State of the Art in Perceptual VR Displays

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Abstract. Wearable computing systems, i.e. virtual and augmented reality (VR/AR), are widely expected to be the next major computing platform. These systems strive to generate perceptually realistic user experiences that seamlessly blend physical and digital content to unlock unprecedented user interfaces and applications. Due to the fact that the primary interface between a wearable computer and a user is typically a near-eye display, it is crucial that these displays deliver perceptually realistic and visually comfortable experiences. However, current generation near-eye displays suffer from limited resolution and color fidelity, they suffer from the vergence–accommodation conflict impairing visual comfort, they do not support all depth cues that the human visual system relies on, and AR displays typically do not support mutually consistent occlusions between physical and digital imagery. In this chapter, we review the state of the art of perceptually-driven computational near-eye displays addressing these and other challenges.

Keywords: Virtual reality · Augmented reality · Visual perception · Displays

1 Introduction

Immersive computer graphics systems, such as virtual and augmented reality (VR/AR) displays, aim at synthesizing perceptually realistic user experiences. To achieve this goal, several components are required: interactive, photorealistic rendering; a high-resolution, low-persistence, stereoscopic display; and low-latency head tracking. Modern VR/AR systems provide all of these capabilities and create experiences that support many, but not all, of the depth cues of the human visual system. They fall short of passing a "visual Turing test for displays". Imagine a person using a wearable computing system and that system

M. Magnor and A. Sorkine-Hornung (Eds.): Real VR, LNCS 11900, pp. 221–243, 2020.
https://doi.org/10.1007/978-3-030-41816-8_9

delivering user experiences that are indistinguishable from the real world. That is, the user would not be able to tell whether an image is computer generated or real. While the field of computer graphics has been developing algorithms to generate photorealistic images, to pass the visual Turing test for displays, a VR/AR system must deliver perceptually realistic experiences. This challenge requires displays with high resolution, color fidelity, dynamic range, and adequate support of all the depth cues of human vision. Moreover, for such a system to be practical, device form factor, weight, power, heat, battery life, limited compute power, and bandwidth have to be optimized as well and set physical constraints on the capabilities of a wearable computing system.

Significant research and engineering efforts have focused on optimizing user experiences of AR/VR systems throughout the last few years. As these are interdisciplinary efforts at the intersection of computer vision, graphics, optics, electronics, and human-computer interaction, it is easy to get lost in the diverse nature of available literature. In this chapter, we provide a survey of recent approaches to addressing many of the outlined challenges and we specifically focus on perceptually motivated and algorithm-driven approaches to optimizing VR/AR experiences, rather than trying to survey all hardware components of VR/AR systems. Specifically, Sect. 2 outlines approaches to foveated rendering and display—techniques that build on eye tracking and that exploit the particular characteristics of human vision to render, transmit, and display high resolution imagery within available bandwidth constraints. Section 3 outlines approaches to optimizing perceptual realism and visual comfort of VR/AR displays by adequately displaying all depth cues of human vision, including focus cues and ocular parallax. Finally, we discuss other approaches to optimizing seamless experiences in VR/AR, for example by providing mutually consistent occlusions in optical see-through AR systems, in Sect. 4.

2 Foveated Rendering and Display

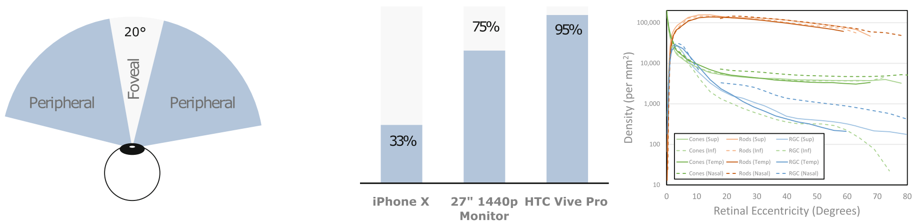

Fig. 1. (Left) While viewing most displays, a fraction of pixels lie in our foveal vision, while the remaining lie in our peripheral vision. For displays like smartphones, foveal pixels dominate, and for computer monitors peripheral pixels are a majority. However, for near-eye displays like contemporary VR, almost all pixels are peripheral. (Right) Density of photoreceptors and retinal ganglion cells (RGCs) varying with eccentricity. There is a strong preference for central vision as compared to peripheral vision. Data measured by Curcio and Allen [26] and Curcio *et al.* [27].

Due to the large field-of-view of near-eye displays, we observe a large majority of VR/AR pixels through our peripheral vision (see Fig. 1, left). Combined with the fact that visual acuity of peripheral vision is significantly lower than foveal or central vision, adaptively and dynamically distributing image quality and detail across the visual field—known as foveated rendering and display—is an important class of perceptual optimizations for near-eye displays. In this section we discuss the physiological and perceptual bases for foveation, as well as the relevant rendering and display technologies proposed in recent literature.

Human visual perception starts at the optical components (the lens, pupil, etc.), followed by retinal cells like rods, cones, and ganglion cells, and finally by higher level neural processing. Each of these optical, retinal, and neural components exhibit a strong preference for the central area of the visual field. On the retina this region is also called the fovea, and is marked by high density of retinal cells (see Fig. 1, right). As a consequence of the variation in processing density across the pathway, our foveal vision has a much higher acuity than our peripheral vision. Hence, it is better for near-eye displays to provide more detail in the foveal region than in the peripheral region.

The degradation in visual acuity from foveal to peripheral vision is also known to be highly non-uniform [139]. For instance, while we cannot perceive fine details in images through our peripheral vision, we are extremely sensitive to moving and flickering images. Researchers have identified several such non-uniformities in peripheral visual acuity, e.g. in color perception [44,116], in existence of a peripheral aliasing zone [144], and the anisotropy of peripheral perception [129]. While designing foveated rendering and display applications, we should be aware of this peculiarity. On the other hand, these effects can create additional opportunities to improve rendering performance or image quality.

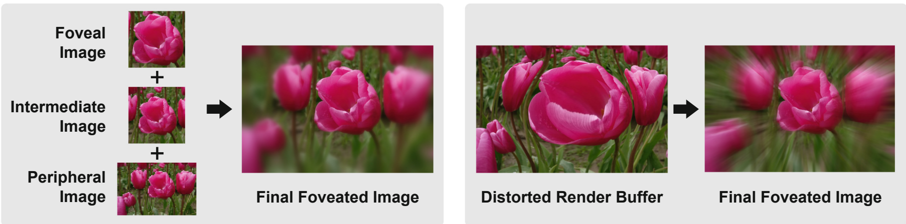

Fig. 2. Illustrations of two prominent techniques for foveated rendering. Left: We can render multiple views of a scene with varying resolution, and blend the resulting buffers to obtain the final foveated image. Right: We can render the scene into a distorted buffer that prioritizes foveal pixels, and after rendering undistort it into the final foveated image.

Many researchers have proposed foveated rendering techniques to improve rendering performance for gaze-contingent displays. The most prominent class of techniques work by reallocating image pixels such that the density is highest at the fovea, and lowest in the periphery. There are can be done in two main ways (also see Fig. 2):

– By rendering the fovea, periphery, and zero or more intermediate regions into different framebuffers of varying size and resolution, and blending them together to produce the final foveated image [41].
– By rendering the image into a distorted framebuffer that oversamples the fovea, but undersamples the periphery [22,23,37,109].

Other techniques for foveated rendering work by reducing expensive computations like pixel shading operations [109,122,136,145] and geometric evaluation [142].

While foveated rendering solutions seek to improve performance by reducing pixel computations in the periphery, a recent class of techniques moves the foveal-peripheral adaptivity directly to the display. Such novel display system designs match the nature of human vision. One example in VR is to expand the 2D foveated to 4D light field display [141]. The system is shown to offer both foveation (performance) and accommodation (comfort). More recently, the idea of foveating display has been advanced to augmented reality as well [69].

3 Optimizing Depth Perception and Visual Comfort in VR/AR

Human depth perception relies on a variety of cues [55,120]. Many of these cues are pictorial and can be synthesized using photorealistic rendering techniques, including occlusions, perspective foreshortening, texture and shading gradients, as well as relative and familiar object size. Compared with conventional 2D displays, head-mounted displays (HMDs) use stereoscopic displays and head tracking and can thus support several additional depth cues: binocular disparity, motion parallax, and vergence (see Fig. 3). All of these cues are important for human depth perception to varying degrees, depending on the fixation distance [28]. Studying visual cues, such as disparity [31] or motion parallax [68], and their impact on computational display applications has been an integral part of graphics research.

In this section, we briefly review two topics of active research and development. First, we outline emerging near-eye displays that support focus cues, i.e. retinal blur, accommodation, and chromatic aberrations. Second, we highlight a recent study that suggest that ocular parallax may also be an effective ordinal depth cue in VR/AR. For a more detailed survey of 3D displays and perceptual related issues, please see [5].

3.1 Computational Near-Eye Displays with Focus Cues

Current near-eye displays cannot reproduce the changes in focus that accompany natural vision, and they cannot support users with uncorrected refractive errors.

For users with normal vision, this asymmetry creates an unnatural condition known as the vergence–accommodation conflict [77,82]. Symptoms associated with this conflict include double vision (diplopia), compromised visual clarity, visual discomfort, and fatigue [77,135]. Moreover, a lack of accurate focus also removes a cue that is important for depth perception [28,50,53,147]. Note that adequate reproduction of focus cues in VR/AR is most important for younger users, while older users tend to be presbyopic, i.e. they lost the ability to accommodate their eyes [117].

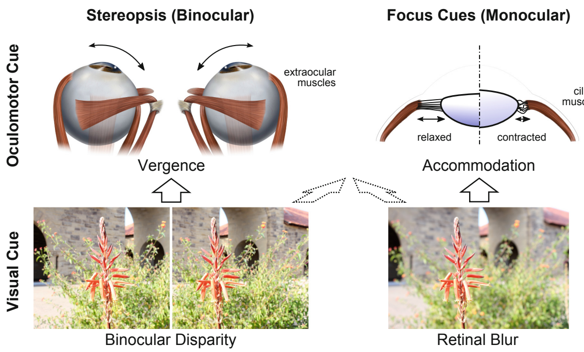

Fig. 3. Overview of several depth cues that are important for near-eye displays. Vergence and accommodation are oculomotor cues whereas binocular disparity and retinal blur are visual cues. In normal viewing conditions, disparity drives vergence and blur drives accommodation. However, these cues are cross-coupled, so there are conditions under which blur-driven vergence or disparity-driven accommodation occur.

In the following, we outline several approaches to enabling focus cues in VR/AR and to mitigating the vergence–accommodation conflict. For a more comprehensive review of this topic, we refer the interested reader to the survey papers by Kramida [79] and Hua [58].

Gaze-Contingent Focus Cue Rendering. Several researchers have investigated the perceptual effects of *gaze-contingent depth-of-field rendering*. Because gaze-contingent retinal blur rendering only requires a gaze-tracker and fast/realistic blur rendering techniques—no specialized optics are needed—it is useful to know if this type of display mode on its own offers improvements over standard displays. Several previous studies have examined the effect of this rendering technique on visual experience and performance with benchtop displays [35,51,66,97,107]. In these studies, gaze-tracking and estimated or ground-truth depth maps were used to adaptively update the depth of field of an image depending on the distance of the object that the participants were fixating. Several studies reported improvements in subjective viewing experience [51,107], however, the results for performance improvements on a variety of visual tasks were more mixed [66,107].

One study showed that combining this technique with stereo display significantly decreased the time needed for participants to achieve binocular fusion under some conditions [97]. Although gaze-contingent rendering may improve perceived realism, several recent studies have demonstrated that this software-only approach alone does not drive accommodation [65,74], therefore it does not reduce the vergence–accommodation conflict.

In another recent study, it was show that *rendering chromatic aberrations* into a perceived image can drive a user's accommodation in a monocular display setup [21]. This surprising result suggests that adequate modeling and rendering of the chromatic aberrations of a user's eye can improve accommodation and also perceived realism. However, driving the user's accommodation away from the focal plane of the display may result in degradation of perceived image sharpness.

Varifocal Displays. Two-dimensional dynamic focus displays present a single image plane to the observer, the focus distance of which can be dynamically adjusted. Two approaches for focus adjustment have been proposed: physically actuating the screen [117,140] or dynamically adjusting the focal length of the lens via focus-tunable optics (programmable liquid lenses or reflectors) [36,46,65,75,78,93,117,137,138]. Several such systems have been incorporated into the form factor of a near-eye display [75,93,117]. Varifocal displays require gaze tracking such that the focus distance can be adjusted in real time to match the vergence distance. Figure 4 shows both benchtop and wearable varifocal display prototypes along with data measured for users of all ages demonstrating that varifocal displays effectively drive accommodation for non-presbyopic users.

Multifocal Displays. Three-dimensional volumetric and multi-plane displays represent the most common approach to focus-supporting displays. Volumetric displays optically scan out the 3D space of possible light emitting voxels in front of each eye [132]. Multi-plane displays approximate this volume using a few virtual planes that are generated by beam splitters [2,32,110], time-mulitplexed focus-tunable optics [18,57,93,94,96,115,123,128,146,155], or phase-modulating spatial light modulators [106]. Naïve implementations with beam splitters seem impractical for wearable displays because they compromise the device form factor, but this concept is promising, especially for see-through AR displays, when implemented with stacked diffractive optical elements [89] or waveguides, such as in the Magic Leap ML1. One of the biggest challenges with time-multiplexed multi-plane displays is that they require high-speed displays and may thus introduce perceived flicker. Specifically, an N-plane display requires a refresh rate of $N \times 60$–120 Hz. Digital micromirror devices (DMDs) are of the fastest available microdisplay technologies and seem particularly promising for this direction, as also realized by recent research [18,123] as well as Avegant's commercial AR Video Headset. Content-adaptive multifocal displays [106,155] seem particularly interesting, because they have the capability of minimizing the number of required focal planes based on the saliency of the content. However, optically generating non-planar or adaptive focal planes is challenging.

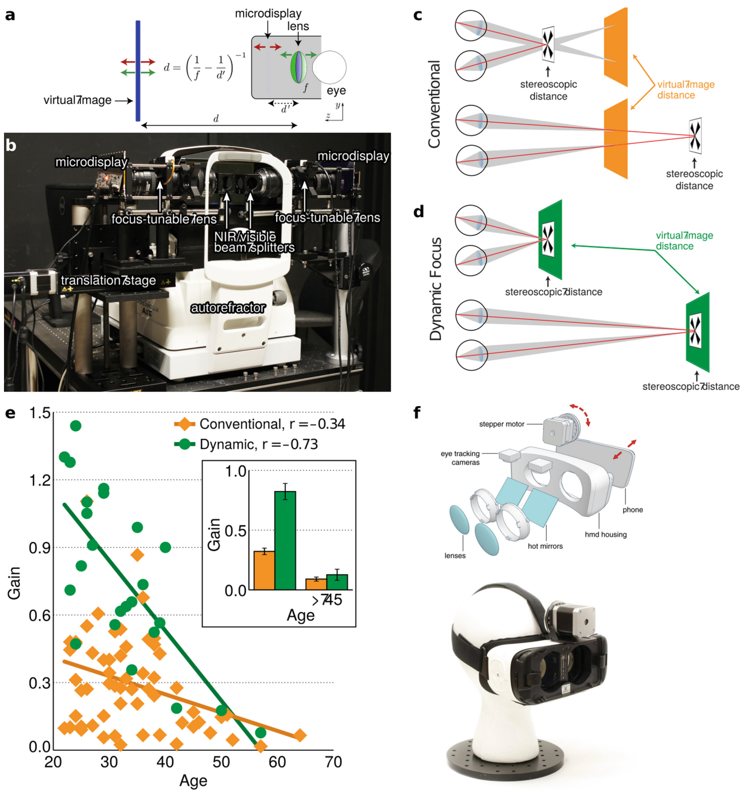

Fig. 4. Varifocal display prototypes and user experiments. (a) A typical near eye display uses a fixed-focus lens to show a magnified virtual image of a microdisplay to each eye. The focal length of the lens, f, and the distance to the microdisplay, d', determine the distance of the virtual image, d. Dynamic focus can be implemented using either a focus-tunable lens (green arrows) or a fixed-focus lens and a mechanically actuated display (red arrows), so that the virtual image can be moved to different distances. (b) A benchtop setup designed to incorporate dynamic focus via focus-tunable lenses, and an autorefractor to record accommodation. (c) The use of a fixed-focus lens in conventional near-eye displays means that the magnified virtual image appears at a constant distance (orange planes). However, by presenting different images to the two eyes, objects can be simulated at arbitrary stereoscopic distances. To experience clear and single vision in VR, the user's eyes have to rotate to verge at the correct stereoscopic distance (red lines), but the eyes must maintain accommodation at the virtual image distance (gray areas). (d) In a dynamic focus display, the virtual image distance (green planes) is constantly updated to match the stereoscopic distance of the target. Thus, the vergence and accommodation distances can be matched. (e) These accommodative gains plotted against the user's age show a clear downward trend with age, and a higher response in dynamic. Inset shows mean and standard error of the gains for users grouped into younger and older cohorts relative to forty-five years old. (f) A wearable varifocal prototype using a conventional near-eye display (Samsung Gear VR) that is augmented by a gaze tracker and a motor that is capable of adjusting the physical distance between screen and lenses. Figures reproduced from [117].

Light Field Displays. Four-dimensional light field displays aim to synthesize the full 4D light field in front of each eye [85,88,101,151,153]. Conceptually, this approach allows for parallax over the entire eyebox to be accurately reproduced, including monocular occlusions, specular highlights, and other effects that cannot be reproduced by volumetric displays. Current-generation near-eye light field displays provide limited resolution due to the spatio-angular resolution tradeoff of microlens-based systems [59,87] or the diffraction limit of dual layer liquid crystal displays (LCDs) [60].

Holographic Near-Eye Displays. A strong interest in holographic display technologies for applications in virtual and augmented reality has emerged. Much progress has recently been made both on hardware implementations and efficient algorithms. For example, several recent near-eye displays combine a holographic projector with various see-through eyepieces in innovative ways: holographic optical elements [90], waveguides [157], and lenses with beamsplitters [19,40,112]. Moreover, algorithms for computer-generated holography have significantly advanced at the same time [99,134]. Although holographic near-eye displays are one of the most promising directions of near-eye display research, they also face significant challenges. Holographic displays may suffer from speckle and have extreme requirements on pixel sizes that are not afforded by near-eye displays also providing a large field of view.

Maxwellian-Type or Accommodation-Invariant Displays. A near-eye display system that removes the accommodation-dependent change in retinal blur, also known as Maxwellian-view display [79,148], allows accommodation to remain coupled to the vergence distance of the eyes, and thus allow for accommodating freely in a scene and mitigating the vergence–accommodation conflict. Conceptually, the idea of accommodation invariance can be illustrated by imagining that a user views a display through pinholes—the depth of focus becomes effectively infinite and the eyes see a sharp image no matter where they accommodate. Such a Maxwellian-view display [148] would severely reduced light throughput and prevent the user from seeing an image at all when moving their pupil by more than half the pupil diameter (i.e., the eyebox corresponds to the size of the pupil). To overcome these limitations and providing a large eyebox and uncompromised light throughput, accommodation-invariant displays [76] use engineered point spread functions in a near-eye display system that are based on the ideas from extended-depth-of-field photography [24,25,33,47,114]. These displays slightly reduce the image sharpness at the (conventional) single focal plane in order to significantly improve image sharpness at multiple planes or throughout the continuous volume. Note that Maxwellian and accommodation-invariant displays do not render accommodation and retinal blur in a physically correct manner, so these displays cannot use such cues to improve depth perception. However, they are capable of driving accommodation [76] and thus of mitigating possible discomfort associated with the vergence–accommodation conflict.

Monovision Displays. Monovision is a common prescription correction method for presbyopia and it was recently proposed to potentially drive the accommodation on non-presbyopes in VR/AR [65, 74]. In this display mode, the virtual image of one eye is placed at one distance and the image for the other eye at a different distance. This can easily be achieved by using two lenses with different focal powers for each eye and this approach does not require eye tracking. Due to the fact that the accommodation of both eyes is linked together, it was hypothesized that accommodation could be driven to either of the two focal planes. However, the measured accommodation response for this display mode was highly variant between users and no consistent verification of this hypothesis was demonstrated [118].

Vision-Correcting Displays. Vision is one of the primary modes of interaction with which humans understand and navigate the everyday world. Unfortunately, the aging process is accompanied by a hardening of the eye's crystalline lens; the end result is that by their late 40 s or 50 s, most people struggle to view objects that are within arm's reach in sharp focus [34]. This reduction in range of accommodation, known as presbyopia, affects more than a billion people [54] and will become more prevalent as the population ages.

While several types of eyeglasses and contacts exist to correct myopia, hyperopia, and also presbyopia, corrective eyewear can also be integrated into AR/VR displays. For example, Padmanaban *et al.* studied age-related effects of accommodation in VR/AR and showed that varifocal displays drive accommodation in a natural way for non-presbyopes [117]; they also demonstrated vision-correcting capabilities for myopia and hyperopia. Varifocal display technology can also correct for presbyopia in see-through AR systems [16] or, integrated into electronic eyeglasses, for presbyopes viewing the real world [45, 91, 119]. Finally, light field display technology has been demonstrated to enable vision-correction for myopia, hyperopia, and higher order aberrations [62, 121].

3.2 Ocular Parallax Rendering

The centers of rotation and projection in the human eye are not the same. Therefore, changes in gaze direction create small amounts of depth-dependent image shifts on our retina—an effect known as ocular parallax. This depth cue was first described by Brewster [13] and has been demonstrated to have a measurable effect on depth perception [12, 80, 81, 104]. Similarly to other monocular visual cues, such as retinal blur and chromatic aberration, the change of the retinal image caused by ocular parallax may be small. Yet, it has been demonstrated to produce parallax well within the range of human visual acuity [12, 42, 104]. Supporting all of these subtle cues with an HMD can improve visual comfort [53], perceived realism, and the user experience as a whole.

Konrad *et al.* [73] recently introduced ocular parallax rendering for VR/AR. Ocular parallax rendering uses eye tracking to determine the fixation point of the user and renders small amounts of depth-dependent image shifts induced by eye rotation. With eye tracking available, there is no additional computational cost to integrate ocular parallax into the existing rendering pipeline. The perspective of the rendered image simply changes depending on the gaze direction. In their paper, Konrad *et al.* studied the perceptual effects of ocular parallax rendering in VR and showed that detection thresholds for ocular parallax rendering are almost an order of magnitude lower than the visual acuity at the same extrafoveal locus, verifying that our sensitivity to small amounts of differential motion are well below the acuity limit, especially in the periphery of the visual field [108]. They also showed that the relative ocular parallax of objects with respect to a background target can be discriminated accurately even for relatively small object distances that fall well within the depth ranges of most virtual environments. Furthermore, they showed that ocular parallax rendering provides an effective ordinal depth cue, that is it helps users better distinguish relative depth ordering in a scene, but that it does not provide an effective absolute depth cue with metric distance information of 3D objects. Finally, they showed that ocular parallax rendering improves the impression of realistic depth in a 3D scene.

4 Towards Seamless Visual Interfaces Between Digital and Physical Content in AR

Optical see-through augmented reality (AR) systems are a next-generation computing platform that offer unprecedented user experiences by seamlessly combining physical and digital content. Many of the traditional challenges of these displays have been significantly improved over the last few years, but AR experiences offered by today's systems are far from seamless and perceptually realistic. Among many image characteristics that help improve seamlessness between digital and physical content, some of the most important ones include mutually consistent occlusions between physical and digital content in optical see-through augmented reality and optimized display resolution, dynamic range, and color fidelity. We will discuss recent approaches that address these challenges and which may improve seamless image display in AR when integrated into near-eye display systems.

4.1 Mutually Consistent Occlusions in Optical See-Through AR

While current AR displays offer impressive capabilities, they typically do not support the most important depth cue: occlusion [28]. Providing accurate, i.e., mutually consistent and hard-edge, occlusion between digital and physical objects with optical see-through AR displays is a major challenge. When digital content is located in front of physical objects, the former usually appear semi-transparent and unrealistic. To adequately render these objects, the light reflected off of the physical object toward the user has to be blocked by the display before impinging on their retina. This occlusion mechanism needs to be programmable to support dynamic scenes and it needs to be perceptually realistic to be effective. The latter implies that occlusion layers are correctly rendered at the distances of the physical objects, allowing for pixel-precise, or hard-edge, control of the transmitted light rays. In the following, we discuss several recent approaches to enabling mutually consistent occlusions in AR.

Projection-Based Lighting. Projection displays can be used to control the lighting of a scene in a spatially varying manner. Using such controlled illumination, mutually consistent occlusions, shading effects, and shadows in projector-based AR systems can be synthesized [3,9,10,102]. The primary disadvantages of these systems are that projectors are required for the AR experience, which are not necessarily portable or wearable, and that they may not work in the presence of strong ambient illumination.

Global Dimming. Commercial AR displays (e.g., Microsoft HoloLens, Magic Leap) often use a neutral density filter placed on the outside of the display module to reduce ambient light uniformly across the entire field of view. An adaptive version of global dimming was recently proposed by Mori *et al.* [113], where the amount of dimming is controlled by a single liquid crystal cell and responsive to its physical environment. While these approaches may be useful in some scenarios, they do not provide spatial control of the occlusion layer.

Fixed-Focus Occlusion. The physical scene can be focused onto an occlusion SLM which selectively blocks its transmission in a spatially varying manner before it reaches the user's eye. This idea was first proposed by the seminal work of Kiyokawa *et al.* [70–72] (see Fig. 5). Improvements of related systems were later demonstrated [14,15,38,39,56,152,154].

Unfortunately, focusing a scene on an SLM usually requires a bulky optical system, first to focus it to the SLM, then to negate the effect of the first lens, and then to flip the resulting image the right way up. Moreover, as this approach only focuses a single distance of the scene on the occlusion SLM, hard-edge occlusion is only achieved at this fixed focus distance. This limitation is similar to the characteristics of fixed-focus near-eye displays, which has been alleviated by varifocal displays.

Two key challenges for fixed-focus occlusion-capable displays are: (1) to ensure unit magnification of the see-through scene and (2) to ensure zero viewpoint offset between the see-through scene and the real-scene as seen without the display, so that the images of the real-world objects are at the correct distance. Kiyokawa *et al.* [70] derive optical design parameters that satisfy unit magnification for all real-world object distances and also propose an interesting geometric configuration of the optical components that make the offset between the real world objects and their images equal to zero. Cakmakci *et al.* [15] propose a compact optical design that satisfies the magnification requirements, but it does not achieve zero offset between the real viewpoint and the virtual viewpoint; however, the offset is small (5 cm). Howlett and Smithwick [56] propose an optical design approach based on ray-transfer matrices to achieve unit magnification and zero viewpoint offset, which is in turn inspired by optical cloaking [20].

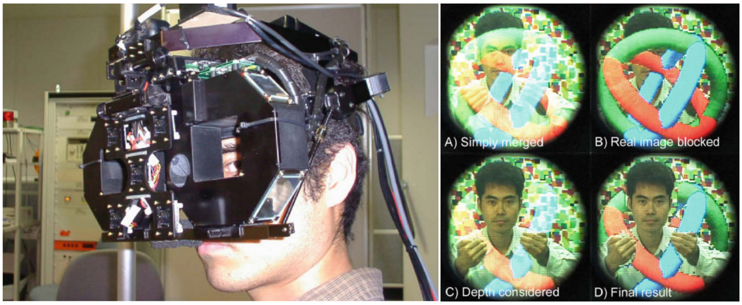

Fig. 5. Occlusion-capable optical see-through AR display (left). The display includes relay optics and spatial light modulators that allow for hard-edge per-pixel control of the observed scene before it hits the user's retina. The right panel shows views through the display with (A) no occlusion control, i.e. digital and physical image are simply superimposed, (B) occlusion enabled to block light from the physical scene everywhere where there is digital content, (C) occlusion disabled but depth considered, i.e. physical objects can occlude digital objects but selectively rendering the latter, (D) occlusion enabled and depth considered, i.e. both physical and digital objects can correctly occlude the other one. Figure reproduced from [70].

Soft-Edge Occlusion. To avoid a bulky optical system, a single LCD can be placed directly in front of the user's eyes [63,152]. However, due to the fact that the occlusion LCD is out of focus, it always appears blurred. Itoh *et al.* [63] recently proposed to compensate for this blur by modifying the digitally displayed image. Such an approach could be interpreted as a hybrid optical see-through and video see-through AR display. Calibrating such a system requires extremely precise alignment and the mismatch in resolution (spatial and angular), latency, brightness, contrast, and color fidelity between digital display and physical world may contribute to perceived inconsistency and reduced perceptual realism in such a system [127]. Maimone *et al.* [100] also used an out-of-focus LCD, where the occlusion mask is calculated as the silhouette of the virtual object. However, none of these approaches achieves hard-edge occlusion, which limits perceptual realism.

Light Field Occlusion. Maimone and Fuchs [98] propose a 4D light field occlusion mask using stacked LCD layers placed out of focus in front of the eye, where the occluding patterns are calculated by light field factorization algorithms [86,151]. The advantage of light field occlusion is that depth-dependent occlusion can be presented for virtual content at different depths simultaneously in a compact form factor. In practice, see-through LCDs mounted close to the eye are light inefficient and result in significant diffraction artifacts, which are due to the electronic components in each pixel as well as the wiring of the display panel. This effect can degrade the observed image quality of any soft-edge or light field occlusion system. Another approach for light field occlusion is presented in [156] using concepts of integral imaging systems. However, this system has a very narrow field of view (4.3°).

Varifocal Occlusion. Hamasaki and Itoh [43] and Rathinavel *et al.* [124] develop strategies for varifocal occlusion-capable AR displays. Varifocal occlusion displays comprise a varifocal optical system and spatial light modulators that enable depth-corrected hard-edge occlusions correctly at multiple distances for AR experiences. While Rathinavel's approach builds on focus-tunable optics to dynamically adjust the depth of the occlusion layer, Hamasaki's approach requires mechanical motion of the occlusion SLM. Each approach has certain benefits and limitations. For example, robust calibration of the mechanically moving parts in their approach can be challenging, especially in a wearable display form factor. The focus-tunable optics approach, on the other hand, requires specialized optical components, such as liquid lenses or Alvarez lenses.

4.2 Optimizing Other Display Characteristics

Spatial AR systems and optical see-through AR display often aim at providing radiometrically consistent, color-corrected or even color-stylized imagery (e.g., [11,64,83,84,149,152]). Some of the most important display characteristics that determine how well a digital visual experience could match a physical one are resolution, dynamic range/brightness, and color. We briefly review computational display strategies to address these display characteristics. A comprehensive survey of these topics can be found in [105,150].

Superresolution Displays. Examples of superresolution displays include optical configurations that combine the contribution of multiple overlapping devices [30], or single devices with either two stacked LCDs [130] or one LCD and a double-lens system [131]. Superresolution display with monitors, as opposed to projectors, can be achieved by fast mechanical motion of the screen [8] or using two stacked LCDs [48,49]. Finally, Hirsch *et al.* [52] proposed a light field and HDR projector using stacked spatial light modulators. They used formal optimization to derive optimal pixel states in the display and demonstrate superresolution on a diffuse projection screen rather than a monitor.

High Dynamic Range Displays. High dynamic range displays overcome the limited contrast of LCDs. In their seminal work, Seetzen *et al.* [133] introduced the concept of dual-layer modulation where a low-resolution LED backlight is modulated by a high-resolution LCD. While the LED array has low resolution, it offers ultra-large dynamic range. An image decomposition algorithm is applied to decompose a target HDR image into the pixel states of the two display layers. This technical approach has become standard practice in industry and is now marketed using the terms "micro dimming" or "local dimming" in consumer products. Extensions to more than two display layers have been discussed [153] and high dynamic range projectors have also been proposed [29]. These typically build on light steering using phase-only spatial light modulators [4], dual layer modulation [52], or adaptive control of the peak brightness over time [17].

High Color-Gamut Displays. Spectral displays can roughly be classified as multi-primary displays [143] and hyperspectral displays [111,126]. Multi-primary displays usually aim for a wide color gamut, as perceived by a human observer. Related algorithmic problems include selecting the optimal color primaries [7, 92,95] as well as gamut mapping (e.g., [6]), where pixels of an image are processed to fit within the fixed gamut provided by a display. Gamut expansion can also help to optimize image presentation with large-gamut displays [103]. Hyperspectral displays have the potential to synthesize more complex spectral power distributions than multi-primary displays. Similar to the latter, applications of hyperspectral displays include extended color gamuts, but in addition these types of devices are also useful for hyperspectral imaging, remote sensing, reflectance estimation, and medical imaging [125].

More recently, computational approaches to content-adaptive color display with multi-primary displays have been proposed [61,67]. For example, Kauvar *et al.* [67] build a custom, multi-primary projector that can dynamically address a large portion of the CIE xy chromaticity diagram. This design is based on similar devices described in the literature (e.g., [1]) but compact and easily built by modifying off-the-shelf hardware. Their perceptually-driven algorithm for joint primary selection and gamut mapping is demonstrated with a custom prototype but also applicable to other displays, such as VR/AR.

5 Conclusion

In summary, we review perceptually motivated computational near-eye displays that optimize rendering, resolution, bandwidth, depth perception, and other display characteristics. Eye tracking is an enabling technology in this space, facilitating a variety of gaze-contingent rendering and display methodologies, such as foveated rendering, varifocal displays that support focus cues, and ocular parallax rendering. To deliver perceptually realistic and seamless experiences, optical see-through AR displays face significant challenges in providing mutually consistent image appearance and occlusions between physical and digital content. Much progress has recently been made in all of the above areas, yet many challenges lie ahead. Open research questions include minimizing latency and robustness of eye tracking systems, miniaturizing occlusion-capable AR displays, and further improving resolution, field of view, color rendition, brightness, dynamic range, power consumption, device form factors, and comfort of near-eye displays.

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