An Affordable Solution for Binocular Eye Tracking and Calibration in Head-mounted Displays

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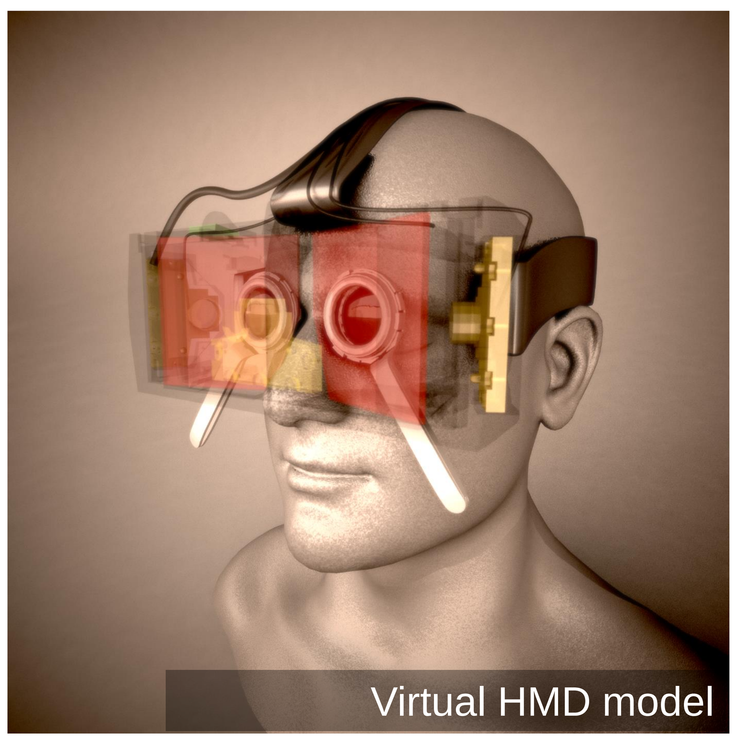
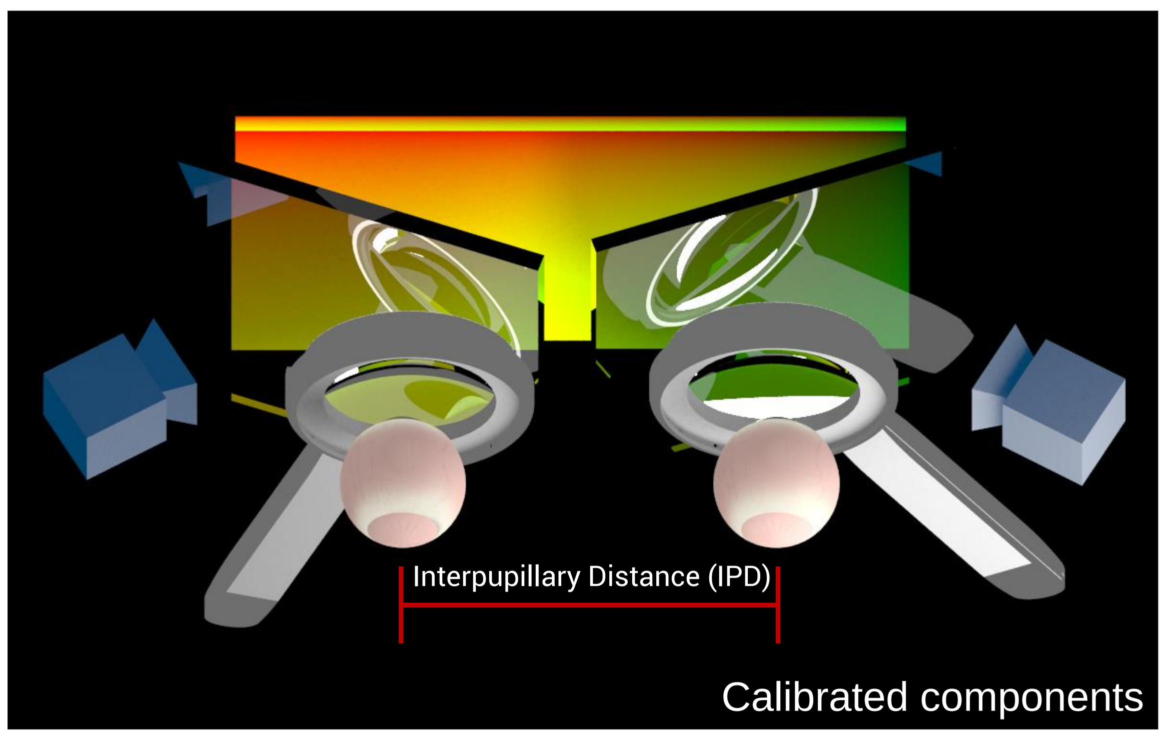


Virtual HMD model

Fig. 1

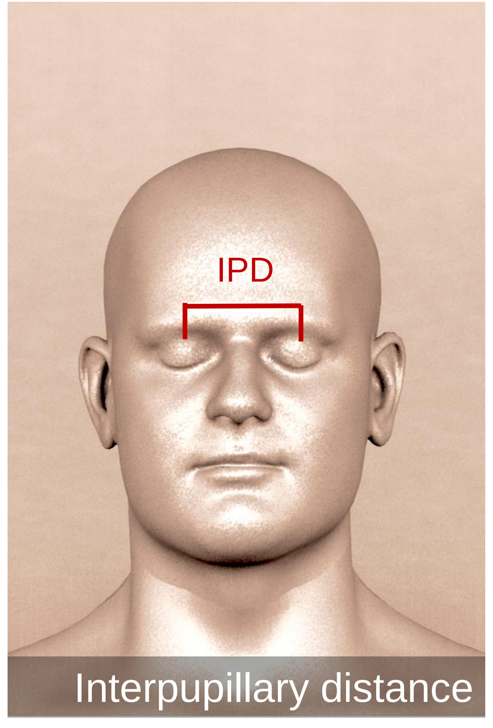
User with HMD prototype

Fig. 2



Calibrated components

Fig. 3



Interpupillary distance

Fig. 4

Motivation

Immersion is the ultimate goal of head-mounted displays (HMD) for Virtual Reality (VR) in order to produce a convincing user experience. Two important aspects in this context are motion sickness, often due to imprecise calibration, and the integration of a reliable eye tracking. We propose an affordable hard- and software solution for drift-free eye-tracking and user-friendly lens calibration within an HMD. The use of dichroic mirrors leads to a lean design that provides the full field-of-view (FOV) while using commodity cameras for eye tracking. Our prototype supports personalizable lens positioning to accommodate for different interocular distances. On the software side, a model-based calibration procedure adjusts the eye tracking system and gaze estimation to varying lens positions. Challenges such as partial occlusions due to the lens holders and eye lids are handled by a novel robust monocular pupil-tracking approach. We present four applications of our work: Gaze map estimation, foveated rendering for depth of field, adaptive level-of-detail, and gaze control of virtual avatars.

Our eye tracking solution

- offers robust and fast binocular eye-tracking for HMDs,
- enables efficient user calibration and IPD estimation,
- is inexpensive and compatible with current lens-based HMD designs,
- enables gaze-contingent rendering by low-latency tracking (**12 to 17 ms**),
- extends the applicability of HMDs in a large variety of use cases for researchers and customers.

Technical Description and Specification

The body of the HMD contains two biconvex convergence lenses and a screen allowing 100° field of view. All basic parts of the body can be printed using a 3d printer at low costs. For binocular eye tracking the body is extended by a tracking unit for each eye. Each unit consists of a dichroic mirror (hot mirror), a low-latency tracking camera and a circular illumination system for the iris area using infrared light.

The surface of the dichroic mirror transmits the visible spectrum of light and reflects in the infrared part. The infrared light is generated by LEDs, reflected on the surface of the eye, then reflected on the mirror and finally received by the eye tracking camera sensor. The user perceives the visible light only generated by the display and transmitted through the mirror and the lens to the eye. For accurate and robust gaze estimation we implemented a robust and fast pupil tracking algorithm. The low-cost cameras for eye tracking used in the current prototype work at a resolution of 640x480@75Hz. The weight overhead caused by the eye tracker is about 126 g.

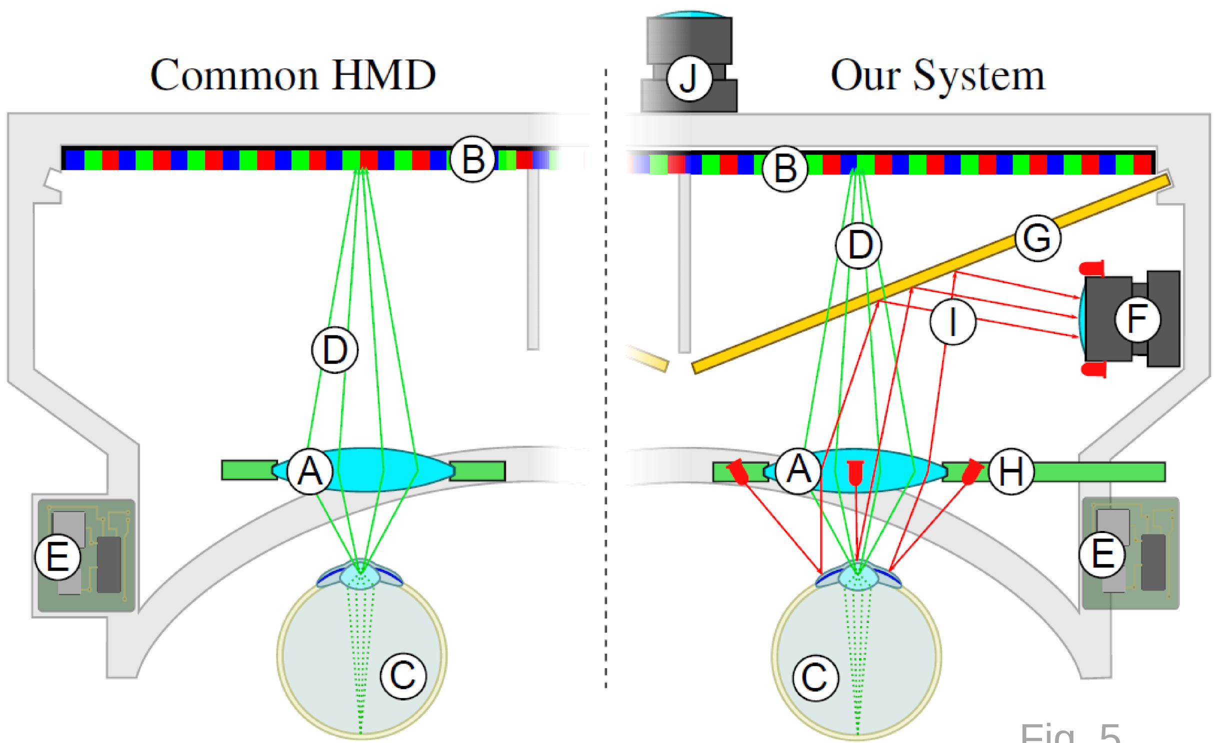


Fig. 5

<u>Hardware components</u>

- converging lenses (A)
- screen (B)
- human eyes (C)
- visible light (D)
- orientation tracker (E)
- eye tracking cameras (F)
- dichroic mirrors (G)
- LED arrays (H)
- infrared light (I)

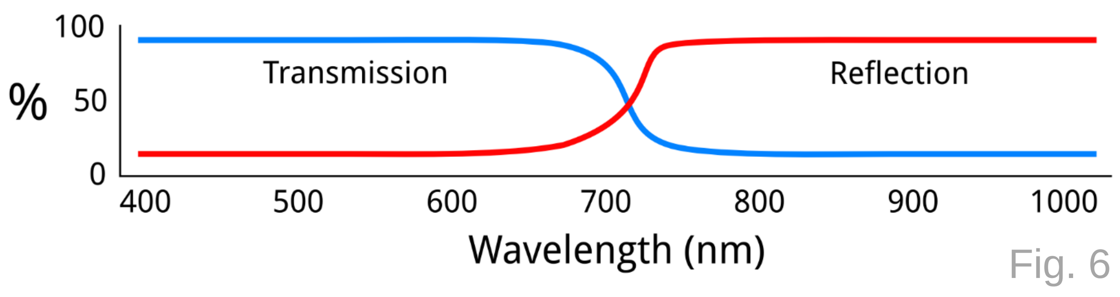


Fig. 6

<u>Dichroic mirror</u>

Visible light for the user (blue) is transmitted, while infrared light (red) is reflected which is only visible for the eye tracking camera.

Gaze Tracking Model

We provide a simple yet efficient user calibration exploiting the visible glints on the pupil and cornea (Fig.7). The glints are created by infrared light emitted from the illumination units (Fig.5,H). For real-time gaze estimation, we then perform a mapping from pupil positions in the eye-tracking camera to screen positions. We rely on our calibrated virtual HMD model (Fig.3) and estimated eye positions. We compute the light path from a pixel, representing a detected pupil center, of the eye-tracking image over the dichroic mirrors, through the lens towards the eye. By construction, this ray has to cross the eye at the pupil center (Fig.5 red light paths). We can, thus, map eye-tracking camera pixels to an eye rotation. Similarly, the eye rotation can be used to determine a screen position by computing the light path from the eye through the lenses onto the screen (Fig.5 green light paths). This mapping is precomputed for approximately 1300 virtual eye rotations per eye covering the full motion range of the human eye.

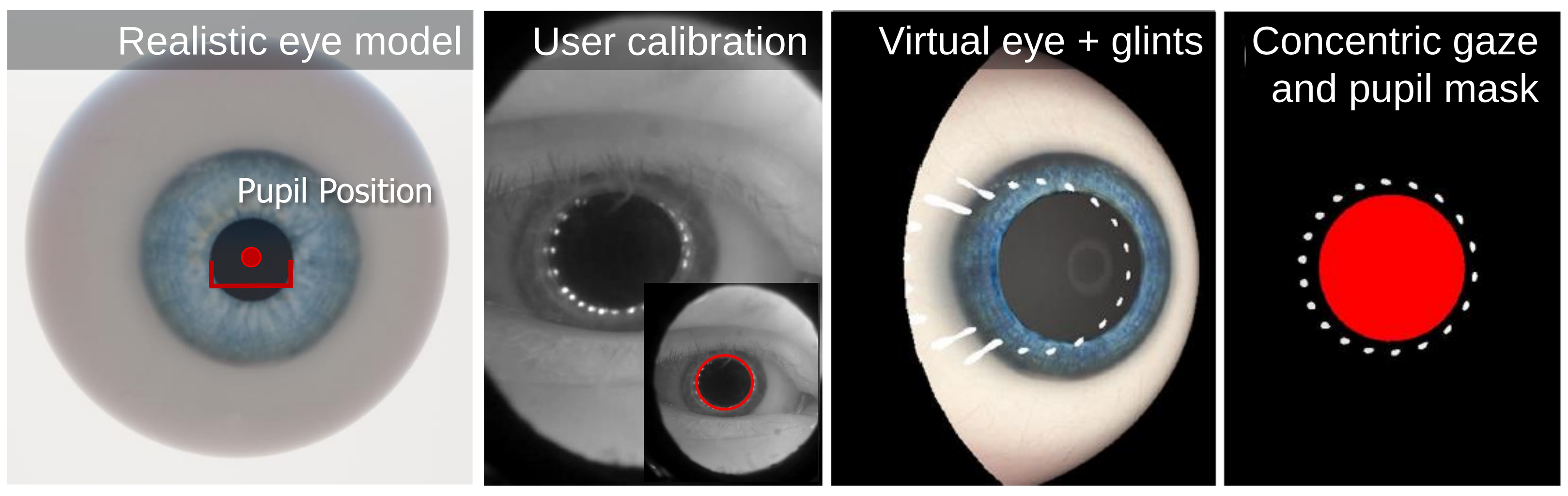


Fig. 7

Applications

- Efficient user calibration with interpupillary distance estimation
- Gaze-contingent rendering (foveal region, depth of field, adaptive HDR)
- Enhanced immersion and presence, gaze-controlled avatars
- Other fields: adaptive visualization, cognitive applications, assistive technologies, user studies, mobile applications

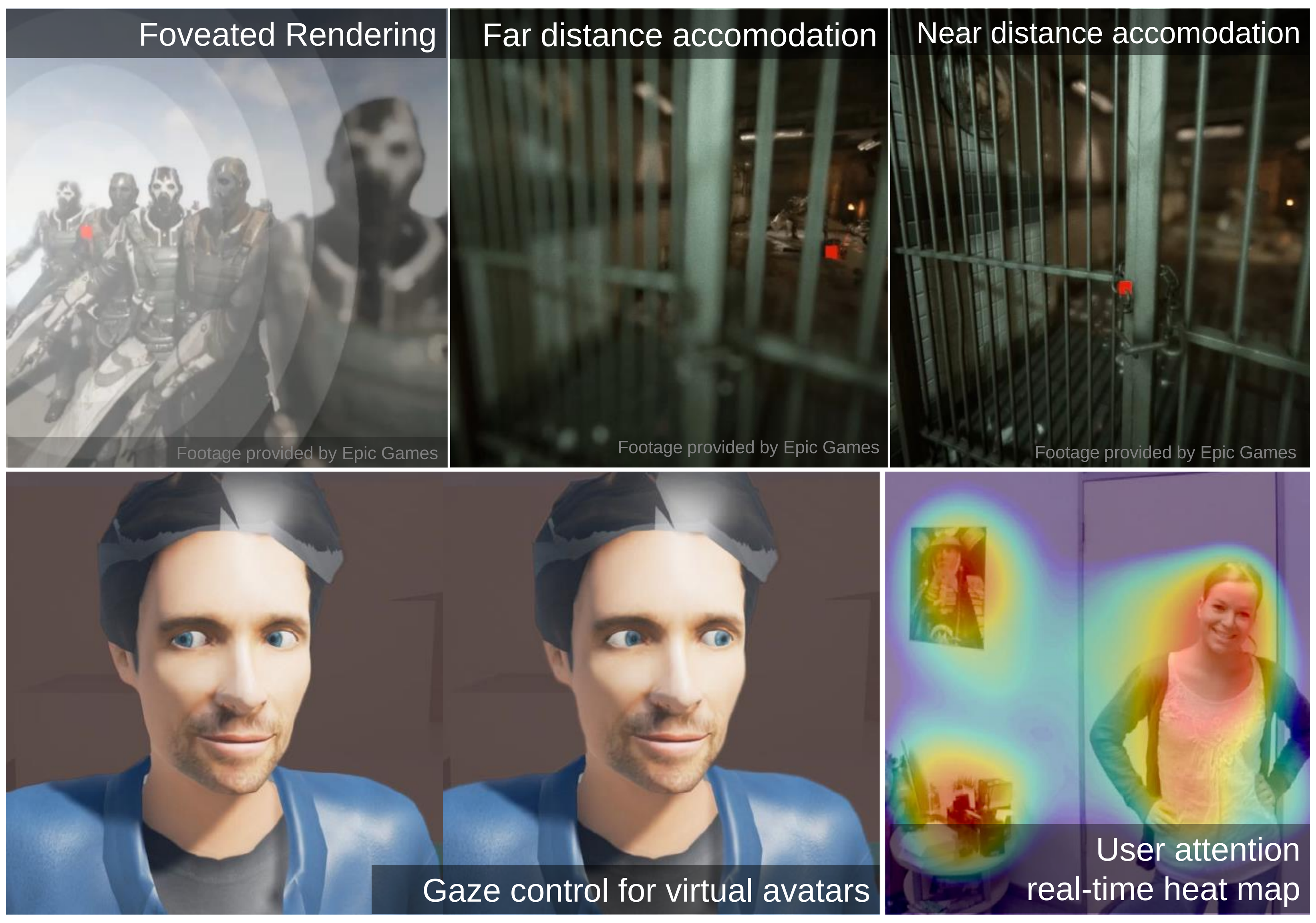


Fig. 8

References

- Foveated Gaze-Contingent Displays [Dorr 06, Duchowski 07, Targino da Costa 14]
- Pursuit Gaze Calibration [Pfeuffer 13]
- Simulating the Visual Experience, Tone-Mapping [Benoit 09 , Ritschel 12, Jacobs 15]
- Smart actors; collaborative VR with gaze support [Duchowski 05, Steptoe 08]

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