating at full dynamic range. The right image in both rows is adjusted down 5 stops to show how specular highlights are preserved in HDR mode.

Figure 2 depicts the headset in operation using a target HDR virtual scene created in Unity using the real-time decomposition described in Section 2. The top row shows a low dynamic range operational mode where output luminances are clipped at 100 nits. The bottom row shows the full dynamic range of the headset. The right-hand column in Figure 2 shows the view through the lens with a 5 stop digital reduction in exposure[1]. Note how the specular highlights in the low dynamic range mode are clipped, whereas they are preserved in the HDR mode. This additional visual information (which is best observed in person) supports the wider range of luminance that we target with this demonstrator. Refer to our supplementary video to view these images in motion.

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[1]These images were captured using a Red Komodo and Sigma EX DG fisheye lens at f/3.5, 320 iso, and 41 millisecond exposure time.