Retinal-Resolution Varifocal VR

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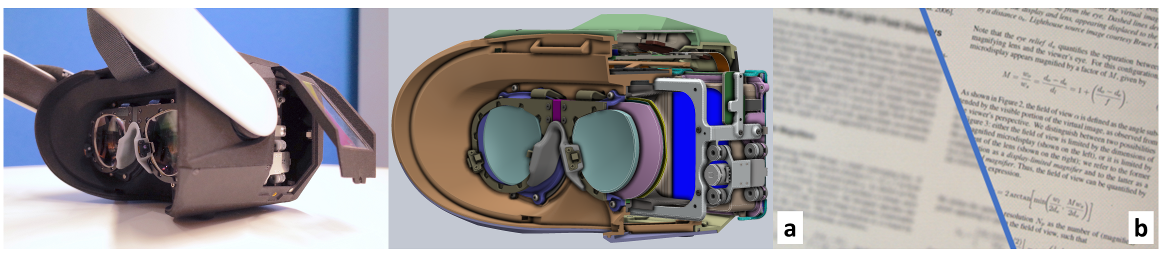

Figure 1: Left: We present a high-resolution varifocal VR headset. Middle: Our prototype is based on a refractive-diffractive hybrid lens design and a mechanically actuated varifocal architecture. Right: Through-the-lens photos of text close to the user (0.3 m) in VR with varifocal displays disabled (a), and enabled (b). Note that resolution in (b) is limited by the capturing camera.

ABSTRACT

We develop a virtual reality (VR) head-mounted display (HMD) that achieves near retinal resolution with an angular pixel density up to 56 pixels per degree (PPD), supporting a wide range of eye accommodation from 0 to 4 diopter (i.e. infinity to 25 cm), and matching the dynamics of eye accommodation with at least 10 diopter/s peak velocity and 100 diopter/s^2 acceleration. This system includes a high-resolution optical design, a mechanically actuated, eye-tracked varifocal display that follows the user's vergence point, and a closed-loop display distortion rendering pipeline that ensures VR content remains correct in perspective despite the varying display magnification. To our knowledge, this work is the first VR HMD prototype that approaches retinal resolution and fully supports human eye accommodation in range and dynamics. We present this installation to exhibit the visual benefits of varifocal displays, particularly for high-resolution, near-field interaction tasks, such as reading text and working with 3D models in VR.

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1 INTRODUCTION

Visual acuity near the fovea for normal human eyes is equivalent to 1 arcminute angular resolution, or about 60 PPD. The average human eye can also accommodate to different object distances, ranging from infinitely far to about 25 cm (0 diopter to 4 diopter) for a non-presbyopic user. In contrast, current mainstream VR systems feature less than 30 PPD, and their fixed-focus displays offer no range of accommodation for different virtual object distances.

This limited resolution in VR impairs the viewing quality of fine details. Moreover, fixed-focus HMDs cause a mismatch between the user's vergence (where eyes are pointed) and accommodation (where eyes are focused) for content away from the virtual display plane, an issue known as the vergence-accommodation conflict (VAC). This causes nearby content to appear blurry and leads to discomfort and fatigue over time [Kim et al. 2014]. Also, performance in near-field tasks, such as reading text, may be impacted under the compromised resolution in fixed-focus VR headsets [Hoffman et al. 2008]. Several approaches to mitigate VAC in near-eye displays, including varifocal displays, have been studied [Kramida 2016], and demonstrated [Akşit et al. 2017; Dunn et al. 2017].

To pursue the optimal viewing clarity in VR, we present a nearly retinal-resolution varifocal VR display system that provides up to 56 PPD resolution, closely matching the foveal resolution on human retina. The prototype supports an accommodation range of 4 diopter, at peak velocity over 10 diopter/s and acceleration over 100 diopter/s^2, covering the range and dynamics [Bharadwaj and Schor 2005] of the eye accommodation. To our knowledge, this is the highest resolution varifocal HMD ever presented, and the first to highlight the advantages of varifocal displays for tasks where the full resolution of the human visual system is necessary.

2 HEADSET COMPONENTS

2.1 Optical System

We use liquid crystal display (LCD) panels in 3.2-inch format with 2880 by 2880 pixels to drastically increase the display resolution compared to current common HMDs. Paired with the viewing lens, the display achieves on-axis angular pixel density of 56 PPD and 53° horizontal and vertical field of view (FOV) at 0.5 diopter virtual image distance. The viewing lens includes two glass lens elements made of material with high refractive index ($n_d = 1.88$) to mitigate monochromatic aberrations. We also use a liquid crystal diffractive lens to correct for in-band lateral chromatic aberration, optimizing the viewing lens' modulation transfer function (MTF) off-axis. The resulting lens design supports the Nyquist spatial frequency corresponding to the display pixel pitch with MTF greater than 0.8 on-axis, and 0.3 off-axis. The lens elements are custom-made with anti-reflection coatings on all surfaces to enhance the contrast.

2.2 Mechanical Actuation

Each eye's display is equipped with an actuation system to alter its depth position. Stepper motors with leadscrews provide the linear motion, paired with crossed roller bearing slides as the guidance mechanism. The position of each display is measured by interpreting quadrature signals from a magnetic encoder. The motors are attached through elastomeric dampers to reduce vibrations. A closed-loop PID control scheme is tuned for smooth and quiet translation between display positions. The headset also features removable transparent panels on the sides of the body for external viewers to witness the varifocal displays' actuation (Figure 1).

2.3 Eye and Head Tracking

The headset is tracked with six degrees of freedom through Constellation Tracking by Rift sensors capturing infrared optical signals from the headset. A camera-based eye tracker provided by Tobii is tightly integrated into the headset with an effort to minimize the air gap between the viewing lens and the eye tracking module, in order to reduce the eye relief without hindering the eye tracking performance. The gaze estimation is based on the eye tracking signal, then used as the input to mechanical actuation.

2.4 Software

The PID control parameters are set so that the display panel is constantly driven to be in focus to the user. The moving displays cause the system magnification and image distortion to change dynamically. Our rendering framework adjusts the image distortion correction depending on the display position. This allows the viewed content to stably appear world-locked in constant scale. Since the user's eye pupil position also affects the image distortion by changing the optical path (pupil swim), the software adjusts the distortion correction based on the user's pupil position, as reported by the eye tracker. Our distortion pipeline utilizes the Light Field Portal approach presented by Guan et al.[2022] to update the distortion in real time. The headset is tethered to a PC to ensure reliable rendering to the high-resolution binocular displays at 90 Hz.

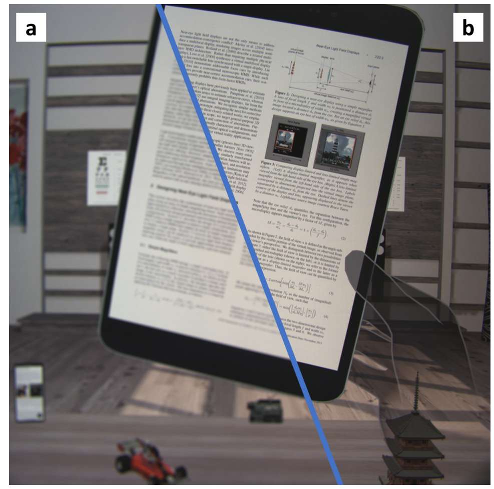

Figure 2: Through-the-lens photos of our VR demo, which includes various objects that users can interact with using Touch controllers. The user can trigger direct comparison of the varifocal functionality being disabled (a) and enabled (b) as shown for a tablet at 0.3 m from the user. Note that resolution in (b) is limited by the capturing camera. See the supplementary video for more details about the demo.

3 DEMO EXPERIENCE

Our installation presents two copies of the same retinal-resolution varifocal headset. After a brief eye tracking calibration, the seated user is placed in a virtual room decorated with high-resolution assets. The scene also includes a collection of objects that feature fine text and detailed geometries. The user can hold any object using a set of Touch controllers and examine them at close range (Figure 2). Users can also trigger the comparison between fixed-focus and varifocal displays to highlight the necessity of addressing VAC to support sharp details when viewing content at near distances in VR. Our installation also features an exploded model of our prototype for visitors to examine the hardware components in detail.

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