Computational Phase-Modulated Eyeglasses

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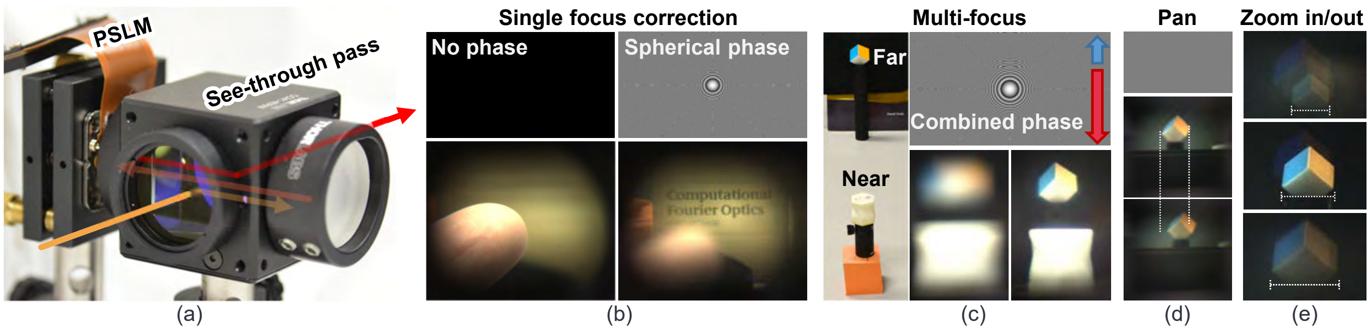

Fig. 1. Overview of our proposed system. (a) The single phase-only spatial light modulator (PSLM) setup in Sec. 4.1. (b) Demonstration of the focus correction with the single PSLM setup where a near-sighted view is corrected by displaying a spherical phase function on the PSLM. (c) Demonstration of a multi-focus function with the single PSLM setup. Rendering different spherical phase functions allows a viewer to focus two objects at different depths simultaneously. (d) A simple image shift is done by displaying a plane wave function on a PSLM. (e) A dual PSLM setup can also provide zooming capability. .

Abstract—We present computational phase-modulated eyeglasses, a see-through optical system that modulates the view of the user using phase-only spatial light modulators (PSLM). A PSLM is a programmable reflective device that can selectively retardate, or delay, the incoming light rays. As a result, a PSLM works as a computational dynamic lens device. We demonstrate our computational phase-modulated eyeglasses with either a single PSLM or dual PSLMs and show that the concept can realize various optical operations including focus correction, bi-focus, image shift, and field of view manipulation, namely optical zoom. Compared to other programmable optics, computational phase-modulated eyeglasses have the advantage in terms of its versatility. In addition, we also presents some prototypical focus-loop applications where the lens is dynamically optimized based on distances of objects observed by a scene camera. We further discuss the implementation, applications but also discuss limitations of the current prototypes and remaining issues that need to be addressed in future research.

Index Terms—Computational eyeglasses, augmented vision, phase modulation, LCoS, spatial light modulator.

1 Introduction

Head-mounted displays and computational eye-wear have been an active research area for decades. While they have seen wide applications in Virtual Reality and Augmented Reality, more recently researchers have also investigated their application for compensating visual impairments [18], [25] or enhancing human vision [20].

The general idea is that by using the integrated display, we can go beyond the limitations of traditional glasses that are constrained by their optics. These kinds of visual enhancements or computational glasses have in common that at their core they utilize head-mounted displays and consequently are actual displays. They all integrate a light-emitting component (e.g. LCD, OLED, laser) and the vision enhancement or vision augmentation is realized by adding light to the environment on a per-pixel level.

However, if we consider traditional optics, there are other ways to overcome the limitations of traditional glasses apart from integrating transparent displays in the optical path of the wearer. In this paper, we propose a completely new approach for computational eye-wear: computational phase-modulated eyeglasses (Fig. 1). Instead of traditional head-mounted displays that add light, computational phase-modulated eyeglasses act as a programmable optical system that allows us to modulate incoming light from the environment using phase-only spatial light modulators (PSLM).

A PSLM is either a reflective or transmissive optical system that can modulate the phase of the incoming light (Fig. 2) and has already found application in observational astronomy and adaptive optics [49]. There, PSLM work as a dynamic lens that can spatially control lens conditions.

In this work, we propose a first prototype exploring the usage of PSLM in digital eye-wear while also showing the potential of its use. In particular, we demonstrate how computational phase-modulated eyeglasses can be used for computational focus correction even allowing to change the focus at runtime or providing several focus planes at the same time.

Both features allow completely new forms of smart eyeglasses

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correcting a refractive error. Furthermore, we demonstrate the capability of computational phase-modulated eyeglasses to shift the image in the user's view or even zoom into/out a scene (Fig. 1, d and e. This allows for new applications that enhance human vision for non-impaired users using digital eye-wear.

There are other head-mounted display systems using phase-only spatial light modulators (e.g. [31], [35]). However, these works are again displays that focus on modulating either collimated RGB laser beams or controlled light from a flat display panel, not environment light. Modulating environmental light realizes to correct human vision. This difference is important as phase-only spatial light modulators only work with correctly-angled polarized light. This is rather easy to achieve for display systems using lasers or flat display panels but challenging for natural light requiring a completely different approach.

Similarly, there are other computer-controlled optical systems that can be adjusted at runtime and are used for example in camera systems and some even in head-mounted displays. Examples are liquid lenses for a focus-tunable camera [36], micro-lens arrays for light field cameras [5], [8], [40], or Galvano mirrors for pan-tilt [41]. Another closely related research is an adaptive camera system [49], where the system uses a PSLM to cancel optical aberration in the optical path from a camera to an object. The correction requires additional wavefront optics to measure the aberration in realtime.

While our system is not a camera system but a computational eye-wear (Fig. 3), the programmable optics using PSLMs can ideally achieve all these functionalities thanks to its programmable phase modulation. Furthermore, our system can realize other optical effects such as a multi-focus function. Consequently, to the best of our knowledge, we are the first to introduce such an eyeglasses system and systematically demonstrate the various potentials of see-through eyeglasses using computational phase-modulation.

In this paper, we describe two see-through prototypes for computational phase-modulated eyeglasses: one consisting of a one PSLM (Single PSLM) and the other consisting of two PSLMs (Dual PSLM). With the Single PSLM prototype, we demonstrate basic optical effects including focusing, pan, light field (lens-array images), and simultaneous bi-focusing effect. With the Dual PSLM prototype, we further demonstrate that the system can also achieve field of view (FoV) manipulation, namely optical zoom. In the discussion section, we also explore current limitations and future research directions of the phase-modulated eyeglasses.

Overall, our main contributions include:

- An eyeglasses concept using one or two PSLM for computationally modulating environment light to enhance human vision.
- Providing the first implementation of computational phase-modulated eyeglasses demonstrating different optical effects and their possible application for enhancing human vision.
- Discussion of research directions by raising current issues of computational phase-modulated eyeglasses requiring further research.

Note that, in our system modules can essentially be cascaded to increase the number of PSLM layers more than two, which could improve the phase modulation resolution and overcome limitations due to the pixel pitch of the panel.

2 Related Work

There are several research areas strongly related to this paper. In the following, we provide a brief literature review for each of these areas, which are (1) applications of PSLM and programmable optics, (2) computational cameras, and (3) vision augmentation using existing computational eye-wear. Table 1 summarizes the capability of different programmable optics that are used in eyeglasses or camera optics including our approach.

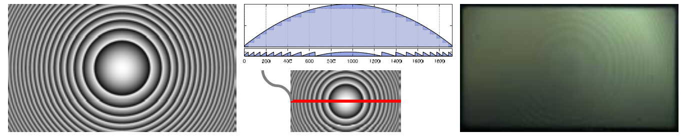

Fig. 2. A PSLM can display a computational lens. (left) An input spherical phase pattern. (middle) The intersection of the pattern. The pattern is a Fresnel lens of a convex lens. (right) An actual lens image captured while focusing at the surface of the PSLM. The phase pattern behaves as if there is a thin lens layer on the PSLM.

2.1 PSLM and Programmable Optics

A PSLM is a liquid crystal on silicon (LCoS) device specifically designed to only modulate the phase of incoming light. The technology is well established in the LCoS community [22], [54] and has been used in a wide range of applications in physics [4], [26]. Here, advanced applications include adaptive optics for ophthalmoscopy to capture retinal cells while canceling image blur due to the eye optics [45] and computer-generated holograms [37], [46]. Some recent works also investigate using PSLMs for near-eye displays [31], [35] where PSLMs have seen applications to build near-eye displays that overcome the restriction of a fixed focal plane.

There are also works on using PSLMs to control scene light. Martinez et al. [33] proposed a wide FoV foveated imaging system for a quasi-monochromatic scene. They use a PSLM to correct aberrations of a plano-convex wide-FoV lens system. They later extended the system to cover a larger FoV [6].

There are other programmable optics, which are mainly used for adaptive zoom systems. Focus tunable lenses are common components used for this purpose [28], [30]. The limitation of the focus tunable lens is its limited FoV. Wick and Matrinez [53] simulated an optical zoom design using a transmissive spatial light modulator (SLM) that achieves diffraction-limited performance for the visible spectrum with 3.9 times magnification. Wei et al. recently presented an optical zoom system with two transmissive SLMs and verified the functionality with a laser [51]. Deformable mirrors are another type of PSLM based on micro electro mechanical systems (MEMS). Huang et al. proposed a compact optical zoom camera module using two deformable mirrors [15]. While they are similar to LCoS-based PSLM, the modulation power is normally smaller.

Digital mirror devices (DMD) are other MEMS devices that can switch the direction of light rays in two directions for each pixel. Galvano mirror devices are two-axis mirror devices that can control the direction of the view swiftly, thus are used in high-speed vision applications [41]. Amplitude-only SLMs with transmissive liquid crystal displays are common for coded aperture applications.

In addition to those active optical components, static programmable optics include micro-lens arrays, such as for light field imaging, and diffractive lenses such as for computational photography [11], [44].

Apart from lens systems, Itoh et al. used PSLM as a pixel-wise color filter by polarization interference and demonstrated an optical see-through subtractive display [19].

TABLE 1
Comparison of the use of programmable optics in the computational camera area. We also indicate if these programmable optics have found application in traditional HMDs or eyeglasses. In each cell with "moderate" in the drive rate column is defined up to around 1000Hz. (*) Assuming the viewing area that is obtained by driving the mirrors. [a]: [41], [b]: [10], [36], [42], [c]: [28], [30],[d]: [27], [e]: [40], [f]: [39], [g]: [39], [h]: [14], [i]: [1], [j]: [15], [k]: [32], [l]: [29], [38], [m]: [38], [n]: [51], [56].

	Optics Feature				Optical Operations						Use
Main optics	Dynamic	Module Size	Drive rate	Aperture	HDR	Light field	Focus	Multi focus	Shift	FoV	HMD
Galvano mirror	yes	large	high	high(*)					[a]		
Liquid lens	yes	small	moderate	low			[b]			[c]	✓
Diffractive lens	no	small	-	moderate				yes			
Diffractive LC lens	yes	small	moderate	moderate			[d]				
Lens-array	no	small	-	moderate		[e]					✓
DMD	yes	moderate	high	moderate	[f]					[g]	✓
Deformable mirror	yes	moderate	moderate	moderate	[h]		[i]			[j]	✓
Amplitude SLM	yes	moderate	moderate	moderate	[k]	[l]	[m]			[n]	✓
PSLM (Our system)	yes	moderate	moderate	moderate	no	yes	yes	yes	yes	yes	✓

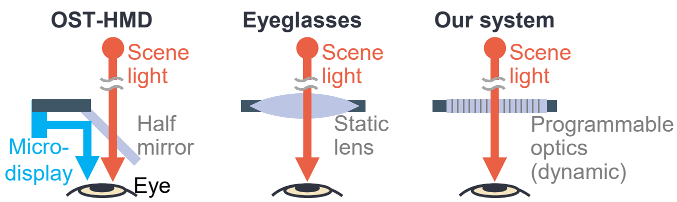

Fig. 3. General overview of traditional eyewear and our approach. (left) A typical OST-HMD optics. (middle) Eyeglasses. (right) Conceptual optics design of our approach.

2.2 Computational Cameras & Imaging

A computational camera applies the joint design of optics with computational algorithms to acquire most plenoptic dimensions that cannot be captured with traditional cameras [52], [55]. Researchers applied not only a static optical element such as a lens-array [40] but also programmable optics as a component of computational cameras, and demonstrated various imaging technologies such as extended depth-of-field (EDOF) videography using a liquid lens [36], high dynamic range (HDR) [32] and flexible field-of-view (FoV) [56] imaging using LCDs, and light field acquisition using an LC (Liquid Crystal) array [29]. Programmable optics also play an important role in computational displays [34] such as an HDR projector using a deformable mirror [14]. In augmented reality (AR), there are works on head-mounted systems to correct human vision when using such displays such as correcting myopia by deformable membrane mirrors [1] or by free-form optics [21] and correcting presbyopia by focus-tunable lenses [42]. Although many computational imaging designs have been explored, most technologies are basically tailored to capture or display lightfields.

Nayar et al. applied a DMD to realize a programmable aperture camera for HDR capturing and two-state FoV [39]. Another programmable aperture camera achieves light field acquisition and defocus deblurring using LCoS [38]. However, these techniques require a long optical path for relay optics.

To the best of our knowledge, there is no survey on PSLM in the context of computational cameras in the computer vision community [34], [52], [55]. For example, an excellent survey of computational cameras by Zhou and Nayar from 2011 [55] mentions phase plates but not PSLMs. A few works recently explored the potential of PSLM in the computational imaging research field [2]. We thus also aim to promote the potential of PSLMs for computational eyeglasses by demonstrating various imaging techniques. Overall, while PSLMs have been used in some applications in the imaging domain, little work has been done that considered to use them for building eyeglasses that have the potential to compensate visual impairments or extend human capabilities [27]. Our computational phase-modulated eyeglasses apply programmable optics for capturing multiple plenoptic dimensions in a compact form factor. In particular, we apply either single or multiple PSLMs, considering each of the elements as a programmable, free-form lens.

2.3 Vision Augmentation

The overall motivation of our work is to enhance our vision using dynamic optics. Some research works already explore vision augmentations by integrating programmable optics and displays. Tamburo et al. developed a smart headlight where they combine an SLM with an automotive headlight to adaptively illuminate a driving scene [48]. Hiroi et al. developed HDR glasses that consist of an amplitude-only SLM (LCD) and a see-through head-mounted display [12]. Their system dynamically and selectively modulates the scene light brightness by filtering overexposed light via the SLM and compensating underexposed light via the see-through display.

Hwang and Peli proposed a vision augmentation system for visual impairment. Their system utilizes optical head-mounted displays to overlay edge information in the FoV of the user via a near-eye display [16]. Similarly, Langlotz et al. proposed to use computational glasses [25], modified optical head-mounted displays that allow pixel-precise moderation of the environment via the display [24], for compensating the effect of color-vision deficiency.

Another example of a recent work on vision augmentations is the work on adaptive optics [10] or Autofocals [42] that use focus-tunable lenses to compensate for presbyopia. Similarly to our work they do not use a display to add light but only modulate incoming light using adjustable lenses. However, both systems are specifically designed for one purpose - dynamic focus correction - while the proposed approach in this paper is a more generic approach which goes beyond simple focus correction and also allows to simulate

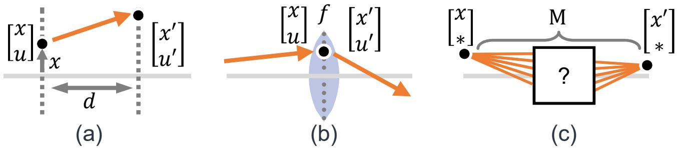

Fig. 4. Ray transfer matrix analysis. (a) A ray transfers space. (b) A ray transfers a thin lens. (c) Two points that are conjugate each other for a given ray transfer matrix.

bifocal lenses for simultaneously focus on near and far objects (not possible with Autofocals) or other optical operations (e.g. zoom or optical shift). This generalizability however, comes yet with the drawback of lower visual quality which we will discuss together with solutions as part of this work.

Overall, while PSLMs have seen application in various optical systems, they have not been considered for computational eyewear to corrects for different kinds of visual impairments or even enhance human vision. Similarly, while there have been different attempts to integrate computational optics in eyewear, they have mainly been used in the context of AR glasses to implement dynamic focal planes or holographic displays. Only a few works have investigated computational optics for enhancing human vision. Those few works were usually designed for a very specific vision problem. Instead, in this work we are the first investigating the use of PSLMs for general vision enhancements. While the visual results are yet behind some specific solutions (e.g. only focus correction) they allow for a wide range of enhancements that is all configurable at runtime while still have enough potential for future improvement of the visual quality.

3 Phase Modulation for Digital Eyeglasses

For centuries, traditional eyeglasses used the same principles. They integrate optical elements that correct the refractive error by refocusing the incoming scene light (see Fig. 3 middle).

More recently, researchers proposed to turn optical see-through head-mounted displays into vision aids. Yet most of these approaches use a common hardware concept. A light emitting element, often integrated into the frame, emits light that later forms a digital image (the display). Within the path of the user's eye sits an optical combiner that combines the light from the display with the incoming light from the scene (see Fig. 3 left). While academia and industrial research have brought up different forms of optical combiners and waveguides for transporting the light towards the user's eye [23], the general principle remains the same. Common to all these approaches is that they do not change the incoming scene light but the scene is moderated (e.g. for visual impairments) by adding light via the integrated display.

In this work, we propose an approach that is contrary to existing approaches for computational eyeglasses. Instead of adding light, we manipulate the incoming environment light via one or several PSLMs. As we will show, integrating and combining PSLMs allows for computational eyeglasses that exceed the potential of traditional glasses that rely on non-computerized optics, as well as traditional computerized optical eyeglasses. The general idea is that incoming environment light is directed onto one or several computer-controlled PSLMs that allow modulation of the incoming light in a way that allows us to refocus the light to correct refractive errors including these requiring varifocal lenses (see Fig. 3 right). We also show applications that support non-impaired users when interacting with their physical environment such as image shifts or zoom. Note that the view shift application may also have potential to support people with strabismus.

In the following, we provide the underlying principles on how to model a lens using PSLMs and introduce the parameter space for PSLMs demonstrating how to tune the lens parameters of PSLMs to achieve certain desired optical effects (Figure 5).

3.1 Phase Modulation Function

In Fourier optics, an optical operation is described by a phase function $\phi(x,y)$ that delays the phase of the incoming light passing through the x-y plane. While the phase function ϕ can be arbitrary, a common function is the spherical wave function representing a thin lens:

$$\phi(x,y) = -\frac{\pi}{\lambda f}(x^2+y^2), \tag{1}$$

where f is the focal length of the lens and λ is the wavelength of the target light.

A phase function $\phi(x,y)$ is normally continuous and not bounded whereas a PSLM is pixelated and has a maximum retardance value $\phi_{\max}$ that describes how much it can delay the phase of an input light wave. We need to consider these conditions to reproduce the phase function on a PSLM.

Given a pixel position (u,v) and the pixel pitch p of the PSLM, a phase function $\phi(x,y)$ is simulated by $\mathrm{mod}(\phi(u/p,v/p),\phi_{\max})$, where $\mathrm{mod}(\cdot,\cdot)$ is a modulo operator and $\phi_{\max}=2\pi$. An example spherical phase image is shown in Fig. 2.

3.2 Ray Transfer Matrix

In the following, we describe the concept of a ray transfer matrix. For clarification, we use lower case letters to denote scalar values such as a distance d. Uppercase typewriter fonts denote matrices such as a space matrix $\mathtt{S}$. Zero elements of a matrix sometimes kept blank for readability reasons.

In geometrical optics, we denote a ray $\mathbf{r}$ by its height and gradient from the optical axis as $\mathbf{r} := \begin{bmatrix} x & u \end{bmatrix}^{\mathrm{T}}$. We have two cases: when the ray transfers the space along the axis at distance d (Fig. 4a), and when the ray passes through a thin lens with the focal length f (Fig. 4b). For each case, the new state of the ray $\mathbf{r}' := \begin{bmatrix} x' & u' \end{bmatrix}^{\mathrm{T}}$ can be defined as $\mathbf{r}' = \mathtt{S}(d)\mathbf{r}$ and $\mathbf{r}' = \mathtt{L}(f)\mathbf{r}$ where

$$\mathtt{S}(d) := \begin{bmatrix} 1 & d \\ & 1 \end{bmatrix}, \; \mathtt{L}(f) = \begin{bmatrix} 1 & \\ -f^{-1} & 1 \end{bmatrix} \tag{2}$$

are called the translation matrix and the lens matrix respectively. In general, such 2-by-2 matrices are called the ray transfer matrix or ABCD matrix $\mathtt{M} = \begin{bmatrix} a & b; & c & d \end{bmatrix}$. When light rays with arbitrary angles from a point are transferred by a ray transfer matrix $\mathtt{M}$, and if the output rays all pass through another point, we call that the two points are conjugate (Fig. 4c). In such a case, $\mathtt{M}$ must satisfy $b=0$.

3.3 Focus Correction in a Single PSLM Setup.

The most common usage of traditional eyeglasses is to correct refractive errors that requiring refocusing the scene light. In Fig. 5a and Fig. 6, we show the general idea of the focus correction. We model our system by thin lenses as in geometrical optics. Assume that we have an eye with the focal length f_{E}, and we place an object at distance d_{O} from the eye so that it forms an image on the retina

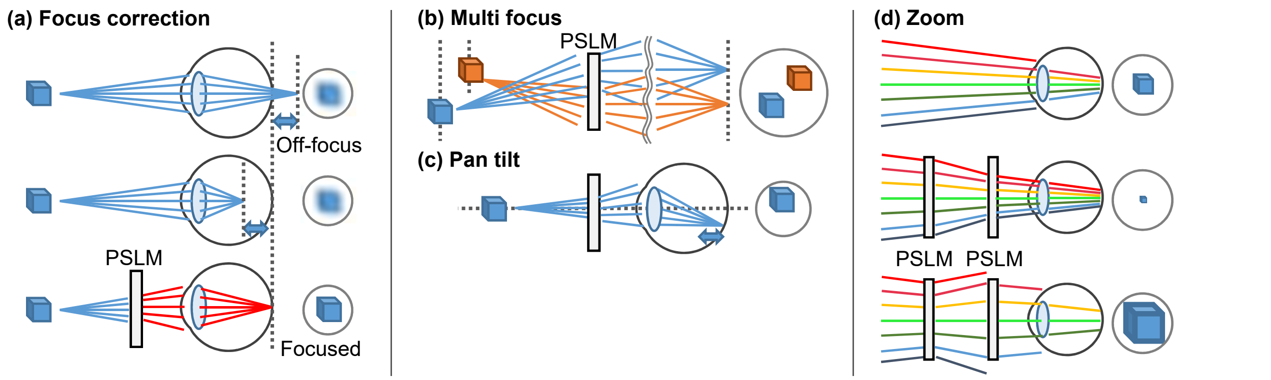

Fig. 5. Optical operations realized in our computational glasses. (a) Focus correction. (top/middle) Native vision with near-/far-sighted vision. (bottom) By controlling the PSLM properly, we can correct the visual imperfection. (b) Multi-focus. We modulate the PSLM so that *all* objects focus at the user's view. (c) Pan tilt (or image shift). We can shift the imaging position of the scene light on the retina. (d) Optical zoom. By combining two PSLMs and modulate them in a synchronized way, we can expand or shrink the FoV of the user.

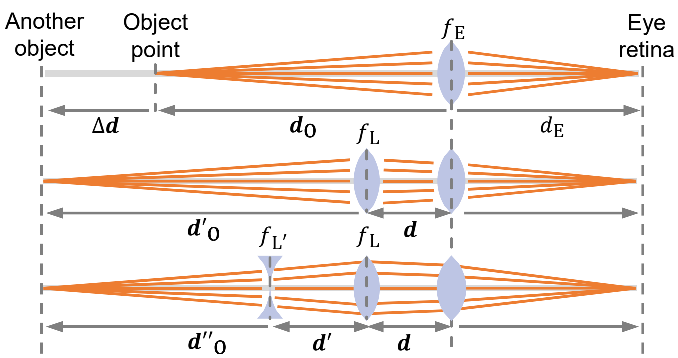

Fig. 6. Schematic diagram for the explanation of the lens simulation in Sec. 3. Note that the focal length of the additional lens, f_{L}, usually takes a negative value, so the lens becomes a concave lens. In this figure, however, we draw it as a convex lens for the readability of the figure, and switching the sign of f_{L} does not affect the derivation of f_{E}.

at distance d_{E}. The ray tracing matrix from a light ray $\mathbf{r}_{\mathrm{O}}$ departing from the object to a ray $\mathbf{r}_{\mathrm{E}}$ at the eye becomes:

$$\mathtt{M}_1 = \mathtt{S}(d_{\mathrm{E}})\mathtt{L}(f_{\mathrm{E}})\mathtt{S}(d_{\mathrm{O}}). \tag{3}$$

We then place an extra lens f_{L} at the distance d from the eye lens center. The two lenses now form a combined lens and we constrain f_{L} so that another object at $d'_{\mathrm{O}} := d_{\mathrm{O}} + \Delta d - d$ forms an image on the retina. The resulting matrix is:

$$\mathtt{M}_2 = \mathtt{S}(d_{\mathrm{E}})\mathtt{L}(f_{\mathrm{E}})\mathtt{S}(d)\mathtt{L}(f_{\mathrm{L}})\mathtt{S}(d'_{\mathrm{O}}). \tag{4}$$

Using the above equations and the conjugate condition of $\mathbf{r}_{\mathrm{E}}$ and $\mathbf{r}_{\mathrm{O}}$, namely $\mathtt{M}_1[1,2] = \mathtt{M}_2[1,2] = 0$, we get

$$f_{\mathrm{L}} = -(d_{\mathrm{O}} - d)(\Delta d + d_{\mathrm{O}} - d)/\Delta d. \tag{5}$$

Note that, in normal eyeglasses, we chose the lenses so that they shift the farthest focus distance of the user's eyes to infinity.

3.4 Zoom in a Dual PSLM Setup.

Assume that we place the second PSLM between the object and the first PSLM. We denote the distance between the object and the second PSLM as d''_{O} and the distance between the two PSLMs d'. The second PSLM works as another lens with focal length $f_{\mathrm{L}'}$, thus the ray tracing matrix becomes:

$$\mathtt{M}_3 = \mathtt{S}(d_{\mathrm{E}})\mathtt{L}(f_{\mathrm{E}})\mathtt{S}(d)\mathtt{L}(f_{\mathrm{L}})\mathtt{S}(d')\mathtt{L}(f_{\mathrm{L}'})\mathtt{S}(d''_{\mathrm{O}}). \tag{6}$$

From the conjugate conditions, we know that $\mathtt{M}_1$ from (3) and $\mathtt{M}_3$ from (6) meet $\mathtt{M}_1[1,2] = 0$ and $\mathtt{M}_3[1,2] = 0$, respectively. Furthermore, we can define the vertical magnification rate of the new setup compared to the original setup as $\alpha = \mathtt{M}_3[1,2]/\mathtt{M}_1[1,2] > 0$. We also know that $d_{\mathrm{O}} = d''_{\mathrm{O}} + d' + d$. From the above conditions, we can compute the lens parameters as:

$$f_{\mathrm{L}'} = \frac{\alpha d' d''_{\mathrm{O}}}{(a-1)(d''_{\mathrm{O}} + d')},\ f_{\mathrm{L}} = \frac{d'(d''_{\mathrm{O}} + d')}{(1-a)d''_{\mathrm{O}}}. \tag{7}$$

For $\alpha \neq 1$. Note that the sign of $f_{\mathrm{L}'}$ and f_{L} differ from each other as expected, and the FoV of the user is scaled by α^{-1}. In other words, the system works as a zoom-out lens when $a > 1$ ($f_{\mathrm{L}'} > 0, f_{\mathrm{L}} < 0$) and a zoom-in lens when $a < 1$ ($f_{\mathrm{L}'} < 0, f_{\mathrm{L}} > 0$).

4 Implementation

We designed two prototypes; one consisting of a single PSLM and the other combining two PSLMs. We first explain the optics design of the systems (Sec. 4.1) and then provide a list of actual optical components and cameras (Sec. 4.2).

4.1 Optics Design

The systems must deliver the scene light to the user's view through PSLM(s) while avoiding the 0-th order reflection, namely light reflected back from a PSLM without phase modulation. We also take into account that the system does not extremely shift the viewpoint of the user. Considering these factors, we designed our computational glasses based on a polarized beam splitter (PBS) and waveplates.

Figure 7 shows a schematic diagram of our optics design. The steps of bypassing the scene light to the eye through PSLM(s) are the following: In (1), the scene light that consists of the p and s waves reaches to a linear polarizer tuned to only pass the s wave.

Now we have two implementations depending on if we have a single PSLM setup or dual PSLM setup. We first explain the single PSLM setup. In (2), the passed s wave is reflected by the PBS and reaches to a $\lambda/4$-waveplate. In (3), the $\lambda/4$-waveplate rotates the polarization of the s-wave light by 45° and the light reaches to the PSLM. In (4), the PSLM returns phase-modulated light. The modulated light comes back to the $\lambda/4$-waveplate, which makes the modulated light as a p wave instead of a s wave. In (5), the modulated p wave passes through the PBS and reaches another linear polarizer of 45° that shifts the p-wave at 45°.

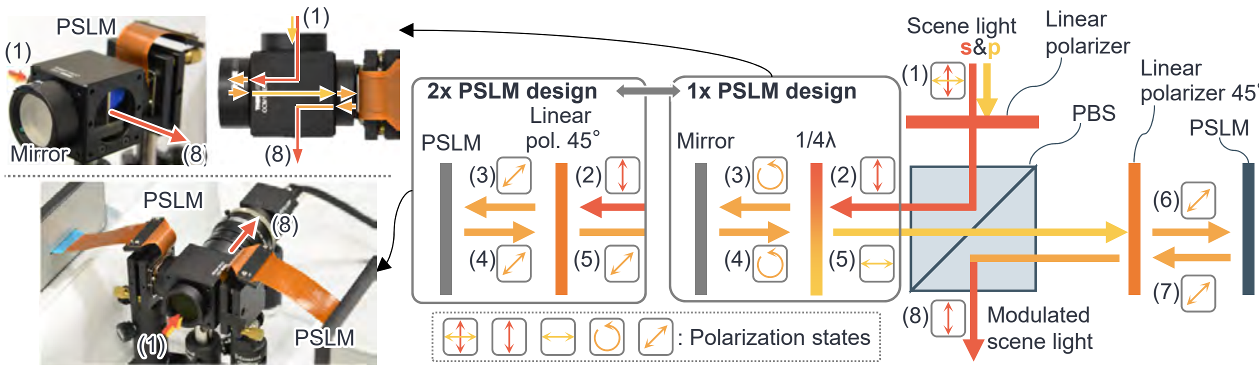

Fig. 7. Schematic diagrams of our optical designs and prototype systems. The right part illustrates how the system delivers the scene light from the world to the user's eye through PSLM(s) while avoiding the scene light directly reaching to the user's eye. See Sec. 4.1 for more details.

In the dual PSLM setup, we have a linear polarizer and a PSLM instead of the waveplate and the mirror. In (2), the polarizer at 45° rotates the polarization of the light by 45° to use the PSLM as a phase modulator. In (4), the returned light passes through the polarizer and passes through the PBS.

In (6), the light reaches the second PSLM. In (7), the modulated light passes through the polarizer. In (8), the s wave is reflected by the PBS and goes to the eye.

4.2 Hardware and Software

The prototype consists of common optical components and PSLMs and is currently realized as a bench prototype. Figure 7 left shows our prototype.

The common optical components include: two Thorlabs LPVISE100-A linear polarizers (1", 400 - 700 nm) mounted inside lens tubes (two Thorlabs SM1L03), a Thorlabs PBS251 polarizing beamsplitter (PBS) cube (1", 420–680nm) mounted on a Thorlabs CCM1-4ER cage cube, a Thorlabs BB1-E02 broadband dielectric mirror (1", 400–750nm), and a Thorlabs WPQ10E-546 1/4 waveplate (1", Polymer Zero-Order, 546nm). The mirror and the 1/4 waveplate are mounted together in a lens tube (Thorlabs SM1P1) so that incoming light passes the plate before reaching the mirror. The three lens tubes are mounted on the cube cage following the design in Fig. 7.

As a PSLM, we used a Jasper Display Educational Development Kit model A+. The kit consists of a 1920×1080 60Hz reflective liquid crystal on silicon (LCoS) SLM with the 6.4 micrometer pixel pitch and a driver board with HDMI connection. By connecting the driver to a computer, we can use the SLM as a second monitor screen.

Through the experiments, we placed a user-perspective camera behind the systems. For the camera, we used a C-mount camera, FLIR (PointGrey) BFS-U3-32S4C-C (2048×1536, 1/1.8").

We used MATLAB to generate phase patterns and two laptops to display the images on PSLMs. One of the two laptops was also used to drive the viewpoint camera. For continuous focus applications, we implemented the software in C++ with OpenCV.

5 Applications

As mentioned initially, one of the advantages of the proposed approach is the generalizability and applicability to different problems in augmented vision as it allows to interactively simulate different optical systems. In the following, we discuss some of the applications scenarios together with our prototypical implementations that demonstrate the potential. In general we see two big application areas which our approach has in common with most vision augmentation approaches: compensation of visual impairments using vision augmentations and enhancement of normal vision to allow for *superhuman vision*.

In the following, we present early application prototypes that demonstrates the applicability of our approach to compensate for these kind of refractive errors. Common to these prototypes is a user-perspective camera that captures the scene as it would be seen by the human wearer while we also add a scene camera to realize a loop-back scenario. The scene camera is responsible for sensing the environment and adjusting the glasses accordingly.

5.1 Compensation of visual impairments

The most common forms of visual impairments are refractive errors and here in particular near-sightedness, far-sightedness, presbyopia, astigmatism. While there are multiple causes for refractive errors (e.g. shape of the cornea, weak action of muscles, or age related hardening of the lens within our eye making it less flexible), the common way to compensate the effect are traditional optical glasses. However, in particular people affected by Presbyopia often need bifocal lenses to allow for accommodation on all distances which reduces the field of view and needs time to get used to. As a result, some people prefer to keep different glasses which they used depending on the context. Existing research suggests that having glasses using adjustable optics could overcome this issue [10], [43].

5.1.1 Focal correction

One of the basic functions that a PSLM can provide is a thin lens (Figure 5a). We thus demonstrate that a single PSLM setup can correct near-/far-sighted views. First, we placed a user-perspective camera behind the system with its aperture fully opened. We then display a uniform image on the PSLM, which means that the PSLM does not refract the incoming light.

After placing two objects, one at a near distance (~10cm) away from the viewpoint, and the other at a far distance (~70cm), we manually set the camera to focus on a near object. Fig. 1b bottom left shows the view taken by the camera where the near object appears sharp whereas the far object gets blurred as the focus of the camera does not match.

We assume that this setup simulates a near-sighted eye. Since we know the specification of the camera and the optical system, we applied Eq. 5 to render a lens on the PSLM that shifts the current

Fig. 8. Conceptual overview over some application of our approach that can be used to compensate visual impairments while also allow to be controlled at run-time to change lens configuration (e.g. from near to far focus)(figure inspired by [43]). (a) image as seen by human that normally require bifocals or progressive lenses as they are affected by presbyopia and other visual impairments (e.g. near-sightedness). (b) Illustration of correcting for near focus with red circle indicating object in focus. (c) correcting for distant focus. (d) Unlike other approaches we can also bring several focal planes into focus simultaneously which also has applications to non-impaired users (e.g. allowing for focus in the periphery)

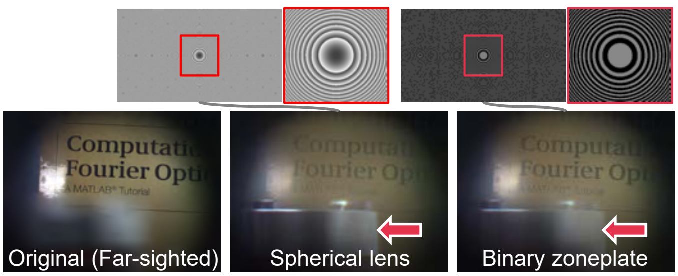

Fig. 9. Diffraction lens demonstration. A viewpoint camera focuses at a far object. We display a spherical lens phase pattern and a binary zone plate phase pattern of the same focal length separately. The resulting images in the bottom center and in the bottom right both focus on a near object. Note that the binary intensities of the zone plate image so that their retardation is a half of the base wavelength.

focus of the camera to the far distant object. In this case, the phase pattern (Figure 1b top right) forms a concave lens and creates a corrected focus ((Figure 1b bottom right). The camera can see the far-distant object sharp while the near distant object gets blurred as the camera focus was shifted by the PSLM.

Note that there are other active optics devices that can achieve such a focus correction. They have, however, their own limitations and, more importantly, cannot be applied to other optical effects that our system can achieve. Focus-tunable lenses have a limited FoV, and membrane lenses [7] require extra air pumps that inevitably increase the form factor. Furthermore, the programmable property of our system allows us to simulate diffractive lenses.

5.1.2 Diffractive Lens

Since PSLM can display arbitrary phase patterns within its retardance range, an interesting application is to simulate diffractive lenses. In Fig. 9, we tested a binary zone plate where we set the phase values so that the even and odd zones have the phase difference of π. As we see in the Fig. 9, the zone plate lens allows the far-sighted view to focus on a near distant object. While not necessarily an issue for our envisioned application, the book in Fig. 9 seems still partially in focus when the modulation is active. This could be due to the imperfection of the polarization filter with the LCOS not being able to modulate some portion of light coming from the book.

Other computational diffractive lenses such as the diffractive achromat are also interesting [44]. Unfortunately, real users can not directly use such advanced diffractive lenses as the captured image requires post-processing to reconstruct actual images.

In the following section, we further demonstrate multi-focus effects by displaying more complex lens patterns.

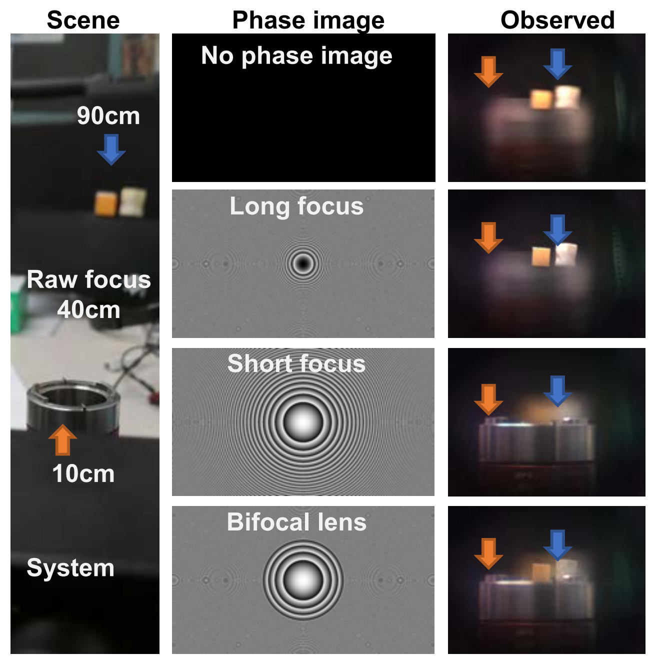

Fig. 10. Bi-focus mode. (left) The scene. The camera focus is set at around 40cm from the system. We located other objects at 10cm and 90 cm respectively. (center) Phase images. The bottom image is a bifocal lens image that renders a concave lens in the inner area and a convex lens in the outer area. (right) The bifocal lens allows the camera to focus on both objects simultaneously.

5.1.3 Bi-/Multi-focus

Given several objects at different depths, if we know the position of those objects in the scene, we can create a complex lens pattern that consists of different lenses so that the viewer can focus on the objects at simultaneously (Fig. 5b). This functionality is something that other common active optics devices cannot achieve easily.

For the multi-focal lens designs, we can think of several designs. One option is to split a PSLM into multiple regions and assign different lenses for each region. Fig. 1c employs a vertical split for a bifocal lens, whereas Fig. 10 employs concentric split where an inner area is one lens and an outer area is another lens. This concentric design is common for interocular lenses for cataract treatments.

5.1.4 Continuous single focus

Within the first prototype we show the capability to continuously focus on a certain object or distance using the dynamic refocusing capability of the single-SLM setup. While it is theoretically possible

Fig. 11. Continuous Single Focus controlled by placement of a fiducial marker. Focus is set to distance given by marker position (left) Focus is on object in front. (center) Focus is set to be between front and back object. (right) Focus is on back object.

Fig. 12. Continuous bifocals controlled by placement of two fiducial markers. Focus is set to distance given by both marker positions (left) Both markers are placed next to front battery. Thus, focus is only on battery in front. (middle) One marker is moved next to battery in background. Focus is on both, front and back batteries. (right) One marker is moved next to the far back battery. Both the battery in front as well as the battery far back are in focus.

to simulate traditional single focus glasses for near-sightedness and far-sightedness, the advantages of such a system are in the potential to compensate the effect presbyopia by compensating for the limited depth the affected human eye can focus on. Similarly to the system by Padmanaban et al. [43], the general idea is to detect where the user is looking at and to compute a configuration of the PSLM that approximates a lens focusing on the depth of the object the user is looking at.

Contrary to Padmanaban et al. who introduced a system combining a gaze tracker and a depth camera for this, we opted for a simpler system to show the potential. Instead of tracking gaze and computing the depth using the depth camera our implementation uses the user-perspective camera that detects and tracks a fiducial marker. The marker tracking provides information about the distance/depth of the marker to the camera and allows for adjusting the focus accordingly (Fig. 11). We show that we can interactively approximate a lens that focuses on the right distance and objects (here the marker and the battery that is placed at the same distance as the marker). Extending the system with a gaze tracker and depth camera similar to Padmanaban et al. would make it more practical but was beyond the scope of this work.

5.1.5 Continuous bifocals

While the previous section demonstrated a single-object case, we further demonstrate a more complex refocusing case with two objects at different depths being refocused simultaneously. The bifocal approach potentially compensates for Presbyopia more comfortably than the single focus approach. In particular, in the former approach, larger areas of a real scene can be in focus at the same time, and consequently, temporal delays caused by refocusing and eye tracking can be alleviated. This scenario is unique in a sense that typical refocus techniques using focus tuneable lenses (e.g. [43] fail as they can only create a single focus plan at a time, whereas our SLM system can create programmable bifocal lenses to refocus two objects simultaneously. In addition, we can also control which area of the optics focuses on which plane.

To demonstrate this scenario we again make use of marker tracking but in this case using two markers that are placed next different objects of interest. The area around the tracked marker and the distance to it will then be used to create a PSLM for that specific region and the corresponding distance and bring the object of interest into focus. Fig. 12 (Right) shows two batteries at different distances both shown in focus when seen through our prototype. Examples where this could be of use is to build bifocal lenses that can be adjusted at runtime (manually or automatically using context information [9]) to reduce the issues normally associated to bifocal lenses. However, this technique could also see applications for non-impaired users where for examples manuals or instruction

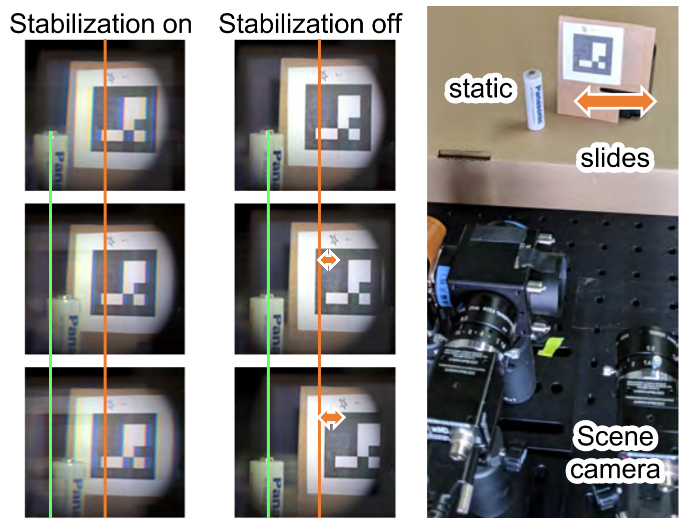

Fig. 13. View stabilization along the x (horizontal) axis controlled by placement of a fiducial marker. The view shift is set to the displacement of the marker's initial X position. (left) Stabilization is on. (center) Stabilization is off. (right) Application setup. The red and green lines are for guidance only.

are brought into focus with the object of interest (e.g. an object to be manipulated) despite the different distance.

5.1.6 Beyond Focus Control

Although we believe the demonstrated functionalities and applications are important ones, there are other potential capabilities in our phase-modulated eyeglasses that are not implemented in the current prototypes but are possible. One example is compensation of astigmatism. Here, Maimone et al. [31] already built a see-through display utilizing a PSLM and demonstrated adapting the displayed image so that a viewer with astigmatism can again see a sharp image. Such fine control of phase patterns could be realized but requires a user's eye parameter. This could be provided by a wearable autorefractometer that can measure each user's eye properties including focus and lens distortion. However, due to this additional challenges, it is beyond the scope of this presented work.

5.2 Enhancing normal vision

Apart from applications that compensate visual impairments, we also see interesting applications of this technique for enhancing vision for non-impaired users. We already provided an example by stating how the focus functionality could be use to keep objects

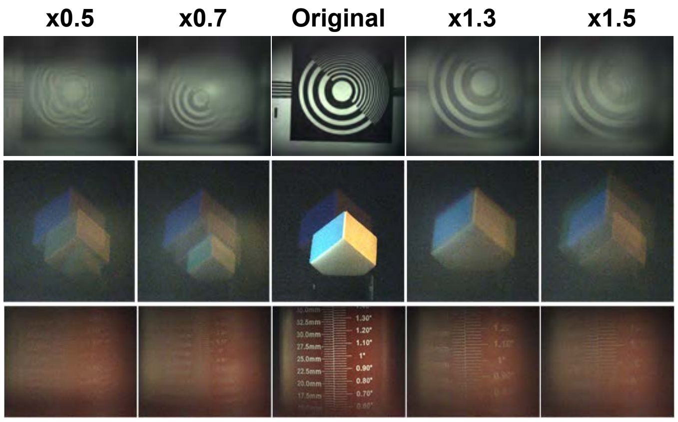

Fig. 14. The summary of the zoom control experiment with the dual-PSLM setup showing remaining artifiacts which can be further reduced by increasing the view brightness. Three different backgrounds with four magnification rates are captured.

always in focus which could be useful for scenarios where one needs to focus on two objects at the same time. However, there are also other applications that could be realized with our approach.

5.2.1 Zoom

When we want to have a better view at something in the far distant, even people with normal vision often rely on binoculars which usually come with a bulky form factor. However, as we showed in Fig. 14, if using a Dual PSLM setup we are able to integrate Zoom and Magnification functions into our computational eyeglasses. This allows enhancing normal vision by bringing distant objects look bigger to the wearer. Similarly, as for the other functionalities, this function can be switched of or configured at runtime.

We tested our dual PSLM setup that enables optical zoom (Fig. 5d) by displaying phase patterns based on Eq. 7. Fig. 14 shows the results. Although the light efficiency decreases and images appear somewhat foggy, the computed phase patterns successfully realize zoom effects. The ghost images are due to 0 th-order reflection and unblocked scene light. The latter issue could be addressed by improving the see-thorough brightness as we discuss in Sec. 6.3.

5.2.2 View stabilization

Another application and functionality, that cannot be reproduced with most approaches is view stabilization. While our brain is stabilizing our view when doing rapid eye movements, we cannot compensate the effect when objects make rapid movements or when we need to stabilize our head movements (e.g. when using the zoom function). Here, another capability of the system, the pan feature (Fig. 5c) of the system (Figure 1d), can be utilized to stabilize the view. In our prototype, we can shift the view towards a direction $[a,b]^{\mathrm{T}}$ along the PSLM panel by displaying a plane wave phase $\phi(x,y) = ax + by$. Note that phase images are additive—we can create a combined lens by adding two phase images. For example, adding a thin lens pattern to a plane phase image, we can shift a focus corrected view.

We built again a prototypical setup that uses a scene camera to observe the environment. To be able to stabilize the view, this scene camera needs to track the object with respect to the glasses. For a proof of concept implementation, we used a marker which is tracked by the scene camera (see Fig. 13). Knowing the relative position of the object with respect to the glasses allows us to configure our system to counteract the relative movement and stabilize the view for the viewer despite either moving objects or strong head movements when using the zoom function. Some proof of concept results can be seen in Figure 13) where we stabilized a marker in the users view (see *Stabilization on*) despite movement (see *Stabilization off*). The red and green grid are just for visualization purposes to help noticing the different positions.

Overall, we showed several application cases targeting visual impairments or enhancing human vision. However, despite the current limitations of the system we would argue that there are many other application scenarios that we have not covered here but are possible.

6 Limitations and Potential for Future Improvements

While we demonstrated the potential of phase-modulated computational eyeglasses, the current implementations raise various limitations that need to be addressed in future research to fully exploit the potential.

6.1 Field of View and Form Factor

The field of view of our current systems is severely limited to about 11° and 7° for the single and the dual PSLM, respectively. This issue is mainly caused by our design choice of using a beam splitter cube. A desired solution would be an optics design that first guide and concentrate scene light rays of wide field of view angles onto a PSLM inside the system then guides the rays back to the users' eyes. Existing solutions include using freeform prisms and waveguide optics using diffractive or holographic optical elements (DOE, HOE). Unfortunately, these optical elements are usually custom built and expensive when only used for research prototypes and consequently not used in our prototypes. Also, waveguide elements still pose challenges when used in our setup because handled light rays are wideband.

The form factor of the current system currently prevents its use as a wearable system but only presents itself as an optical bench prototype. The main factor is that the PSLMs come with external driver boxes. Although we are optimistic to foresee that such controller boxes will be smaller in a future generation of the panels, other components such as the used beamsplitter still limit the current form factor. But again optical see-through head-mounted displays have replaced bulky beam splitter or optical combiners with other more compact optics such as a free-form prism [3], light guide optics such as those from Lumus Ltd., and DOE/ HOE such as Microsoft Hololens. Note that DOE and HOE are usually wavelength dependent, thus they might not directly be applied to our setups. Also instead of reflective PSLMs, the usage of available transmissive PSLMs would allow for improving the general design and form factor.

6.2 Computing Eye - PSLM Distance

In our experiments, we estimated the distance between the camera and the first PSLM d by the specification of the camera lens. Once we get a wearable system, we need the distance from eyes to PSLMs. Although the estimation accuracy of d does not strongly affect when the target focus depth is far enough, $d_{\mathrm{O}} \gg d$, it is still desirable to have an integrated 3D eye tracker in the wearable systems. However, we argue that this is a reasonable assumption as also future head-mounted displays are likely to utilize eye trackers for eye-display calibration and a future version of computational phase-modulated eyeglasses could use similar technology such as those used in the see-through display community [17].

6.3 View Brightness

The see-through brightness of the current system is limited due to using the 45° polarizers inserted in our optics. A simple estimation gives the final brightness of the single PSLM setup is at most 1/8 of the original light which is similar to typical sunglasses. However, the light throughout is worse for the dual PSLM setup: at most only 1/32. A practical solution is to replace the 45° polarizers with 1/2 waveplates that can rotate the polarization angle of incoming polarized light by two times the angle of the wave against the primary axes of the waveplate.

Note that such waveplates must be achromatic, namely the amount of polarization is almost same along the visible band. Otherwise, a system may suffer from the color shift. The waveplates are also preferably zero-order waveplates for the stability against temperature change during the use. In this setup, the dominant light loss happens at the entrance linear polarizer in front of the PBS. In this case, both the single and the dual PSLM can achieve at most 1/2 of the original brightness. Since the brightness sensitivity of the human eye is logarithmic [13], the brightness loss is likely to be acceptable in practice.

6.4 Chromatic Aberration

Our experiments show that simple phase patterns such as spherical waves or simple zone-plate patterns inevitably cause chromatic aberration at the viewpoint. A common approach is to combine a refractive lens to cancel the aberration [47]. This standard solution is, however, not suitable for our see-through eyeglasses because it is a static element and it affects our view when the PSLM is not active.

Unlike such hybrid designs, Wang et al. designed achromatic diffractive lenses with grooves of different depths. They find an optimal groove pattern through a direct binary search algorithm in simulation so that the resulting lens minimizes the chromatic aberration for a given broadband wavelength [50]. Since their design is diffractive, we can directly apply the design to PSLMs once their pixel pitches reach to the designed pitch of 3μm.

6.5 Cascading LCOS modules

One LCOS has limited power of controlling the phase, one thus may think about cascading LCOS panels to increase the design space of the light modulation. With this, we could improve the phase modulation resolution, handle some chromatic aberration, and overcome limitations due to the pixel pitch of the panel. However, using multiple of LCOS panels apparently increases the system complexity, the form factor, and power consumption.

6.6 Light field image

Another application which is not necessarily beneficial for actual users, yet interesting in computer vision is the light field image. By tiling spherical lens patterns on a PSLM, we can create a lens array. Fig. 15 shows a view from the camera with another lens (TAMRON M13VM550, 5-50mm). Note that bare eyes can not focus on the images as the lens array patterns had short focal lengths. This application could be useful when using our system with a camera for improving sensing of the environment or computational photography applications .

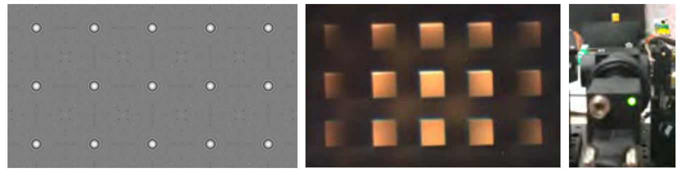

Fig. 15. Lens array view. (left) Micro-lens phase patterns. (center) captured images. (right) The scene setup

7 Conclusion

We presented the concept and prototypical implementation of computational phase-modulated eyeglasses that modulate the users' vision by using PSLMs. Unlike existing approaches that use PSLMs, e.g. computational cameras in computational photography that generate intermediate images to be reconstructed via computation, our focus is to directly manipulate user's vision by utilizing programmable phase modulation devices to enhance human vision capability. We see promising application areas in compensating visual impairments and enhancing normal human vision.

In this work, we introduce two hardware prototypes, one with a single PSLM and the other with two cascaded PSLMs, we demonstrated various optical operations including focus correction, multi-focus, view shift, and field of view modification. We also showcased that a diffractive lens can be implemented on the systems. While the introduced prototypes are fully working, they are currently implemented as an optical bench setup to reduce hardware costs and ease prototyping. However, we argue that many components can be miniaturized and we also outline how the performance (e.g. brighness or clarity of the view) can be improved in future systems.

We argue that the concept and first implementation presented in this work opens up a new pathway for implementing computational eye-glasses which is of relevance to communities investigating visual computing, human-computer interaction, optics, and wearable computing.

Acknowledgments

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