A pair of diopter-adjustable eyeglasses for presbyopia correction

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ABSTRACT

We describe and demonstrate a pair of diopter-adjustable eyeglasses aimed to correct presbyopia; the glasses provide a tunable optical power in the whole surface of the lens cell, eliminating the optical distortion typical of bifocal/trifocal or progressive glasses. The wearer can actively control the optical power by a simple sliding gesture on the bridge of the glasses, so that presbyopic vision can be interactively corrected. Results from a preliminary experiment showed that a presbyopia sufferer could clearly observe near and far objects under the assistant accommodation of the glasses. Designing a truly wearable system poses some challenges – none of them theoretical – so the system should be feasible in the near future.

Keywords: Presbyopia, vision correction, eyeglasses, variable-focus lens, liquid lens, assistive technology, interface.

1. INTRODUCTION

Presbyopia is a natural occurring ophthalmic disease. When over 40 year of age, most people start to experience vision difficulties[1–12]. These are most noticeable when reading material at close range, such as books or newspapers: it appears necessary to hold them farther away than before to achieve clear focus. A menu in a restaurant may appear blurred, especially under dim light. This inability of the eye to focus sharply on nearby objects, resulting from loss of elasticity of the crystalline lens and the loss of power of the ciliary muscles with advancing age, is called *presbyopia*.

Presbyopia is unlike myopia and hyperopia: the latter two can be simply corrected by adding or subtracting a fixed amount of optical power through corrective glasses, while in presbyopia, the loss of elasticity of the crystalline lens affects and reduces the eye's *accommodation power*[13–17]. Therefore, a fixed lens cannot correct presbyopia. A typical treatment for presbyopia is to solve the reading problem only, but this, of course, is not a complete satisfactory solution. More sophisticated solutions involve dividing the lens into sections with different optical power, each appropriate for a different seeing condition[18–30]. However, this leads to a segmented field of view, each viewing window being smaller than the natural field of view of the eye. Moreover, wavy distortion is unavoidable at the boundaries of these areas of different optical power, and unfortunately these boundaries are not in the periphery of the lens but must transverse its central area. This distortion affects daily life, especially when looking up a book on a shelf or going down the stairs. Eliminating wavy distortion is important for achieving comfortable vision, and this implies using a lens cell with a *single*, but *variable*, optical power.

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We propose here a pair of diopter-adjustable glasses providing a uniform optical power over the whole lens cell; Optical power can be controlled by the wearer through a miniature roller ball attached to the right bridge of the glasses; opposite rolling directions cause a rapid, positive or negative step-by-step change on the optical power. Our preliminary experiments demonstrate that it should be possible to use this system as a pair of active correction glasses for presbyopia.

2. STATEMENT OF THE PROBLEM AND CURRENT TREATMENTS

2.1 Human eye and accommodation loss

The lens of the human eye (or crystalline) is a bio-convex structure located just behind the iris, and held in position by suspensory ligaments (ciliary zonules) extending from an encircling ring of muscle, the ciliary muscle. When the ciliary muscle is relaxed, the suspensory ligaments stretch the lens thin. It contains little focusing and helps us to focus on distant objects. When the ciliary muscle is contracted, the ligament tension is reduced and the lens becomes rounder, making near objects appear in focus. The changes of the lens shape enable the eye to adjust its focus between far objects and near objects[15]. The crystalline behaves like a variable focus lens[15].

Accommodation is the ability of the eye to adjust its optical power in order to maintain a sharp focus on an object as its distance varies[2,11,27,31]. The average 12-year old child can accommodate by 13 diopters (D, diopter is the reciprocal of focal length in meters) allowing a nearest point of clear vision of about 7 cm, which occurs as a consequence of a reduction in zonule tension induced by ciliary muscle contraction. The tunable range of accommodation declines with age, because the crystalline loses elasticity and the ciliary muscle loses its strength. Vision accommodation ability decreases 0.07 diopters every year; by the fifth decade of life the decline of accommodative range is clearly noticeable so that the near point of the eye is more remote than the ordinary reading distance. For example, the average 48-year-old adult can accommodate by only 3D, pushing the nearest point of clear vision to about 33 cm. Accommodation decreases to essentially zero diopters at the age of 70-year old.

Presbyopia differs from myopia and hyperopia, since what is affected is the accommodation capacity of the eye. In pure myopia or hyperopia, the crystalline elasticity is not the problem: instead the length of the eyeball is not adequate (too short or too elongated). Hence, after adding an appropriate fixed correction, people can use their own accommodation to focus on near or far objects. In the case of presbyopia, adding a single corrected lens can help people see an object clearly just in a certain range; however, due to the loss of accommodation of the crystal lens, different correction is needed for far or near range. Hence, a corrective solution for presbyopia involves exchanging glasses, or a way to actively change the power of the lens as the system needs to mimic the accommodation process of the eye.

2.2 Prevalence and incidence

Population ageing is a phenomenon that occurs when the median age of a country or region rises due to rising life expectancy and declining birth rates. United Nations reported that as for today, population ageing is without parallel in the whole history of humanity[11,32–35]. Increases in the proportion of older persons (60 years or older) is accompanied by a decline in the proportion of the young (under age 15). By 2050, the number seniors in the world is expected to exceed the number of the young for the first time in history.

The Chinese one-child policy (enacted in 1979) delayed by only 4 years the world population into reaching 6 billion[36–40]. But this one-child policy brought another problem: an unbalanced population growth resulting in an aging society which will represent a big challenge in the next coming decade. Old people represented 0.185 billion in 2011, and with an increase of 7 million per year, this aging population will reach 0.4 billion by 2050. As for 2012, the total population of Japan is around 127.52 million people[11,32,41,42], from which the old (over 65) represent 30.79 million (the highest number the past years – it was 29.75 million the year before). Furthermore, it is expected that Japan's population will keep declining by a steady million every year in the coming decades, which will leave Japan with a population of 87 million by 2060. By that time, more than 40% of the population will be over the age of 65. According to the pathogenesis of presbyopia, most of them will suffer presbyopia. Since most of presbyopia experience appears from 40, *it is easy to predict that half of the population will be presbyopic in Japan in the next 50 years.*

The International Centre for Eyecare Education (ICEE) addressed that half billion of the presbyopia patient were not receiving any form of corrective care[11,43]. According to their comprehensive study, it is estimated that 1.04 billion people in the world experience vision impairment caused by presbyopia, and an estimated 517 million had either no eyeglasses or inappropriate eyeglasses. As a result their ability to complete important daily tasks is restricted. Most (386 million, or 94 percent) live in the developing world. A massive number of people cannot work or read properly because they do not have glasses, with an obvious enormous impact in their everyday life. It is now predicted that the worldwide prevalence of presbyopia will increase to 1.4 billion people from the total of 7.7 billion by 2020, and to 1.8 billion people of the whole population of 9.6 billion by 2050.

2.3 Treatments and research motivation

There are many treatments for presbyopia. The simplest way to (partially) mitigate the problem is to carry an additional pair of eyeglasses specifically for reading. Presbyopia patients are always taking a pair of glasses with them and use it when reading materials. This has been the traditional treatment for hundreds of years[13,14,44]. Because the accommodation degrades year by year[1,2,45], in order to maintain an appropriate level of vision these glasses need to be changed from time to time. Moreover, since the glasses are only used for reading, it is common to forget them in restaurants or bus stations.

A single lens divided into two or more different vision zones (for far and near vision) is called bifocal, trifocal, or progressive lens[21–30]. Most bifocals are created by molding a "reading" segment into the lower half of a primary lens. Users look through the primary (or upper) lens to see far objects, and use the lower lens for reading. It is easily to understand that there will be some form of wavy distortion at the connecting boundaries of the lenses, and unfortunately this does not happens in the periphery of the glasses, but around the center. This distortion will affect daily life, especially when looking for a book on a bookshelf or attempting to get down the stairs. The reports shows that bifocals can cause headaches and even dizziness in some users[46–48]. Acclimation to the small field of view offered by the reading segment of bifocals will take some time, as the user learns to move the head or the reading material rather than the eyes. Computer monitors are generally placed directly in front of the user, so it leads to muscle fatigue due to the unusual straight and constant movement of the head. Trifocal lenses are similar but with an additional segment for an intermediate vision. Trifocals are mostly for people with advanced presbyopia who have been prescribed 2 diopters or more of reading addition[23–25]. The intermediate addition is normally half the reading addition. Trifocals are becoming rarer nowadays as progressive lenses are becoming prevalent. Progressive lenses, also called progressive addition lenses, are designed with a smooth gradient of increasing lens power to correct presbyopia and other disorder of accommodation[23–26,49,50]. Normally, the gradient starts at the top of the lens and reaches a maximum addition power at the bottom of the lens, so that the user could smoothly focus from distant to near range. Progressive lenses avoid the image-jumping distortion in the field of vision produced by bifocals and trifocals. However, there are disadvantages inherent to progressive glasses: because the lenses combine a range of powers in one single lens cell, there will be a continuous variable geometric distortions on the whole vision field. Some patients find that the visual discomfort caused by these distortions outweighs the benefits of wearing progressive addition lenses.

An alternative solution is to use adaptive, *tunable power* lenses. The "Alvarez Glasses" was invented by Dr. Luis Alvarez, a Nobel prize physicist[51–53]. This kind of glasses works by sliding two specially-shaped lenses across each other, so it also called Slide Lens. The lens consists of two optical lenses with third grade surfaces. Because one lens is the exact inversion of the other, the moment they are placed exactly behind each other the strength of the lens is zero. By sliding the lenses, the power of the lens can be changed to either positive or negative. Although this solution looks simple and efficient, unfortunately it is not ever quite like that. The available vision area is narrow and a strong distortion is found on the boundary when looking askew. That is a challenging problem, because it narrows the vision area and the optical distortion may induce dizziness and headache.

Fluid-filled optics forms another type of tunable lenses. The basic idea is to contain a fluid on an elastic membrane and control the curvature of the structure by changing the volume of the liquid inside. The first pair of self-adjustable glasses was invented by Professor Joshua Silver, a physics at University of Oxford, who came up with the idea of using fluid-filled lenses to correct the vision of people in the developing world[53–57], because there were lot of people who needed glasses but did not have access to optometrists. He founded the Centre for Vision in the Developing World in 2009 and then co-founded "ADLens", a company who commoditized the eyeglasses. Its products are mainly for the developing world, and the price fall under $100 dollars. ADLenses are not designed for presbyopia though: once the optical power is adjusted by the wearer, the mechanism locks to prevent the spill of the fluid and the optical power becomes unchangeable. The structure of the lens is a typical liquid-membrane-air structure, so the lens profile suffers the influence of the gravity force. Because such asymmetrical deformation happens on the membrane, its optical performance is not very high. Hence, in some countries, such as in Japan, it is only sold for emergency use and not recommended for long time wearing.

3. PROTOTYPE AND EXPERIMENT

3.1 Design principles

Our purpose is to design a pair of diopter adjustable glasses for presbyopia patients. The lens is a variable focus lens with a liquid-membrane-liquid structure, with a large aperture and tunable focus. Since presbyopia starts in the fourth decade of life, and the accommodation capacity decreases by an average of 0.07 diopter per year and stabilizes at around age 60, we can conclude that 1.4D is the required additional power required to correct normal presbyopia (actually 1.47 ± 0.56)[1]. The tunable eyeglasses studied here can cover a power range from 0 to +3 diopters, so that presbyopia needs are well covered.

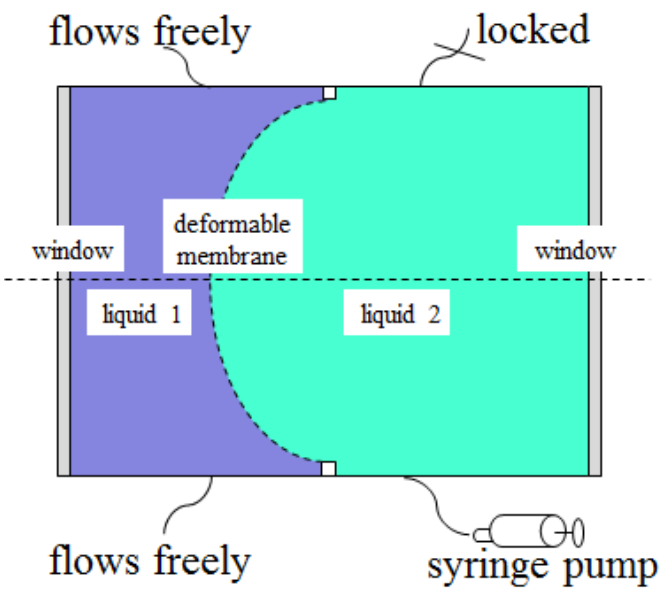

Figure 1. Structure of the adjustable focus lens

We calculated the optical power of our prototype lens based on the structure of its liquid-membrane-liquid. The infused liquids are glycerin (refractive index of 1.47, density of 1.25 g/cm^3) and santolight5267 (refractive index of 1.67, density of 1.26 g/cm^3). Glycerin was made to freely flow into and out of its chambers, while the santolight5267 chamber is closed; the lens can shift its power by pushing or pulling the syringe pump, see Fig.1. The lens power depends on the curvature of the refractive surface and the difference in refractive index between the two liquids, so the lens power can be dynamically controlled by adjusting the shape of membrane. We found that its optical power could achieve a variation of 10 diopters by means of injecting ±1.5 ml of fluid. If our plan is to design a lens with a tunable optical power in the [0 +3] range, we need to control only 0.6 ml of fluid. Analyzing the geometry of the parabolic cap, we concluded that an axial deflection range of [0 5] mm of the elastic membrane in its optical axis is enough to realize a tunable diopter range of [0 +3] diopters. Hence, the lens cell could be designed with a thickness of only 5 mm for use as presbyopia corrective eyeglasses. If a pair of fluids with a higher ratio for their refractive indexed is used, the lens could be made even thinner.

A concept drawing of diopter adjustable eyeglasses is shown in Fig.2. A person suffering from presbyopia is represented at the left of the figure. She/he needs zero diopter to contemplate a tree in the distance, and needs a positive diopter to read a book. The presbyopia correcting glasses contain liquid filled tunable lenses; the shape of the liquid—membrane-liquid surface is deformed in real time by the user by commanding a small roller ball on the side of the glass frame.

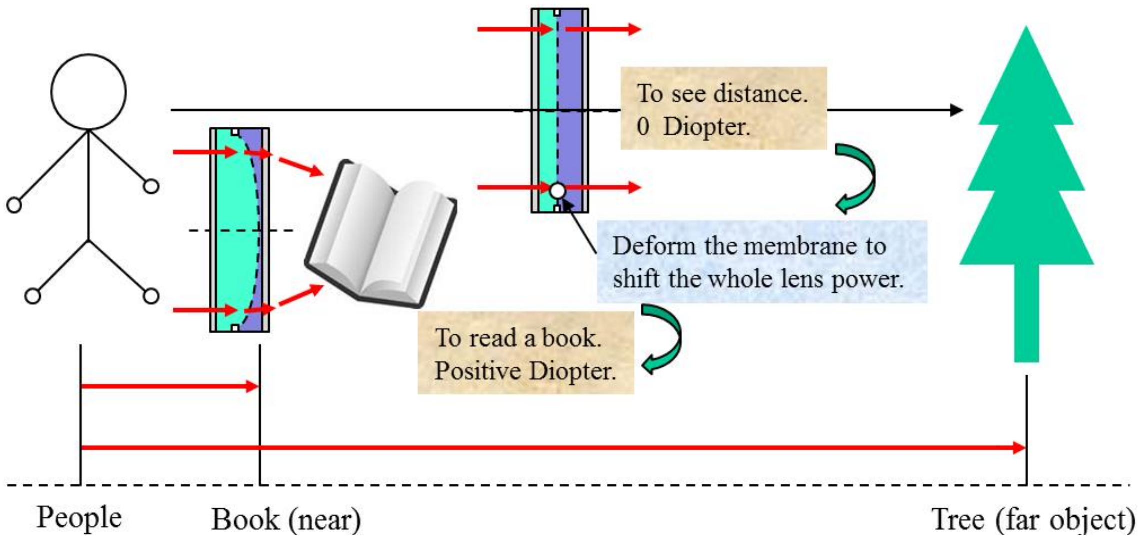

Figure 2. A variable focus glasses provides tunable diopters to correct presbyopia; the wearer can observe far and near objects in sharp focus by adjusting the lens power interactively.

3.2 Prototype setup

At present the setup is not integrated in a single pair of wearable glasses. The test subject wears a pair of (zero-diopter) plastic glasses. These glasses are fitted with a touchable interface sensor (roller ball) whose output is polled using an Arduino microcontroller connected via a serial port with a computer. The computer will process the signal and sends commands to a pump controller that actuates a high precision syringe pump. This pump infuses and withdraws fluid from a pair of variable focus lenses. The subject looks to the target objects through these lenses and adjust their power using the roller ball. The following describes each sub-system in detail:

<u>Presbyopia Eyeglasses Set</u> is composed by a pair of transparent glasses and a pair of variable focus lenses. The transparent glasses are just safety googles, without diopter power. The variable focus lenses[58] are fixed on an optic platform; their aperture is 26mm. The user wears the transparent goggles and put his head right behind the variable focus lenses and look through as they would do in a standard ophthalmic test. These two devices are considered together as a pair of diopter adjustable glasses (Fig. 3).

<u>Driving Mechanism</u> consists on a programmable syringe pump controller (Legato 110 from KDS) represented in Fig. 4. A 50 ml syringe pump (Terumo Company) was assembled on the pump controller achieving a maximum speed (for infusing and withdrawing) of 106.579 ml/min. Hence, an infusing/withdrawing “step” of 0.1 ml could be finished in 56 milliseconds. The pump communicates with a computer through a serial port, and commands were issued from a custom Processing[59] program.

<u>Interactive Interface</u> consists on a touchable roller ball from a blackberry mobile phone (Fig. 5). This device provides four directions, from which we use only the upward and downward motion. A motion in one direction commands a step of infusing (resp. withdrawing) movement, in turn increasing or decreasing the lens power by 0.4 D. The roller ball sensor is pooled by an Arduino processor[60] sending the readout to the computer on a serial port. A Processing applet process this data and converts it to appropriate serial commands for the pump controller.

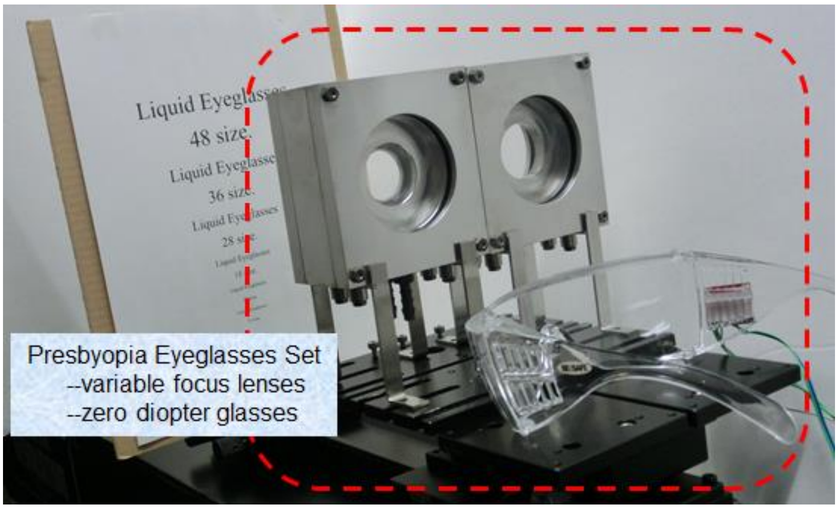

Figure 3. *Presbyopia Eyeglasses Set*, composed by the variable focus lenses and a zero diopter googles.

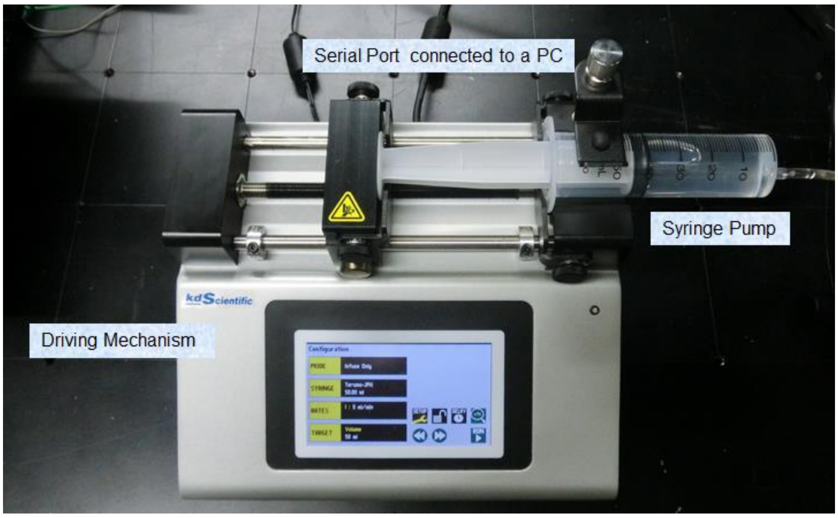

Figure 4. *Driving Mechanism*, consisting on a programmable syringe pump connected to a computer via serial port.

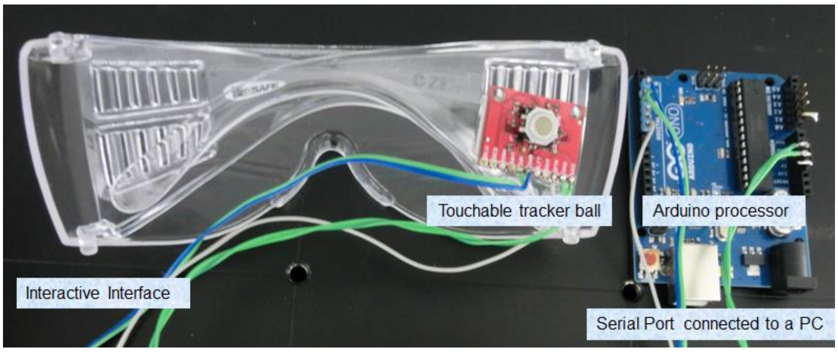

Figure 5. *Interactive Interface*, consisting on a tracker roller ball set on the right side of the wearable google. Data is collected by the Arduino and sent to the PC for processing.

3.3 Proof-of-principle experiment

A proof-of-principle experiment was conducted to confirm the diopter adjustable eyeglasses can correct for presbyopia. As described in Fig.6, three objects were placed at different distances away from the glasses - respectively 0.3 m, 1.0 m, and 3.5 m (standing from far, middle and near targets). Seeing the targets clearly represents a challenge for a presbyopic person - especially the near target. With the help of the adjustable eyeglasses, these objects can gradually be brought to focus.

A subject (first author) judged whether the adjustment is appropriate or not in a subjective manner. The goal is to adjust the diopter of the glasses in real time, trying to eliminate the perceived blur. This (human-actuated) feedback loop rapidly converges to an acceptable adjustment.. The lens starts at zero diopter and could be tuned in both directions, resulting in a negative or positive diopter, which is useful to correct for presbyopia combined with myopia or hyperopia.

To record the change of the focal length, we added a digital camera right behind the glasses, set at F/4 and initially focused on the far target (3.5m). The recorded image in this situation resembles the real presbyopic view (only the far object in focus, the others being out of focus, as seen in image A in Fig.7). In order to see the closer objects in focus, the subject had to roll the controller to increase the glasses' power gradually. In Fig. 7 (B and C) we see in focus the objects in middle and close range. These images are taken from a video that recorded the smooth diopter shifting. In the beginning, the image A was manually focused, so that it performs like the normal presbyopia vision. This series of changes means that under the assistance of the diopter adjustable glasses, presbyopia's vision could have the accommodation performance again and it could clearly see the far and near object. This principle experiment showed that the proposed glasses could dynamically correct presbyopia's vision from far to near object.

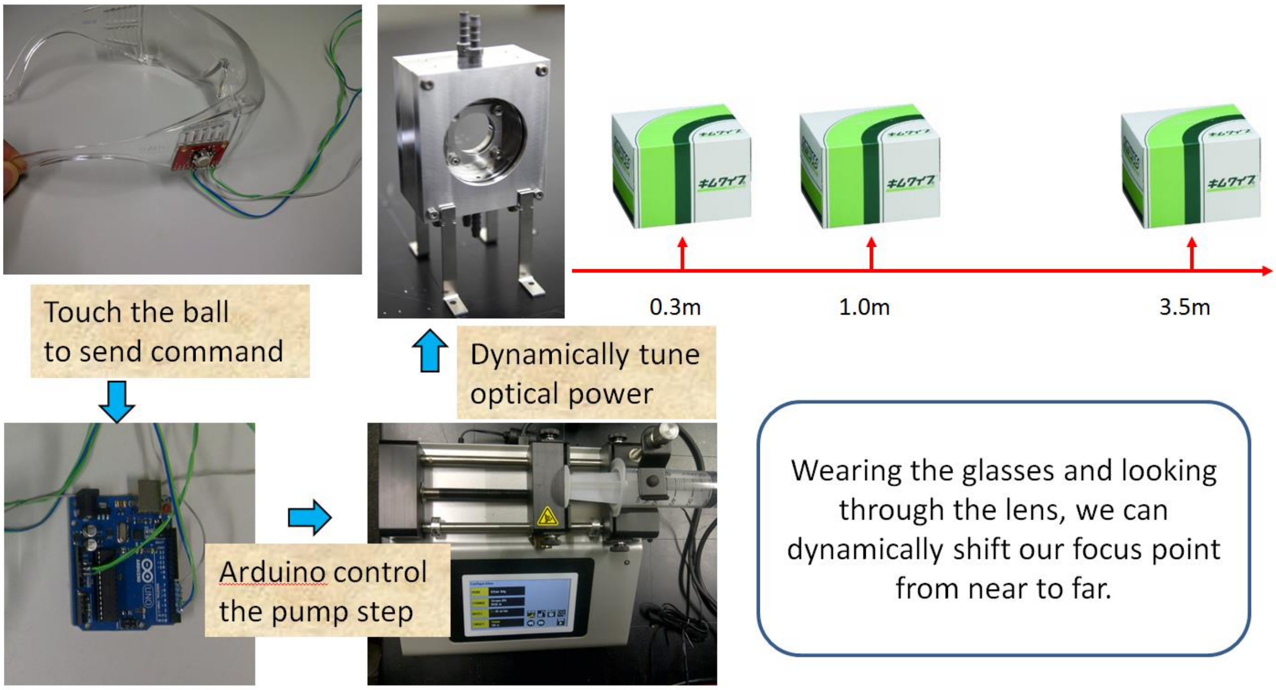

Figure 6. Experimental Setup.

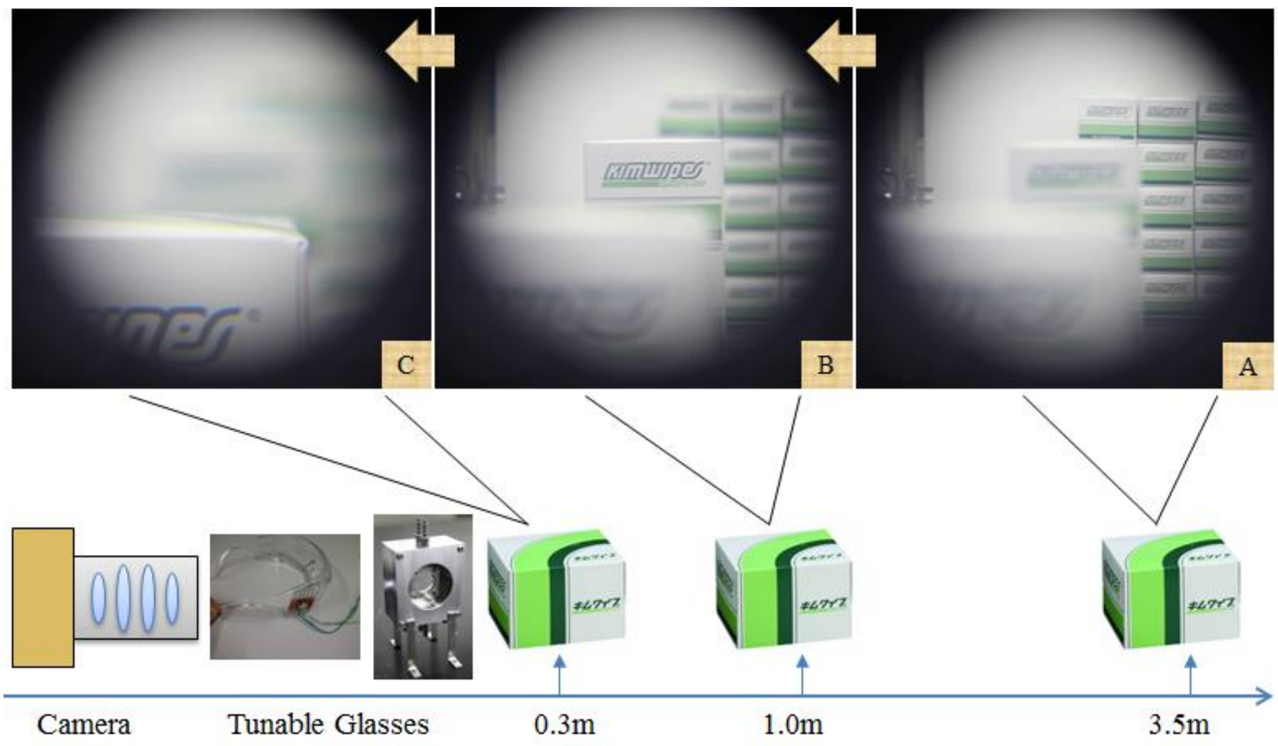

Figure 7. Experimental results (three snapshots from a video recording).

3.4 Preliminary Results

The maximum achievable diopter correction in this experiment was 4D. The test subject found vision to be clear without noticeable optical distortion on the lens surface. Owned to the fact that he was situated at some cm behind the lens, and their aperture was 26 mm, some reduction of vision field was unavoidable; however, there is no technical challenge involved in making the aperture larger. Interface and mechanical delays did not seem to introduce noticeable hysteresis in the feedback loop. Proper accommodation at any distance was achieved with in the order of seconds, and depended on the target range.

4. CONCLUSION AND FURTHER WORK

This paper proposes and demonstrates a prototype of "diopter adjustable eyeglasses", an assistive technology aimed to correct presbyopia. Presbyopia cannot be corrected by a adding (or subtracting) a fixed amount of optical power – it is necessary to adaptively correct the optical power of the lens, depending on the viewer's target. Classic treatment involves composite optical systems (bifocal/trifocal/etc.) that create optical distortions, a reduced field of view and/or unnatural head postures. We propose here a dynamic, liquid based lens that is capable of changing its optical power in a range well over what is necessary for correcting presbyopia, while at the same time doing so in the order of seconds (the actual lens can tune its power in a fraction of a second).

An important aspect of this (and future) works is the real-time, interactive response of the glasses: the user can rapidly change the optical power by a simple manual gesture on the side of the googles (much like the Google Glass command). Although this study needs to be followed up with a more in-depth characterization of the response time for manual adjustment in controlled and natural situations, the results are promising. We are currently studying other ways to interactively modify the lens' optical power not relying on hand gestures. An intriguing possibility is to detect the *natural squinting gesture* that people often do when not being able to properly focus (in order to reduce the eye's aperture). This can be done mechanically - using the deformation of the glasses frame - or using electro-myographic monitoring on the temples. A more complex system - albeit in the reach of present wearable technologies - could come handy in particular situations or for people with reduced head/neck mobility: detecting the direction of the gaze, computing the distance to the target, and adjusting the corrective power accordingly. Alternatively, if the mobility problem comes from the eyes, a laser pointer could be used to indicate the target to “focus”.

In the short term, however, the most important challenge is miniaturization; we believe that this device could be integrated in a single glass frame (there is no obstacle for miniaturization other than a theoretical thickness of about 5mm for the fluids used in this experiment; also, the amount of fluid that needs to be moved is less than 2ml, so it should be possible to design a micro-pump on the glass frame).

We believe that developing an affordable and truly wearable diopter-adjustable eyeglass for presbyopia correction is of outmost necessity given the huge (and ever growing) aging population in the whole world. That being said, it is interesting to note that this line of research can go beyond assistive technologies but form the basis of an opto-mechanical sensory augmentation device (enabling for instance telescopic or macroscopic functionality not based on digital image processing).

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