aFoveAR: Combining an Optically See-Through Near-Eye Display with Spatial Augmented Reality Projections

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Figure 1. When using optically see-through display glasses (A), the viewer is presented with a limited field of view, impacting their sense of immersion and presence (B). FoveAR extends the glasses experience (C) by adding a view-dependent projection in the environment (D). Note: All first person images in this paper were photographed through the glasses. Due to the relative brightness of the glasses display and limited dynamic range of the camera, projected content appears subjectively dimmer than in reality.

ABSTRACT

Optically see-through (OST) augmented reality glasses can overlay spatially-registered computer-generated content onto the real world. However, current optical designs and weight considerations limit their diagonal field of view to less than 40 degrees, making it difficult to create a sense of immersion or give the viewer an overview of the augmented reality space. We combine OST glasses with a projection-based spatial augmented reality display to achieve a novel display hybrid, called *FoveAR*, capable of greater than 100 degrees field of view, view dependent graphics, extended brightness and color, as well as interesting combinations of public and personal data display. We contribute details of our prototype implementation and an analysis of the interactive design space that our system enables. We also contribute four prototype experiences showcasing the capabilities of FoveAR as well as preliminary user feedback providing insights for enhancing future FoveAR experiences.

Author Keywords

Augmented reality; projector camera system; head-mounted displays; see-through displays.

UIST '15, November 08 – 11, 2015, Charlotte, NC, USA

ACM 978-1-4503-3779-3/15/11…$15.00
DOI: http://dx.doi.org/10.1145/2807442.2807493

ACM Classification Keywords

H.5. 1. [Information Interfaces and Presentation]: Multimedia Information Systems—[Artificial, augmented, and virtual realities]

INTRODUCTION

Augmented reality (AR) offers a captivating vision of the future in which computer-generated (CG) content is presented directly over the real world and precisely registered in such a way that it appears part of the real world. AR scenarios in popular media and film typically feature CG content that fills a large portion of the viewer's field of view (FOV) and appears almost indistinguishable from the real scene. However, current AR technologies are far from fully realizing this vision.

Forerunner commercial AR solutions rely on optically see-through (OST) near-eye displays (i.e., "smart glasses"). Current optical designs and weight considerations limit the FOV of OST glasses to 40° diagonal which pales in comparison to the overall binocular human vision FOV of close to 180° horizontal (~130° vertical). In particular, this is due to the nature of the optics used (e.g., a beam splitter embedded in a waveguide) which require a greatly increased thickness to obtain a wider FOV [20]. Only a few recent research prototypes [6, 19, 20] offer a glimpse of potentially wider FOV albeit at a costly tradeoff of reduced image quality and display resolution.

In this paper, we propose a novel approach to extending the FOV of the AR near-eye display by creating a hybrid augmented reality display system, called *FoveAR*, which combines an OST near-eye display with projection-based spatial AR display (Figure 1). This combination is compatible with the existing set of OST glasses, while enabling a wider FOV and offering a number of other unique benefits to the viewer (e.g., private stereoscopic views, per-pixel controlled ambient lighting, surface shading effects not affected by head tracking lag or mismatch, etc.). In particular, we demonstrate the capabilities of our system in four prototype experiences including 3D model animations, wide angle immersive simulation, a 3D life-size AR telepresence, and a gamepad controlled AR shooter game.

While we are not the first to combine projectors and near-eye AR displays, to the best of our knowledge, previous approaches use the projector only for spatially controlled background lighting [21] or object highlighting [31], and not for extending the FOV of the viewer. In contrast, our work considers the projected periphery to be *equally capable of providing spatially-registered view-dependent AR experiences as the near-eye displays*. It is by combining these two technologies that we achieve more compelling AR experiences and a greater sense of presence [18, 26].

Contributions

In summary, we contribute a novel approach to extending the FOV of the OST near-eye display by complementing it with projection-based spatial AR display. Specifically, we contribute:

- A proof-of-concept FoveAR system which combines an eyeglasses OST AR display with a custom projector + depth camera unit for a wide FOV AR experience;
- Implementation of 4 experiences that demonstrate the important characteristics of our hybrid display;
- A set of considerations that frame the design space for implementing FoveAR experiences.

RELATED WORK

Our work builds on previous research in near-eye OST displays, Spatial Augmented Reality, and research on peripheral projected displays.

Extending the FOV of See-Through AR Displays

It is difficult to specify a minimum FOV requirement for a display since the impact of a change in FOV depends on the task at hand, and seems to have a continuous impact on performance. However, research has shown that widening the FOV has a positive impact on immersion and presence (e.g., subjects are better at estimating distances with wider FOV displays [15]).

Table 1. Commonly used commercial OST glasses (including past and future/announced) and their reported FOV values.

Near-Eye Glasses	FOV	Near-Eye Glasses	FOV
Epson Moverio BT-200	23°	Osterhout Design Group R-6	30°
Lumus DK-32	40°	Sony Glasstron LDI-D100B	30°
Meta Pro	40°	Virtual I-O I-glasses	25°
Microvision Nomad 1000	21°	Vuzix M100	16°
Optinvent ORA-1	24°	Vuzix Star 1200XLD	35°

In Table 1, we summarize the most widely used commercially available OST near-eye displays and their reported FOV. None offer a FOV higher than 40° diagonal. Kress and Starner [16] provide a more thorough survey of the state-of-the-art in near-eye displays.

There are several recent attempts to increase the FOV of the OST glasses [6, 19, 20]. Such solutions usually trade off resolution, brightness and image quality to achieve increased FOV. Cheng et al. [6] leverage the free-form optics to improve the traditional beam splitter design and show a prototype OST display with a 56° horizontal FOV. They propose tiling multiple displays to further increase the FOV.

Related to our approach is the use of head-mounted [11] or shoulder-mounted [9] projectors instead of near-eye displays for projecting augmentations on the real world. Such displays are limited by the FOV of the projector used as well as by the suitability of the available projection surfaces.

There have also been attempts to create a wide FOV near-eye displays using light-field displays instead of beam-splitters [17, 19, 20]. Probably the most promising development is the recent work on Pinlight Displays [20] which demonstrated a 110° diagonal FOV prototype based on an LCD backed with an array of point light sources that act as grid of miniature see-through projectors. While capable of potentially arbitrarily wide field of view, this approach has significant limitations: the display must render a full light-field (assuming no eye-tracking), and its ultimate resolution is diffraction-limited.

Spatial Augmented Reality

As an alternate to near-eye AR displays, Spatial Augmented Reality (SAR) approaches merge the physical and virtual worlds through video projection [4]. Shader Lamps [25] first developed the idea of changing the appearance of physical objects with video projection. Several projects since have demonstrated the use of SAR to augment the environment either through multi projector-camera installations [14, 24, 29] or by mounting the projector and the camera onto a movable platform to steer the projection [9, 23, 30].

MirageTable [3] was the first to demonstrate using the real-time geometry capture from depth cameras for view dependent projections on a dynamically changing real world scene. Recently, Benko et al. [2] have extended this concept to handle two simultaneous view-dependent projection for two viewers in the scene in a face-to-face arrangement. Our work builds on these concepts and extends them by incorporating the near-eye OST display for additional visualization capabilities.

Peripheral Projected Displays

Extending the display field of view can cause the user to feel more present and immersed [10, 18], but is also more likely to cause simulator sickness [26]. Extending the FOV of the experience usually results in higher display cost, and lower display resolution and brightness. To balance these tradeoffs, Baudisch et al. propose Focus+Context screens [1] that combine a high resolution computer monitor (focus) with a lower resolution projected periphery (context). Feiner and Shamash showed that one can use AR glasses to extend the working area of their computer monitor [7]. Olwal and Feiner extend these concepts by combining tracked handhelds and large projection screens [22].

We are inspired by IllumiRoom [13] which combines a large television display with projection around it and showed how the peripheral projection can be used to enable completely novel visual effects for games and video content. FoveAR builds on this work, by enabling completely movable and view-dependent views in both the near-eye display and the projected periphery. In addition, FoveAR can affect the image in the near-eye display by projecting content directly behind it.

Bimber et al.'s Occlusion Shadows [5] uses a projector as a replacement for ambient lights in order to programmatically dim the background in the area where AR content is displayed in the OST display (a stationary half-silvered mirror AR display). Extending that work, Maimone et al. [21] uses the projector to compensate for the transparency of OST glasses by projecting light around the virtual objects seen in the glasses. In their work, the augmented content appears only in the glasses and the projector does not extend or add any color content to the user's HMD view, but is rather used as a smart light source.

Zhou et al. [31] combine OST AR glasses with projectors for industrial welding applications. Two displays perform two independent functions: glasses display heads-up 2D information (text and images) and the projector annotates the world by highlighting objects of interest. The projector does not display any view-dependent information, and this approach is not capable of uniformly extending the FOV of the glasses as we demonstrate with FoveAR.

While both Maimone et al. [21] and Zhou et al. [31] combine glasses and projectors, they address different problems than FoveAR. None enables wide FOV view-dependent AR experiences, nor do they explore scenarios that exploit such overlapping displays: e.g., FoveAR demonstrates how surface-bound content can be delegated to the projector, improving its stability (no head tracking noise), and enabling multi-user (view-independent) rendering.

FOVEAR SYSTEM OVERVIEW

FoveAR combines of an OST near-eye display (Lumus DK-32[1] 1280x720) with a ceiling-mounted wide-angle projector (Optoma GT760 DLP[2], 1280x800) paired with a Microsoft Kinect v2 depth camera[3]. Both the projector and the glasses are connected to the same Windows 8 machine (Dual Xeon 2.66GHz, 24GB RAM, Nvidia GTX 980) responsible for processing and rendering all the CG content.

Our OST glasses are equipped with 6 retro-reflective spheres that are tracked using a ceiling mounted, motion capture system, Natural Point's OptiTrack Flex 3 system[4] (8 cameras). The tracking system reports 100 frames per second with a reported tracking latency of ~10ms which ensures relatively smooth low latency operation. We render at 60Hz refresh rate corresponding to the refresh rate of our glasses. Figure 2 shows FoveAR system components.

We use the Unity 5 game engine[5] for rendering both the projected CG content and all the content displayed in the glasses. Unity allows us to use state of the art animation and rendering tools to easily experiment and create compelling content for our experiences.

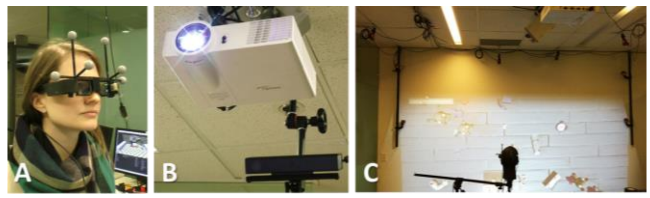

Figure 2. FoveAR hardware: A) Lumus DK-32 display with retro-reflective markers, B) projector and Kinect mounted on the ceiling, and C) OptiTrack Flex 3 motion tracking system.

FoveAR is currently restricted to a single side of our lab, but methods to extend the projection mapping to the entire room have been previously demonstrated (e.g., [14, 30]. If the user stands 6ft away from our projection wall, their visible FOV for the projected content covers more than 100°. However, the user is also free to move around the room and can thus achieve both wider and narrower FOV. All our examples are currently designed for a single user; however, we discuss multi-user possibilities in the Limitations section below.

Prototype FoveAR Experiences

We implemented four FoveAR experiences.

3D Model Animation: In this experience the user can inspect a variety of 3D models placed and animated around the room. For example, Figure 3a shows a 3D virtual helicopter hovering around the room. There is a spotlight attached to the helicopter that illuminates various parts of our real room which is a surface-shaded projected effect. We designed this experience to highlight the difficulty of keeping a moving object in the narrow FOV of the glasses.

Wide-Angle Immersive Simulation: Our second experience shows an AR Rube Goldberg machine where different virtual balls travel along a variety of virtual shelves and obstacles as well as the real furniture in the room (Figure 1). This immersive experience also features different surface shaded textures applied to the real room to change its appearance and it illustrates the full visualization capabilities of FoveAR.

3D Life-Size Telepresence: In this experience, FoveAR shows a life-sized virtual 3D capture of a remote collaborator and enables the viewer to carry out a face to face telepresence

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[1] http://www.lumus-optical.com/

[2] http://www.optomausa.com/

[3] http://www.microsoft.com/en-us/kinectforwindows/

[4] http://www.optitrack.com/products/flex-3/

[5] http://www.unity3d.com

conversation (Figure 3c-d). Without FoveAR, it is impossible to keep the entire remote person visible in the glasses and maintain a comfortable conversational distance (Figure 3d). FoveAR's projection fills in all the relevant peripheral details which allows the viewer to shift their focus without losing the overview of their partner.

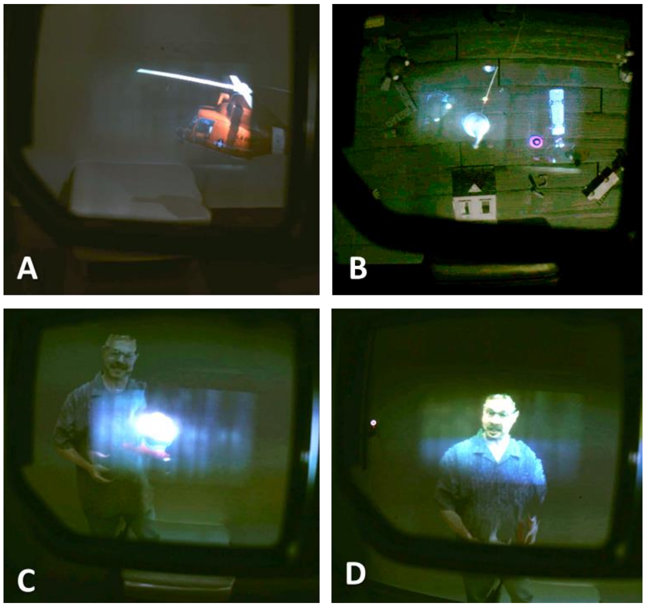

Figure 3. Three FoveAR experiences: A) 3D helicopter animation, B) AR shooter game; C-D) 3D life-size telepresence.

AR Shooter Game: This third-person shooter game allows the player to control a virtual character via a Microsoft Xbox 360 game controller (Figure 3b). The character can run around the surfaces of the room (including the walls and the furniture) fighting the attacking virtual sock puppets. The player benefits from having a wide field of view to keep an eye on the incoming attackers and by seeing all game characters as 3D objects in their stereo glasses.

Dynamic View-Dependent Projections

Given the precise viewpoint and orientation of the glasses as well as the geometry of the room, it is straightforward to render graphics in the glasses so that they appear correct for that viewer's perspective. It is also relatively simple to render graphics in the projector or in the glasses that change the surface appearance of the objects in the room following a surface shading model [25, 29].

Using a projector to render a virtual 3D object so that it appears correct given an arbitrary user's viewpoint is more complex. We implemented it as a multi-pass rendering process similar to [2]. In the first pass, the virtual objects and the real physical geometry are rendered in an offscreen buffer. That rendering is then combined with the surface geometry from the perspective of the projector following a standard projective texturing procedure where only the physical geometry is rendered. We implemented this projection mapping process as a set of custom shaders operating on the real-world geometry or on the real-time depth geometry captured by the Kinect camera.

One significant difference from previous projection mapping approaches is that in the first pass, we render the view from the perspective of the user twice: once for the wide FOV *periphery* and once for the *inset* area which corresponds to the FOV of the near-eye glasses. In the projection mapping pass, we combine both those offscreen textures into a final composited image.

This rendering pipeline requires us to render the scene five times for each frame: twice for the glasses (once for each eye), once for the projected periphery (offscreen), once for the projected inset (offscreen), and once for the projection mapping and compositing process for the projector view. This multi-pass process enables us to have complete control over what content will be presented in which view.

We experimented with four different combinations of content placement between the glasses and the projected inset (Figure 4). The simplest combination is to have completely *replicated* content, i.e., the same content in both the glasses and the projector. The projected inset can also show an *occlusion shadow* for the glasses content or only show the *surface shaded* content that is not view-dependent. Finally, to reduce visual discontinuities, we apply a smooth transition between the periphery and the inset (*surface shaded + blended*).

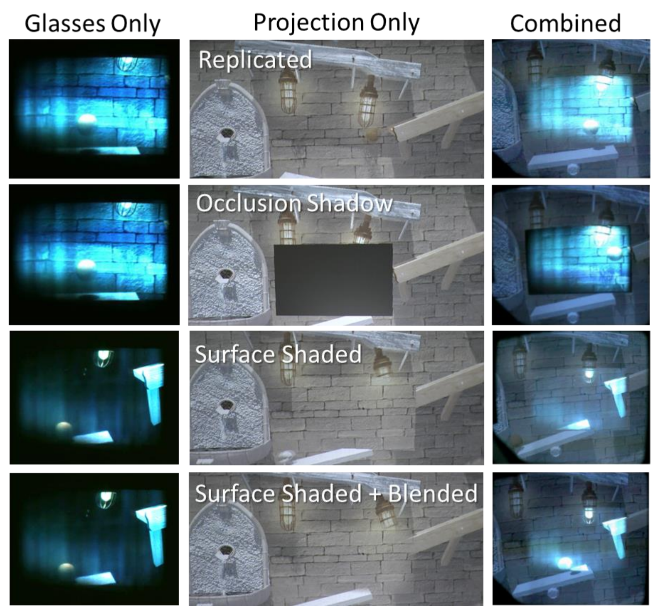

Figure 4. Four content combinations demonstrated in FoveAR.

Calibration

There are four calibration steps needed to ensure that all components are operating together. First, we calibrate the projector with respect to the Kinect camera by projecting Gray code sequences to establish dense correspondences between the Kinect's color camera and the projector. This calibration procedure is described in detail by Jones et al.

[14] and is publicly available as the RoomAlive Toolkit[6]. As part of this calibration we also capture the room geometry and appearance which is then used for view-dependent projection mapping. Alternatively, we can use the live depth-camera feed to drive projections over a changing room geometry similar to [3, 30].

Second, we calibrate the OptiTrack tracking system with respect to the Kinect's infrared camera by imaging the same known calibration pattern consisting of a right-angle bracket with three rigidly mounted retro-reflective markers.

Third, we measure the offsets between the retro-reflective tracking markers and the glasses displays to find the precise location of the two displays. Our glasses tracker mount is custom 3D printed and tightly fitted to the glasses to ensure that the calibration accuracy is maintained.

Fourth, we use a pupilometer to measure the interpupillary distance for each user of our system to ensure that they can correctly fuse the stereo image and that their views correctly align with both the projections and the real world.

DESIGN SPACE CONSIDERATIONS

Jones et al.'s IllumiRoom [13] showed a variety of *peripheral illusions* possible for a static non-transparent inset (TV) and a projected periphery. All such illusions are also possible in FoveAR; however, the range of content combinations in our system is even greater since the experience designer has an unlimited choice of what content to place in the glasses vs. the projector periphery vs. the projected inset. In addition, the FoveAR designer has an additional choice regarding how those views interact with and overlay each other. To help frame the design space, we elaborate on three ways one can reason about the FoveAR content and experiences.

Projection Aids Glasses

In addition to the core idea of extending the FOV, the projection can be thought of as an *assistive modality* to the glasses. Many forms of assistance are possible. For example, the projector can add brightness to the scene, highlight a specific object, or act as dynamic light source to provide Occlusion Shadows [5] for the glasses content. Furthermore, when projecting effects that are bound to real-world surfaces and therefore non-view dependent (i.e., surface-shaded effects), one can avoid any tracking lag or jitter that is often present in the glasses view by including these renderings in the projection only (and not in the glasses). In fact, since both the projector and the room are in static arrangement, such virtual augmentations appear very stable and persistent. This can be also effective for rendering virtual shadows of 3D objects (e.g., see the helicopter shadow in the 3D Model Animation experience – Figure 3a).

Glasses Aid Projection

Alternatively, glasses can be considered an assistive modality to the projector. Glasses can provide stereo views of virtual objects, making them appear spatially three-dimensional rather than as decals projected on the wall. They can add more resolution and brightness to the area of focus. Glasses can also visualize objects when out of FOV of projector or in the projector shadow (i.e., when projection visibility is compromised).

Glasses and Projection Provide Different Content

In some scenarios, it is best to consider the glasses and the projector as being able to provide different, but complementary content. The most obvious example is to enable the private content (e.g., playing cards) to be shown only in the glasses, while the public content is visible in the projection (Figure 5). Similar distinction could be made with other semantic rules. For example, one could chose to display large distant objects as projected, and nearby objects in the glasses, or only the non-view dependent surface-shaded objects in the projection. The glasses could also be treated as a "magic" lens into a projected space offering additional information.

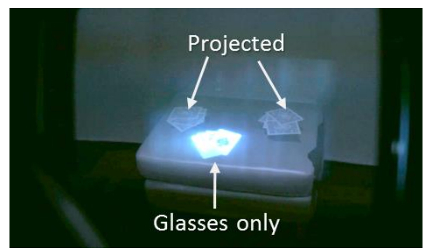

Figure 5. An example FoveAR scenario showing private content (viewer's cards) in the glasses, and the public content (other cards) in the projection. The game is played on real furniture.

The designer could choose to exploit the findings of Benko et al. [2] that the viewer is better able to comprehend the spatial nature of a perspectively projected virtual object if that object is placed close to the projection surface. In FoveAR, one can display the objects close to the real surfaces only as projected to achieve reduction of tracking lag and noise, and move them to the glasses once they are in mid-air away from the surface.

Glasses can also enable an interesting multi-user experience, which is traditionally difficult to achieve with only view-dependent projections [2]. For example, each user's glasses could provide the personalized perspective views for the virtual 3D objects that require them, while the projector can be tasked with projecting the non-view dependent surround to connect the two experiences.

Finally, if precise pixel alignment is achieved, FoveAR could be used to display complimentary content in both the glasses and projection inset to facilitate high-dynamic range virtual

[6] http://github.com/Kinect/RoomAliveToolkit/

images. Currently, the calibration and tracking in our system does not achieve the adequate level of accuracy to verify that.

LIMITATIONS

Our current implementation suffers from noticeable tracking lag, tracking noise, and content misalignment. These issues could be addressed with better tracking and calibration. The literature offers many additional calibration techniques for OST near-eye displays that improve the calibration between the viewer's eye and the displays in the glasses (e.g., [8, 27]). Such techniques, while capable of achieving sub-pixel alignments, tend to be tedious, and need to be repeated each time the user puts on the glasses since we cannot ensure a rigid head mount in our setup. Itoh and Klinker [12] have recently demonstrated a promising approach to automate this calibration by adding a built-in eye-tracker into the glasses.

Another limitation of our system is the lack of radiometric compensation to equalize the brightness and colors across the glasses and the projection as well as across a variety of surfaces in the environment. There are numerous approaches to radiometric compensation (e.g., [28]); addressing this issue is an important consideration for future work.

There are some fundamental challenges with superimposing stereoscopic views on top of monoscopic projections. For example, since our glasses do not allow for any focus control, there will be a focus mismatch for a majority of virtual objects in the scene. Since our projector projects monoscopic content, we assume the "middle" eye position, to minimize disparity in each eye. However, this approach creates a noticeable mismatch between the views shown in the OST glasses at each eye and the projection. This is particularly visible for virtual objects far away from a projection surface (i.e., with big disparity). We have also experimented with setting the projection point to the dominant eye of the user, however that makes the disparity even more obvious in the non-dominant eye. An interesting solution (and future work) would be to project stereo content and convert our OST glasses to also function as shutter glasses [3, 30].

FoveAR is not a mobile solution, which restricts the user to a particular space. While other solutions [14, 30] have demonstrated enveloping entire rooms in projection experiences, those solutions come with significant installation and monetary costs. In the future, it might be interesting to consider combining OST glasses with body-worn projections [9], which could make FoveAR mobile. Also, FoveAR currently requires a rather complicated setup and calibration. However, if the tracking technology is integrated into the glasses themselves, FoveAR could easily be implemented with an addition of a single integrated projector-camera unit.

PRELIMINARY USER FEEDBACK

We demonstrated FoveAR to 5 users (1 female, 31-52 years old). Three out of five were very familiar with VR gaming and head-worn displays. All users commented on the tracking problems which we discussed in the Limitations section. We focus our discussion here on the user feedback regarding the potential of FoveAR.

All users were surprised by the narrow FOV of our glasses (especially those familiar with wider FOV VR goggles). A few commented that OST glasses alone were inadequate to fully appreciate our experiences. While we have specifically designed our experiences to showcase the benefits of FoveAR, we believe that they are representative of many desirable AR scenarios. Three users mentioned that motions in their periphery attracted their attention and all commented that extended FOV was beneficial. This was particularly obvious when looking at the helicopter (Figure 3a) which is difficult to keep in sight due to constant motion. One user (a VR gamer) noted that because the periphery was very stable and virtually noise free, they did not experience simulator sickness even with some tracking noise and lag present in the glasses. Another user commented that they did not have any problems fusing stereo images in the glasses even when the object was partially shown in the glasses and partially in the projector, albeit they noted that the color and brightness differences were more disruptive.

Everyone also noticed the system's complexity and were unsure whether the benefits were large enough to motivate them to install it in their house. Two suggested only using the view-dependent projection. We believe that with the availability of tracking integrated in the glasses and a combined projector-camera unit, much of the complexity in the setup and tracking could be reduced.

The wide-angle immersive simulation and 3D life-size teleconferencing were the two experiences that resonated the most with our users who commented that without the periphery one would have a difficult time understanding the action in the scene. One user commented that the most interesting aspect of FoveAR was the ability to seamlessly combine public and private views. While this is not unique to our system [31], we hope to investigate this further.

CONCLUSIONS

FoveAR is a proof-of-concept hybrid AR display which combines a tracked OST near-eye display and a spatially-registered view-dependent projection. We believe that FoveAR is a unique solution in its ability to create a rich and immersive set of wide-angle AR experiences. We also demonstrate how the glasses and the projector complement each other and offer private stereoscopic views, per-pixel controlled ambient lighting, and surface shading effects not affected by tracking lag or noise. These improvements are beneficial regardless of the FOV.

We believe that our current implementation shows the potential of using FoveAR in real-world scenarios and we are excited to work with content designers to prototype new experiences that take advantage of our unique configuration.

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