Verifocal: a Platform for Vision Correction and Accommodation in Head-Mounted Displays

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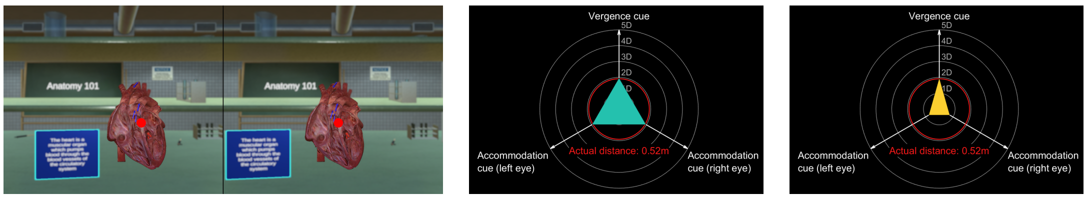

Figure 1: In a dynamic VR scene with eye tracking (left), the proposed varifocal platform generates accommodation cues consistent with vergence (middle). This eliminates the vergence-accommodation conflict common in standard headsets (right).

ABSTRACT

The vergence-accommodation conflict is a fundamental cause of discomfort in today's Virtual and Augmented Reality (VR/AR). We present a novel software platform and hardware for varifocal head-mounted displays (HMDs) to generate consistent accommodation cues and account for the user's prescription. We investigate multiple varifocal optical systems and propose the world's first varifocal mobile HMD based on Alvarez lenses. We also introduce a varifocal rendering pipeline, which corrects for distortion introduced by the optical focus adjustment, approximates retinal blur, incorporates eye tracking and leverages on rendered content to correct noisy eye tracking results. We demonstrate the platform running in compact VR headsets and present initial results in video pass-through AR.

CCS CONCEPTS

•Computing methodologies →Virtual reality; Perception;

KEYWORDS

varifocal, vision correction, vergence-accommodation conflict

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1 INTRODUCTION

Vergence and accommodation are important oculomotor cues which help perceive environments in three dimensions and are naturally coupled in human vision. However, standard head-mounted displays (HMDs) are focused at a fixed distance and do not lead the user's eyes to accommodate. This results in a sensory conflict known as the vergence-accommodation conflict, which has been shown to contribute to distorted depth perception, visual fatigue and general discomfort, especially when using such displays over long periods [Hoffman et al. 2008; Vienne et al. 2014].

Varifocal approaches mitigate this vergence-accommodation conflict by dynamically adjusting the optical focus inside a HMD. Recent research has explored the use of varifocal optical systems, such as mechanically actuated or electronically-tunable lenses. We compare solutions to achieve a compact form factor, large field of view (FoV), wide range of focus adjustment, and fast refocusing speed to induce natural accommodation.

We present a novel software platform for generating accommodation cues and correcting the user's refractive errors (e.g. myopia or presbyopia), coupled with multiple varifocal optical systems integrated into compact VR headsets. This allows us to evaluate the advantages and tradeoffs of such systems in terms of FoV, latency and comfort level, as an an important step toward building commercially viable varifocal systems for VR and AR. In addition to these system contributions, we make the following specific contributions:

- We propose the world's first varifocal mobile VR headset based on Alvarez lenses [Alvarez 1967];
- We describe a novel varifocal rendering pipeline which incorporates eye tracking, dynamically estimates the optimal focus, approximates retinal blur, and corrects for varifocal distortion introduced by the optical focus adjustment;
- We present a content-aware method for estimating the depth observed by the user, which can handle noisy eye tracking results without requiring access to the depth buffer or content-level integration, and can be applied in both VR and AR.

2 RELATED WORK

The vergence-accommodation conflict is extensively reviewed in [Hua 2017; Kramida 2016]. Existing varifocal approaches use the

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Figure 2: We propose the world's first varifocal mobile headset based on Alvarez lenses (left). We adjust focus by shifting Alvarez elements laterally, creating spherical power (right).

eye fixation point to adjust the focal distance of single plane displays, but suffer from a small field-of-view when using electronically tunable lenses [Konrad et al. 2016; Koulieris et al. 2017]. Other approaches rely on mechanically actuated or deformable optical elements to offer a wider FoV, at the expense of a large form factor [Aksit et al. 2017; Dunn et al. 2017; Padmanaban et al. 2017]. In [Laffont and Hasnain 2017], we showed an integrated VR system with independent dynamic adjustment of focus for each eye.

However, these methods require to have direct access to the depth buffer of the virtual scene renderer or game engine (e.g. Unity or Unreal) in order to know the depth of the object observed by the user. This implies that they are platform-dependent and limited to VR only. In contrast, the proposed approach enables adaptive dynamic refocusing for both VR and AR without requiring content-level integration, allowing the use of broader content.

Furthermore, many of previous approaches assume the viewer's eyes are aligned with the display system (e.g. on the lens optical axis) and do not handle deviations from those positions, or neglect distortions caused by the focus change of the varifocal system. The proposed approach addresses both limitations simultaneously, eliminating artifacts commonly associated with varifocal systems.

3 OUR SYSTEM

Our varifocal rendering pipeline introduces three key components into the VR rendering pipeline, as illustrated on Fig. 3.

Dynamic focus estimation. We estimate the depth of the observed object using the user's gaze direction determined through eye tracking. Rather than directly using the vergence obtained from two monocular gaze directions, we constrain the point-of-regard to lie on a surface of the scene, which is determined by analyzing the stereoscopic images rendered on the GPU and transmitted to the display. This helps handling the noisy input from any image-based eye tracker, and does not require direct access to the depth buffer or content. In addition, the dynamic focus estimation module combines the estimated observed distance with the user's eyeglasses prescription, leading to an optimized focus distance that enables a sharp and comfortable viewing experience without eyeglasses.

Focus adjustment. A closed-loop **adaptive optics** system adjusts the focus based on the output of the dynamic focus estimation module. We compared four types of varifocal optical systems:

- a standard lens mechanically actuated along its axis, in a telescopic manner similar to [Laffont and Hasnain 2017];
- a moving display, actuated to adjust its distance to the lenses;

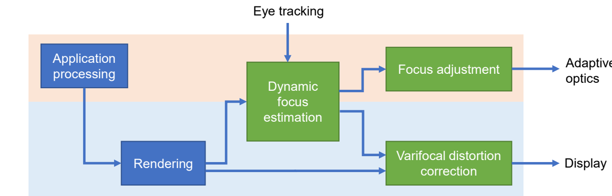

Figure 3: Overview of our varifocal rendering pipeline. The dynamic focus estimation module uses the eye tracker output and stereo images rendered on the GPU to estimate an optimal focus distance, also considering user's prescription. This distance is used to drive focus adjustment of the adaptive optics. In parallel, varifocal distortion correction is applied to the rendering output, compensating for magnification and apparent translation introduced by a focus change.

- an electronically-tunable lens Optotune EL-16-40-TC-VIS-5D, which enables fast focus adjustment but results in a small FoV;
- a pair of Alvarez-like lens elements placed in front of a standard VR eyepiece [Stevens et al. 2018]; the Alvarez-like elements are mechanically actuated such that a relative lateral shift of its two elements introduces a spherical power change (Fig. 2).

We demonstrate the use of Alvarez lenses in a varifocal platform for solving the vergence-accommodation conflict. This novel varifocal system provides several key advantages, such as a large FoV that does not change with focus adjustment, a compact form-factor, and it may be integrated as a simple add-on to existing headsets.

Varifocal distortion correction. A common artifact in varifocal systems is the distortion introduced by the change in focus. We synchronously modify the stereo rendering on the GPU to correct the distortion, thus preserving the size and position of the apparent image. In addition, we apply gaze-contingent depth-of-field blur to approximate retinal blur, on platforms with sufficient computational resources (e.g. with tethered VR headsets).

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