1D Eyewear: Peripheral, Hidden LEDs and Near-Eye Holographic Displays for Unobtrusive Augmentation

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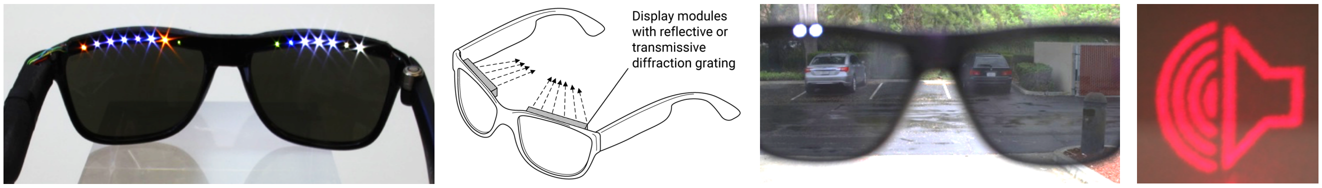

a) Wide-FOV, wireless LED glasses **b) Embedded CGHs** **c) Perspective-correct rendering** **d) Hologram**

Figure 1. 1D Eyewear uses 1D arrays of LEDs and pre-recorded holographic symbols for socially acceptable industrial design. We demonstrate near-eye optical designs using computer-generated holograms (CGHs) for compact presentation of symbology.

ABSTRACT

1D Eyewear uses 1D arrays of LEDs and pre-recorded holographic symbols to enable minimal head-worn displays. Our approach uses computer-generated holograms (CGHs) to create diffraction gratings which project a pre-recorded static image when illuminated with coherent light. Specifically, we develop a set of transmissive, reflective, and steerable optical configurations that can be embedded in conventional eyewear designs. This approach enables high resolution symbolic display in discreet digital eyewear.

Author Keywords

Wearable computing; Head-worn displays (HWD); Head-up displays (HUD); diffractive optics; augmented reality

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies, Interaction Styles.

INTRODUCTION

Compared to cell phones and smart watches, head-worn displays have the unique capability of adapting contextual graphics to the tracked direction of the user's field-of-view. This potential enables seamless and unobtrusive digital augmentation of the user's interactions in the real world.

It is, however, currently challenging to create smart eyewear in small and compact form factors. Current head-up and head-worn systems rely on micro-displays, display drivers, and image generation on a CPU or GPU. These dependencies, in combination with requirements for illumination, make current designs costly and complex from mechanical, electrical, thermal and computational perspectives. The requirement to fit all the electronics, optics and image-generating components, in addition to batteries of sufficient capacity, greatly affects the possible industrial design options. The variations of styles that end users may choose from is thus limited by these constraints, with reduced flexibility in wearability and aesthetics. Recent in-lens displays have started to address some of these issues in more elegant form factors, but widespread adoption is still challenging due to the requirement for high-precision optics engineering [3]. In this paper, we explore perspective-correct rendering for limited displays and advanced near-eye optical designs for advanced image presentation in compact form factors.

CONTRIBUTIONS

- *Wireless glasses* with wide field-of-view LED-arrays and invisible electronics for motion-based navigation guidance in a conventional eyewear design.
- *Optics designs* for transmissive, reflective and steerable display configurations for symbolic displays using compact diffraction gratings.
- *Transmissive optical element* proof-of-concept implementation using computer-generated holograms (CGHs) to display 16 high-resolution symbols.

MINIMAL NEAR-EYE DISPLAYS: LEDS OR SYMBOLS

Similar to the many approaches in previous work, we focus on opportunities for digital eyewear designs that do not rely on microdisplays or image generation, which also frees us from requiring traditional display driver circuitry with dedicated power and thermal implications [3]. We focus less on semantic notifications, however, and instead target interactive applications that require wide field-of-view rendering and smooth inter-pixel transitions (Figure 1) in a practical form factor. We also show how point light sources

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can be extended with high-resolution symbology displays, using pre-stored holographic images that can be projected in the near or far field. This approach allows us to use compact display elements embedded in the actual frames, hiding the technology from the outside world and avoiding modification of the lens optics. [1, 3].

We first describe our 1D AR system, applications and a preliminary evaluation. Based on these results, we developed a set of optical designs and a proof-of-concept optics implementation of a compact self-contained symbology display system.

1D AUGMENTED REALITY PROTOTYPE

Our first prototype implements wireless glasses with an array of 16 LEDs embedded in the top part of a 3D-printed frame. To minimize visibility of the LEDs, they are covered by small apertures, as shown in Figure 1. The left temple of the glasses contains a RedBear Labs Blend Micro microcontroller (Atmel ATmega32u4) with a Nordic nRF8001 Bluetooth Low Energy (BLE) radio. It interfaces with an STMicroelectronics LSM9DS0 inertial measurement unit (IMU) with 9DOFs (degrees-of-freedom) from the accelerometer, gyroscope and magnetometer. The electronics are powered by a 40 mAh LiPo battery. The 16 LEDs are controlled through a Maxim MAX6969 constant-current LED driver using the common shift-register-plus-latch-type serial interface. We implemented custom PWM-multiplexing routines to enable per-pixel brightness control and inter-pixel anti-aliasing. Our main application logic is running on a BLE-connected Android device that provides functionality through different applications. The eyewear streams the 9DOF IMU data to the device and receives LED rendering instructions from the app. This prototype enabled exploration of the most limited perspective-correct rendering using a minimalistic approach with just a sparse row of LEDs invisibly embedded in the glasses frame.

APPLICATIONS

There are three major advantages [1] with minimal eyewear displays, which we explore in our three prototypes.

Discreet Visuals: Notifications

Our hardware uses 16 single-color LEDs, which we choose in a functional way. The leftmost and rightmost LEDs are orange for indications, such as turn-left and turn-right. Next to them on each side are six white LEDs used for continuous animations across the frame using binocular rendering. The center four LEDs (orange, green, green, blue) are exclusively used for notifications. Our Android software allows remote triggering of different notification patterns for all LEDs. See Figure 2.

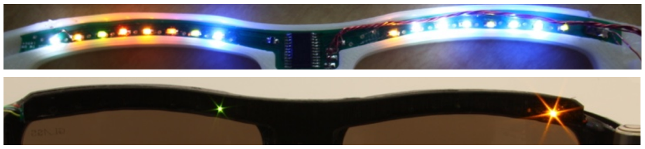

Figure 2. LEDs in different colors and locations allow encoding of 1D spatial guidance and basic semantics.

On-head Sensors: Activity Monitoring and Biofeedback

We implemented biofeedback in the display by leveraging the on-head 9DOF IMU for proof-of-concept activity recognition. Our phone application receives IMU data from the glasses and evaluates the user's head acceleration to detect if the user is active. The number of lit LEDs increases during activity and decreases when motion stops to provide simple biofeedback (Figure 3).

Figure 3. The number of lit LEDs increases after user motion.

First-person Field-of-View: "1D AR" Navigation

We implemented a navigation application using the Google Maps API on Android. The glasses continuously stream 9DOF IMU data to the application over BLE, which is used to calculate the user's field-of-view relative to their location provided by the phone's location services. The angle to the destination is calculated using the user's view frustum and the phone streams the derived position to the glasses such that the appropriate LED(s) can be lit (Figure 4). The microcontroller uses anti-aliasing and binocular rendering to provide a perceived continuous point that moves across the frames (Figure 5).

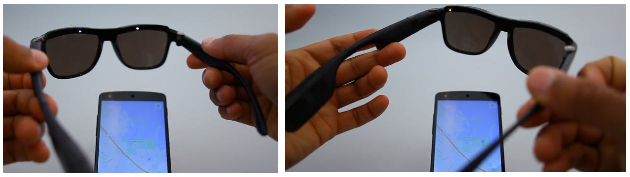

Figure 4. The navigation application fuses location from the phone and head orientation from the glasses. It estimates user's field-of-view to render world-stabilized pixels.

Figure 5. Binocular rendering and anti-aliasing ensures that the pixels animate smoothly across the frame.

PRELIMINARY EVALUATION

For a preliminary qualitative evaluation of our system, we recruited seven participants (two female) from our organization. They were compensated with a gift card.

Procedure

Our interviewer presented the 1D AR navigation scenario and conducted a semi-structured discussion with the participant on potential interest and perceived usefulness. The participant was then fitted with 1D AR glasses, a Nexus 5 mobile phone with our application and a bicycle. We set a destination using our map application, which continuously updates the LED array based on current location and head orientation. This enabled an anti-aliased pixel to always point towards the destination like a compass. The participants were familiar with the area and were told that they were going to one of the restaurants. The route required the participants to reorient themselves multiple times as they had to bike around buildings and natural obstacles. Their \only guidance was the LED array. The task took approximately ten minutes.

Results

Participants ranked the concept and the navigation experience on a 5-point Likert Scale (shown in Figure 6). Everyone, except one participant, were very or extremely interested in the concept. All participants found it very, or extremely useful and everyone were able to complete the navigation task. The majority (6/7) found the instructions easy to understand and were confident in the directions (5/7). However, most participants also found the directions slightly (4/7) or moderately (2/7) distracting, as shown in Figure 6.

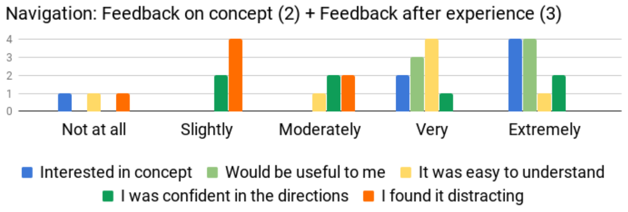

Figure 6. The majority of the participants found the navigation concept interesting and potentially useful, and appreciated the experience using the 1D AR system, even if it was slightly distracting.

Discussion

Our qualitative concept evaluations show a positive attitude towards these types of displays. The experiments indicate that even a simple array of LEDs can support minimal interactions by taking advantage of discreet visuals, hands-free access and motion sensing. Each application and use case must however carefully consider ergonomic aspects, such as brightness, location, motion and emission cone to carefully balance noticeability against distraction and discomfort, as well as light leakage and noticeability to the outside world for social acceptance. The result from the navigation experiment is encouraging, although it also illustrates some perceived distraction. The main criticism, unsurprisingly, seems to be related to the limited semantics that can be conveyed through point light sources. This feedback inspired us to develop an in-eye symbology display that would be compatible with a similar unobtrusive, lightweight form factor, but that could show content with more meaning.

IN-EYE SYMBOLOGY PROJECTION PROTOTYPE

The expressiveness of an array of light sources in a near-eye form factor is limited to notifications and directionality. However, by using them as illumination for holographic optical elements, we can also encode meaning through high-resolution symbology. We use CGHs to enable very compact symbol generation. The CGHs encode far field diffraction patterns that project a pre-recorded static image when illuminated with coherent light.

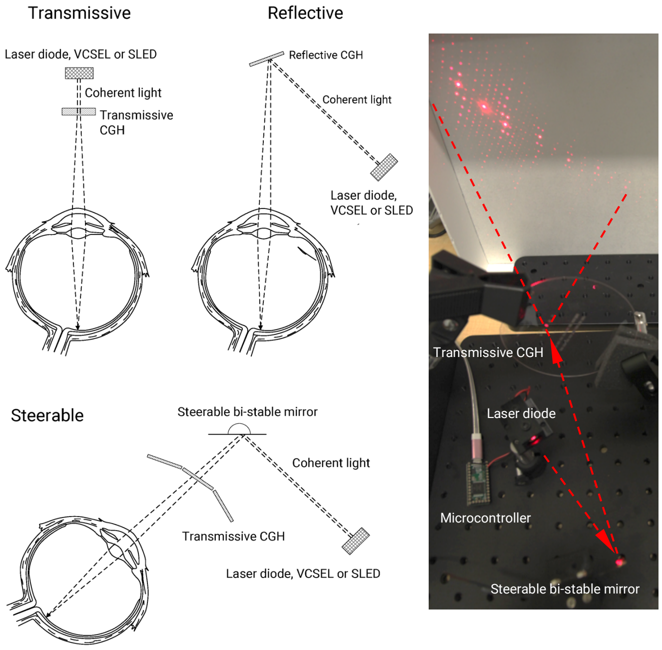

Figure 7. The *Transmissive* CGH projects images in a compact form factor. The *Reflective* CGH allows flexibility for use with offset lasers, but compromises compactness. The *Steerable* configuration uses a bi-stable mirror to redirect coherent light onto an array of transmissive CGHs for addressability with a single light source. Photo shows Steerable proof-of-concept configuration.

Light Sources and Display Configuration

Although we tested our device with traditional laser diodes, more compact, low-threshold coherent light sources are better suited for a wearable device. Superluminescent diodes (SLEDs) or vertical-cavity surface-emitting lasers (VCSELs) are particularly promising for our applications. Figure 7 shows how our designs may operate in either transmission or reflection modes.

Addressable Symbol Display

SLEDs or VCSELs coupled to each symbol enables direct addressability. In our prototypes, we also consider a laser diode in combination with a steerable mirror. We use a custom-designed bi-stable mirror, which has two hall effect sensors and 2D actuation to control mirror orientation in 2D. This approach has a small footprint and only uses power when changing the displayed symbol.

Computer-Generated Hologram Design and Fabrication

We designed and fabricated 16 different CGHs on a strip (2×8 symbols), each producing a different far field diffraction pattern that we imaged using our compact projection setup. The CGHs were designed using an iterative algorithm (IFTA: Iterative Fourier Transform Algorithm) and fabricated via traditional optical lithography (via a mask aligner), followed by dry etching into the underlying silica wafers. The etching can be set to produce optimum efficiency in transmission mode, or in reflection mode by using an additional sputtered metal layer. A key advantage of our approach is that we can make the different images

Figure 8. CGHs of common icons for mobile devices. For illustrative purposes, we show the zero-order image (center dot). Icons are shown with conjugates, a result of our binary fabrication. Only one symbol is visible to the user at a time.

appear in the same location in the line of sight, despite being produced by spatially offset CGHs. Their different incident illumination angles are compensated in the CGHs to create matching diffraction angles that control the object location in the far field.

Transmissive Imaging in Projected Setup

Our projection setup steers a laser beam using our electronic mirror onto one of the 16 transmissive diffraction gratings. Figure 8 shows what the eye would see using a diffuse screen behind the transparent layer. The center dot is a zero-order image and is an artifact of diffraction (low efficiency in our configuration). The CGHs are duplicated in order to increase the eye box. Only one of these icons would be visible at any given time. As the user switches viewpoint, a different replicated icon would appear.

FUTURE WORK

We are currently further miniaturizing the driver electronics and are investigating SLEDs or VCSELs that could be placed much closer to the diffraction strips bearing the CGHs. Furthermore, mass replication of such CGH strips will be done via embossing on thin plastic sheets (plate-to-plate or roll-to-roll) from an etched fused silica master to reduce costs and allow for curved integration. That will, however, require addressing process challenges to develop assembly, bonding and connectorization techniques to enable a fully integrated optoelectronic system. We are also interested in evaluating our prototypes at scale for better ecological validity.

RELATED WORK

A comprehensive review of head-worn optical designs [3] highlights interdisciplinary challenges across many engineering fields to enable systems that are compatible with ordinary eyeglasses. In-lens display optics that are compatible with ophthalmic processes are yet to appear at scale. Amft et al. discuss alternative approaches for “Making Regular Eyeglasses Smart” [1], including the opportunity to embed optical feedback in the glasses rim. Researchers have leveraged this potential for using peripheral vision displays for subtle notifications and feedback. Costanza et al. [4] leverage “visual field narrowing” [8] during high workload to implicitly manage the distraction of peripheral displays. Their eye-q system has 4 LEDs on the left and right edges of the temple front for peripheral notifications. Campbell and Tarasewich [2] explore expressivity and comprehension with a 3-pixel display in a controlled lab study. Xiao and Benko [9] show how 4×14 LED arrays can complement main displays for extended field-of-view, whereas Nakao et al. [6] report on smart glasses with 8×8 dot matrix displays at each temple for peripheral notifications. AmbiGlasses [7] show that study participants can successfully approximate LED location. In parallel, Maimone et al.’s Pinlight Displays [5] demonstrate wide field-of-view AR using a sparse array of near-eye point light sources and spatial light modulators.

CONCLUSIONS

In this work, we demonstrate the potential for lightweight augmentation through arrays of miniaturized light sources, optionally coupled with diffractive gratings to enable semantic expressivity in a compact, low-power form factor. While we acknowledge the limitations of not having access to a fully addressable digital matrix display, we also observe the opportunities for lightweight interactions in a socially attractive industrial design. We would like to emphasize that this design is intended to complement existing head-worn displays, rather than replace them. One promising opportunity is to combine these wide field-of-view, low-resolution, low-power displays with emerging in-lens optical designs.

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