Computational Glasses: Vision augmentations using computational near-eye optics and displays

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Abstract

Wearable computing devices are small enough that they can be worn on the body and are a constant companion to the user. While many wearable devices have been associated with monitoring health or managing diseases, head-mounted displays are traditionally linked to Augmented and Virtual Reality, and generally overlay 3D information that supports professionals or for edutainment. This is surprising as prescription glasses, their traditional siblings, are widely accepted as a standard device for managing focusing errors of the human eye. In this work, we want to make the case for Computational Glasses that utilise technologies from optical see-through head-mounted displays or computational optics to compensate visual impairments. We will introduce some of the seminal works in the field as well as introduce our own work in the field. We will also include some of the challenges for doing research on Computational Glasses as well as give an outlook for future developments.

1 Introduction

Augmented Reality (AR) has traditionally seen its uses for overlaying digital information on top of the view of the physical world. This has been achieved using a projector-camera system or *Spatial Augmented Reality* [1], using hand-held or mobile systems usually implementing a video see-through AR interface [10], or using an *optical see-through head-mounted display* (OSTHMD) [14]. In the past this information has often been 3D content or textual information supporting the users in their task or for entertainment purposes.

More recently, OSTHMDs have seen major investment from industry which has contributed to this technology making significant advances over the last years. Products like the Microsoft Hololens have shown that it is possible to build completely self-contained OSTHMDs that do not rely on external computing devices or power sources. Other OSTHMDs like the Epson Moverio BT300 have shown that we can build systems with a form factor and weight close to traditional glasses albeit at the cost of having the battery and computing power in an external pocket-sized device. Still, we can foresee this miniaturisation will continue to develop OSTHMDs into a state where they have a similar form factor to traditional glasses. This miniaturisation raises the question of whether we can utilise OSTHMDs as a permanent vision aid to compensate visual impairments or even enhance human vision.

In this position paper, we want to outline the concept of *Computational Glasses* as a computerised vision aid using techniques traditionally used for AR head-mounted displays. We will outline existing works that utilise either computational near-eye display, computational near-eye optics, or a combination of both. We put a particular emphasis on our own work in this field and the lessons we have learned whilst doing this research. We will finish by giving a general outlook on the future challenges that need to be addressed by research and briefly discuss some of the application areas and unexplored possibilities.

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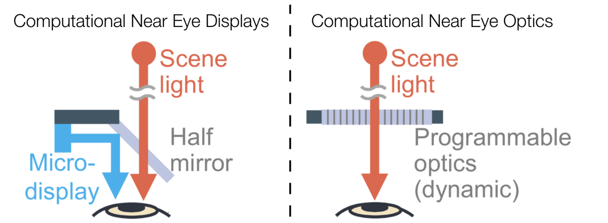


Figure 1: Illustration of two forms of Computational Glasses. (Left) Using computational near-eye display to change the appearance of the physical world. (Right) Using computational near-eye optics.

2 Computational Glasses for Human Vision Augmentations

There are existing approaches that aim for vision augmentation using technologies that have been used in AR which we would not consider as Computational Glasses.

For example, approaches that use the concept of video-see through AR. Here the world is captured by one or more cameras, the camera feed is then processed and manipulated in real-time to support the user. Examples include work such as CueSee [17] or Foresee [18] and the commercially developed Samsung Relumino prototypes[1]. While the latter shows the potential for miniaturisation, all of these approaches share the downside that the user relies entirely on the manipulated camera feed, as a direct view of the physical world is blocked by the displays. This brings issues with acceptability if vision is already impaired and in addition, possible social issues; users of such as system cannot establish mutual eye contact, an important social cue.

Another category of vision aids use OSTHMDs but the displayed overlay is not registered with the real world. Examples are approaches that utilise devices such as Google Glass where the display is in the users peripheral view and they are not designed to precisely overlay digital information [15]. There are also several early works by Peli et al., to our best knowledge the first proposing using AR technology for compensating visual impairments, that do not utilise truly registered overlays but instead show the camera feed of an wide-angle camera giving the feeling of a double exposure to compensate tunnel vision or allow for a small angle of error in registration when applying edges to enhance contrast [13].

While we would argue that these could already be seen as Computational Glasses, our vision of Computational Glasses is different as we aim to precisely manipulate input from the physical world to support the visual perception of the user, in particular in the presence of visual impairments. Precise manipulation of input from the physical world should be possible within a wearable device that,

[1] samsungrelumino.com

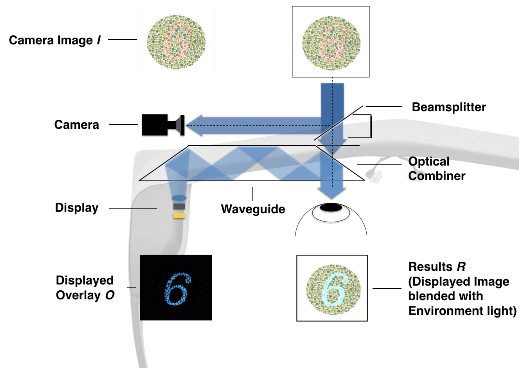


Figure 2: Overview of the conceptual set up for computational near-eye display used for CVD compensation. [11]

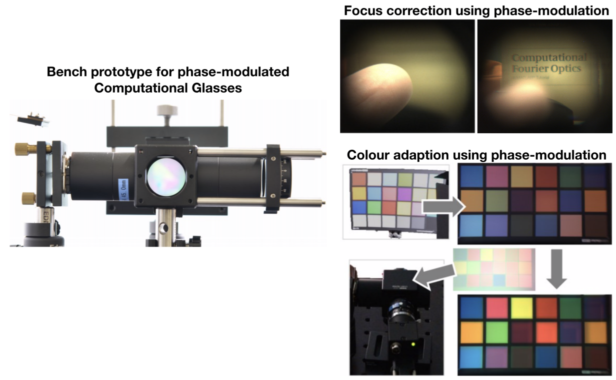


Figure 3: Bench prototype of Computational Glasses using phase-modulation as an example for computational near-eye optics and examples of their application to focus correction and colour modulation [6].

in future, should resemble traditional glasses and consequently be optical see-through. We see three ways that this can be achieved; with Computational Glasses using semi-transparent near-eye displays (Fig. 1, Left), with computational Glasses using computational near-eye optics (Figure 1, Right), and approaches that combine both, displays and programmable optics. An example of Computational Glasses using semi-transparent near-eye displays is our own work on ChromaGlasses [11], while the work on Autofocals would be an example for Computational Glasses using near-eye optics [12]. There are only a few examples known to us that combine both approaches such as the work by Chakravarthula et. al who presented a prototype for replacing vision corrections when using AR displays by integrating them in the actual OSTHMD [2].

In the following we will give an overview over of our own work and subsequently some core works on Computational Glasses by grouping them by their application area.

3 Computational Glasses Case Studies

So far we have completed two case studies using Computational Glasses, one where we used near-eye displays, and another using near-eye optics. Our near-eye display study focused on the ability of Computational Glasses to work as visual aids for colour vision deficiency (CVD), also known as colour blindness [9]. The second case study focused on near-eye optics and developed bench prototypes using phase modulation capable of pixel-wise colour modification and another prototype that allows for the correction of even complex refractive errors.

3.1 Computational Glasses using near-eye displays

One of the best understood visual impairments that cannot be compensated with traditional glasses is CVD which was consequently one of the first targets for showing the feasability of Computational Glasses using near-eye displays. Fig. 2 shows the conceptual design for our near-eye display Computational Glasses. Here a beamsplitter is used to virtually place a camera on axis with the users view. Once the system is geometrically calibrated (see [9] for details) the camera image can be analysed to detect colours in the environment that are critical to the wearer. As we are able to create a pixel-precise mapping from the camera to the display as seen by the user we can create a compensation image that is displayed to the user via the OSTHMD. Seen from the users point of view, the compensation image (the displayed overlay in Fig. 2) merges with the physical world and changes the perceived colour in a way that it can be perceived by the user affected by CVD. The mathematical implementation of the colour shift (often refered to as Daltonization) is based on prior work on correcting CVD in graphical user interfaces [7, 15]. In several user studies with over 50 participants affected by CVD, results showed participants were able to significantly increase their accuracy and confidence when doing standard tests for CVD. We showed these results in evaluations using an optical bench-prototype where participants look through the glasses using a user perspective camera (Fig. 1, Left) and a replication of this first study using a see-through prototype where participants are were able to look directly through stereo Computational Glasses (Fig. 1, Centre). A comparison against a Google Glass-based approach by Tanuwidjaja et al. [15] also highlighted the benefit of details [11].

3.2 Computational Glasses using near-eye optics

In the second case study, we developed prototypes of Computational Glasses using near-eye optics based on phase modulation [6]. This research is in the early stage and uses optical bench prototypes (Fig. 3, Left). Our optical see-through system utilises a phase-only spatial light modulator (P-SLM) to control the polarisation state of incoming light. Combined with polarised optics, our system works as a programmable colour filter that can change the colour of the view pixel-wise which has application again for compensating CVD and also to adapt the contrast of the scene (Fig. 3). Spatially modulating the phase of light is equivalent to controlling the refractance of the display. This feature connects to another application that uses phase-modulation to implement a programmable lens, allowing for real-time adjustment of focus and even bi-focal lenses which have many applications for complex refractive errors. Given the early state of this work only technical evaluations with a user-perspective camera have been performed.

4 Application for Computational Glasses

Besides the application areas covered by our case studies, there are many areas where Computational Glasses have the potential to aid those afflicted by visual impairments.

The primary use for prescription glasses is to correct for refractive errors. Work by Padmanaban et al. [12] shows the ability to create near-eye optic glasses which aid presbyopes by adjusting their focus based on where the users is looking, removing the need for progressive lenses that limit the focused area of a wearers view. Similar work has been done for general AR and OSTHMDs [2, 5].

As mentioned, Computational Glasses can have an application to colour adjustment and aiding those with impaired colour vision [11].

Peli et al. [13] discussed the use of edge outlining as an aid for those with central vision impairments (such as resolution or contrast sensitivity loss), but faced issues with achieving the correct registration and visual quality of their system. As shown by our prior work [11] where we used edge overlays as a compensation technique this effect is achievable with Computational Glasses.

Another potential application area for Computational Glasses is in aiding sufferers of night blindness. Similar to the previously discussed edge outlining for central vision impairments Peli et al. [13] also showed its application to night vision. Computational glasses could also be applied to this using properly registered overlays or an enhancement technique such as that by Kellnhofer et al. [8].

Other age related vision impairments can also be compensated for. This includes afflictions such as early stage glaucoma, which present the symptom of reduced FOV; and can lead to tunnel vision, or macular degeneration, which has symptoms such as; blurred central vision, distorted vision, loss of contrast sensitivity, and degredation of colour vision.

5 LESSONS LEARNED

There are a few lessons that we learned from our research on Computational Glasses that we want to share with the community.

Prototypes. One of the biggest challenges when doing research on Computational Glasses is to develop prototypes that can be used for user studies, whilst also reducing external factors that affect the study. Over the years we have had good experience developing a series of at least three prototypes; an optical bench prototype using a user-perspective camera (Fig. 4, Left), a stereoscopic prototype that cannot be head-worn but allows users to see through the prototype (Fig. 4, Centre), and finally, a head-worn stereoscopic prototype that shows the potential for miniaturisation (Fig. 4, Right).

Each prototypes has distinctive advantages. The optical bench prototype allows for quick adaption by changing components. Most of the components are relatively large as miniaturisation is not an important factor at this stage. This allows for more affordable cameras (e.g. larger cameras) and, normally, better adjustability (e.g. changing the spatial attributes of optical components or adjusting cameras). It is also more forgiving of errors in early 3D prints or low quality optical components. Furthermore, using a user perspective camera is a simplification of the human eye in many aspects (resolution, dynamic range, ability to focus to name only a few) but usually allows for an easier calibration (e.g. camera display calibration), can capture first results (e.g. images and videos) that can be compared offline, and finally, guarantees easy reproduction of results which is often challenging when actual users are involved (e.g. because of the per user calibration process). We often used these optical bench prototypes for early pilot studies by showing the actual camera feed of a well calibrated system to participants. The same calibration can be used for all the users and we can almost guarantee that they all see the same result, increasing internal validity.

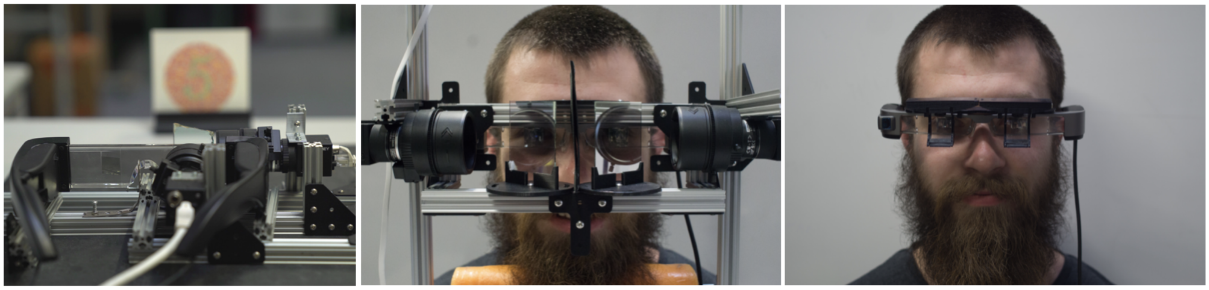
The second prototype has advantages over the initial one by allowing the user to actually see through the glasses whilst also being stereo. Besides an increase in hardware costs and effort, calibration usually becomes an issue as we need to calibrate the system specifically for each user. While these calibrations can be challenging on their own (Sect. 6 discussing challenges), they often loose validity once the users moves their head only slightly (more precisely, changes the spatial relation of the eye and the display or computational optics). Thus we often integrated a chin-rest that allows the user to comfortably rest their head and keep it reasonably stable over extended periods, such as in user evaluations. We often centred our user studies around the usage of this prototype as it has a good balance between realism (e.g. users actually looking through the glasses) and control of external factors. Furthermore, we often correlated the results achieved with this prototype to results achieved with the earlier prototype to show the quality of the more complex calibration and remove it as a confounding factor.

The final prototype is a miniaturised one that can be worn on the head. We had good experience using large head-straps similar to those on consumer VR displays to fix the Computational Glasses to the head minimising the need for re-calibration. We also explored using mobile hardware such as Intel Compute Sticks and battery packs to build fully self-contained prototypes. However, the miniaturisation comes at cost as smaller components are often more expensive (at least for small quantities) while also being often of inferior quality (e.g. small cameras or lenses).

There are different commercially available OSTHMDs that can be a good starting point for prototyping Computational Glasses. While OSTHMDs such as Microsoft Hololens or Magic Leap are great devices for AR research, they tend to be expensive and are relatively complex in particular when considering the construction of their waveguides and integrated sensors. Thus they are unsuited to customisation. For our research, in particular when using near-eye displays, we often started with devices such as the Lumus DK52 or the Epson Moverio Series. While both are relatively small, the former offers a good *field of view* (FOV), colour reproduction, brightness, and can be plugged into computers using its HDMI port, but is not easily available. Epsons Moverio series has a good colour reproduction (BT 300 and above) but only a limited FOV. However, it is relatively affordable and thanks to its simpler wave-guide design lends itself to customisation. Other headsets such as Leap Motion's Northstar also have potential, in particular, because of the low price, availability of 3D prints that can be customised and a relatively large FOV. However, the standard displays used are relatively dark when compared to competitors and they are large even before being modified.

Calibration Calibration of Computational Glasses is challenging as often several calibrations are required, all dependent on each other. Several components need to be calibrate in relationship to each other. A camera-display calibration is needed to correctly align modulations, as defined by camera input, on the screen, whilst a camera-eye calibration is needed to adjust the cameras to match the camera view to the individual user's eyes. Overall this creates the necessary eye-display calibration to modulate the users view with pixel precision. For the bench prototype the calibration can be done with a camera-display calibration in a replicable and verifiable manner. However in the see-through prototype a per user calibration is needed for both eye-display sets in a stereoscopic system. If either calibration is out anomalous effects can be generated, such as binocular rivalry, or distortion of visual information. For the see-through prototype we found that user calibration has been problematic, initially we looked to use SPAAM [16] however decided, for practicality in our user studies, to create a 2D homography between known display points and camera points whilst the user is looking through the system, completing the eye-display calibration as one step. Currently our solution to calibration is to allow the user to manually adjust the calibration until they can visually align a test pattern in the glasses to a test pattern at a set distance from the user. A rigid structure is used to maintain camera-display relationships during use and a chin rest and side arms provide a structure to help maintain eye-display and eye-camera relationships. These calibrations cannot be verified. For the mobile prototype we are currently still using the calibration method from the see-through prototype as it allows for a degree of movement without problematic misalignment, and we are greatly restricting the use of the device to scenarios where the calibration remains valid.

Accommodation-vergence conflict. While there have been solutions documented in the research labs for the use in AR displays that overcome this problem (e.g. Dunn et al.'s deformable, varifocal near-eye display [3]) they are not yet available in consumer devices and still have their own challenges (e.g. small eye box when using holographic approaches). However, for some of our existing research we realised that the accommodation-vergence conflict is less of an issue than in AR. This is, in particular, true if the aim of the research is to highlight areas such as when compensating colour vision deficiency or supporting users with extremely strong



Optical bench prototype | See-through prototype | Miniaturized prototype

Figure 4: Prototypical near-eye display Computational Glasses. (Left) Bench prototype with user perspective camera. (Centre) See-through prototype for direct user view. (Right) Example of potential miniaturisation.

refractive errors. As the overlays are usually low frequency patterns they do not emphasise the plane on which they are projected, rather they just modify the light entering the user's eye. The user's eyes are not drawn toward a virtual plane that does not align with the real world so accommodation-convergence is not an issue, rather the modulation is slightly blurred.

6 Challenges and Future Directions

To further develop Computational Glasses as aids for visual accessibility we have seen several challenges that need to be overcome.

As previously mentioned the accomodation-vergence conflict has yet to present a significant issue in our research due to the nature of modifications, however if the modification required precise, in-focus, adjustments this will become a problem. Furthermore, whilst so far adjustments have been designed to be minimal so the effect of incorrect cues is minimised, if the presence of problematic cues increases the detriment to user's sight may also increase.

A major challenge currently facing our research is the eye-display calibrations. As we covered, there are a number of aspects which all must be calibrated together for each user and maintained during use. Currently we use 2D homographies manipulated by the user to create eye-display calibrations. This works well for our see-through prototype, however in moving to a mobile system this becomes more problematic. In order to achieve better calibration problems such as the non-uniform curved nature of displays needs to be accounted for as described by Itoh et al. [4]. 3D calibrations that are robust and remain valid as spatial relationships vary need exploration.

Another challenge we see going forward with Computational Glasses is the FOV. With Computational Glasses looking to compensate the users entire view, the limitations of the current generation of near-eye displays needs to be overcome. The low FOV causes problems as the area of effect for Computational Glasses becomes reduced and integration with the physical world is limited. This problem is being reduced as OSTHMD developers increase the FOV of their products. The Northstar shows the potential for a large FOV, and developing FOV is demonstrated with the Hololens and Hololens 2.0 FOV increasing from 34° to 52°[2] .

The loss of light caused by successive optical elements redirecting and refracting light is also a concern and challenge that needs to be considered. With our near-eye display case study, light levels are reduced both by the OSTHMD display and by redirection toward the FPV camera. For our applications to date we have not had problems with light dropping consequentially, however the reduction in light is notable. This effect is amplified the more optics that are involved and, if not overcome, complicated optical systems face the problem of acting similarly to sunglasses, inadvertently reducing the users visual perception.

[2]twitter.com/akipman/status/1100069645661495298

An aspect of Computational Glasses that remains unexplored and presents potential challenges is long term use. This includes investigating any potential effects on the visual system from prolonged interference, as well as more practical issues such as maintaining calibrations for extended periods.

Whilst the concept of Computational Glasses as devices with similar form factor to traditional glasses, as can be seen in Fig. 1, they are currently still large and cumbersome. However we believe with continued research they can reach the desired form factor.

Finally as we found moving from a bench prototype to a user system, and then moving to a mobile prototype, there are many problems that arise reducing control over the system and we foresee the same happening as Computational Glasses are extended beyond a lab environment. These challenges will need to be overcome before Computational Glasses can truly find a place as new devices for visual aid.

Although we detail the use of Computational Glasses as visual aids, there is great potential to extend them beyond aiding vision into areas of enhancement and augmentation. Applications such as visual guidance, thermal vision, or x-ray vision could be explored.

7 Conclusion

We have detailed the concept of Computational Glasses that use AR techniques to provide computerised vision aid. We believe these glasses have many applications and have shown one such case in the aid of CVD. We propose that there are many more ailments that can be aided such as refractive errors and reduced contrast sensitivity. Through out our development we have found that using various prototypes, each building on the last, has enabled us to more readily test and verify concepts, with each stage having new advantages and disadvantages. Calibrations for systems such as these are problematic and we have found that constraining the system as much as possible and comparing results against those gained in situations where the calibration is verifiable has proved successful. We have also found that, whilst oft being touted as one of the major issues with HMDs, the accommodation-vergence conflict is of little consequence to some applications.

Acknowledgments

Tobias Langlotz and Jonathan Sutton are partially supported by the Marsden Fund Council from Government funding and a Catalyst Seed Grant, both administered by the Royal Society of NZ and by Callaghan Innovation, host of the Science for Technological Innovation National Science Challenge, Seed Project 52421, New Zealand. They also would like to thank Lumus for providing hardware donations supporting this research. Yuta Itoh is partially supported by JSPS KAKENHI Grant Numbers JP17H04692, Japan; and by JST PRESTO Grant Number JPMJPR17J2, Japan.

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