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Lightweight Smart Autofocusing Eyeglasses

N. Hasan[a], M. Karkhanis[a], C. Ghosh[a], F. Khan[a], T. Ghosh[b], H. Kim[a], C. H. Mastrangelo[*,a]

[a]Electrical and Computer Engineering Dept., University of Utah, Salt Lake City, UT 84112, USA

[b]SharpEyes LLC, Salt Lake City, UT 84102, USA

Abstract

More than 100 million people in the United States of America alone suffer from age-related presbyopia caused by a loss of focal accommodation of the eye crystalline lens as the lens stiffens with age. The resulting accommodative error or lag produces blurred images of objects placed at different distances. Conventional fixed uniform or graded power eyeglasses cannot provide accommodation thus resulting in significant visual impairment. In this paper we will discuss the implementation of lightweight auto-focusing eyeglasses that augment the accommodative range thus partially or fully restoring normal vision function. The paper discusses some aspects of the construction of tunable power eyepieces and the implementation of accommodation correction algorithms.

Keywords

Biomedical optics; presbyopia; accommodation loss; adaptive eyeglasses

1. INTRODUCTION

Refractive vision errors develop in most humans after 45 years of age due to the progressive loss of focal accommodation in the eye, a condition known as age related presbyopia affecting more than 1.7 billion people worldwide [2]. Focal accommodation defines the ability of the eye crystalline lens to change its optical power [1] in order to focus on objects placed at different distances. The optical power accommodation amplitude of a healthy eye is approximately 12 D, but it is progressively reduced to about 1 D with aging causing blurry vision [3].

When the accommodation loss is severe, prescription eyeglasses are utilized to produce the correct optical power. Unfortunately eyeglasses only provide a fixed power shift and lack any accommodation; therefore one set of prescription eyeglasses can produce sharp images at a particular object distance, but will produce blurred images at other distances. Multifocal and progressive eyeglasses alleviate some of this problem by zoning or grading the lens into regions of different power in exchange for a reduction of the focused field of view. The area zoning approach produces significant discomfort and vision impairment. Fundamentally no fixed power eyeglasses can replace the accommodative function of the crystalline lens. An

[*] carlos.mastrangelo@utah.edu; phone 1 801 587-7587.

ideal corrective eyeglass must have variable focus to compensate for the accommodation loss. The accommodation provided by the variable power eyeglasses adds to the reduced accommodation of presbyopic eyes thus partially or fully restoring normal vision.

The realization of variable power lenses for eyeglasses has been elusive because of practical constrains. First the eyepieces must be relatively large in diameters (≥ 30 mm) yet capable of significant tuning range (> 3 D). Second, the variable power eyepiece must be very light, just a few grams in weight, and third, the optical power adjustment mechanism must operate under very low electrical power for long battery operation hours. In the sections below we describe one realization of such lens with associated electronics, and we discuss some of the algorithms used to compensate for lost accommodation.

2. ACCOMMODATION IN THE PRESBYOPIC EYE

A healthy human eye has the ability to accommodate vision to near and far targets. The mechanism that drives accommodation and the factors that determine the accommodative response are not completely understood; however two major mechanisms are responsible for age related accommodation loss. The first is an effective loss of strength in the ciliary muscles, a circular band of smooth muscle fibers situated around the crystalline that changes its shape and optical power when the muscle band contracts. The second is a stiffening of the crystalline. Figure 1 below shows a typical accommodation loss curve [4] versus age for the human eye.

Generally speaking there is a lot of variation in the above curve and each individual displays a different loss curve. It is important to note that even when the accommodation is significantly reduced, it not completely lost; hence any remnant accommodation plays a role in focusing of the image. Furthermore, at any given time, the eye’s behavior is characterized by its accommodative response (the change in its optical power) which is somewhat different from that required to produce sharp images. The difference between the power response versus the expected (the accommodative stimulus *S)* is known as accommodative response function *AR(S)* which is also individual dependent. Figure 2 shows a typical accommodative response curve [5]. The slope of the curve in a healthy eye should be one, but as presbyopia develops over time the curve flattens at progressively lower powers. The curve also is also a function of the amount of ambient lighting with accommodation worsening at dimmer light levels when the pupil is enlarged.

Because to first order the lens eyepiece and eye optical powers can be added, in order to restore normal vision it is necessary for the variable focus lens to reproduce the accommodative deficiency curve or $AD(S) = (S-AR(S))$ for a particular individual and each of his or her own eyes. In practical terms this means that such curve should be programmed into the individual’s autofocusing eyeglass set. Furthermore, the accommodative stimulus corresponding to the optical power along the horizontal axis in Figure 2 is inversely proportional to the distance to the observed object; therefore such set must include an object distance range sensor.

3. LIGHT-WEIGHT TUNABLE-FOCUS LIQUID EYEPIECES

There is a large amount of literature on the construction of variable focus lenses with different technologies [6] inclusive of mechanically sliding surfaces, deformable lenses and index-changing liquid crystals. Lenses based on mechanically sliding surfaces have very limited "in focus" field of view and produce large aberrations resulting in poor image quality. Liquid crystal lenses on the other hand do not require moving parts, but they are very difficult to implement when the aperture is beyond 1 cm as this requires very thick LCD layers [7] to produce the required high powers. To bypass this issue many LCD Fresnel lens configurations have been implemented but these type of lenses are subject to step edge effects and chromatic aberrations. Liquid deformable tunable lenses [6] have also been implemented, but many of these require movement of fluid in and out of storage reservoirs which makes them heavy and bulky.

In this work we have developed squeezable-type liquid lenses which do not require external fluid reservoirs. Each tunable-focus eyepiece consists of a cylindrical liquid-filled chamber bound by two flexible polydimethyl siloxane (PDMS) membranes. The lens structure and electro-optical performance is described in [8]. The cross section of each eyepiece lens excluding the actuators is shown in Figure 3. The thickness of the front top membrane of the lens is 1.4 mm, and the bottom membrane is 0.2 mm thick. The lenses are driven by very low profile piezoelectric actuators.

Three curved piezoelectric bimorph actuators are placed along the periphery of the lens as shown in Figure 4(left). One end of the each actuator is attached to the lens rim and the other end is free. This configuration permits the free rotation of the bimorph tip as they bend resulting in a high vertical displacement [5]. A hollow piston with three extended arms is attached to the back membrane. The free ends of the actuators are connected to the piston's extended arms. When voltage is applied to the bimorph actuators, they move the piston up or down making the front surface of the lens convex or concave. Figure 4(right) shows a representative curve of the lens optical power as a function of actuation voltage.

The optical power is linearly proportional to the actuator voltage [3]. The lens has as a mechanical resonance frequency of 70 Hz with a response time of about ~40 ms. Each eyepiece lens has aperture diameter of 30 mm, optical power range of ~5.2 D, overall diameter 52 mm, and weighs 14.2 gm. The tunable eyepieces are driven by a microcontroller system that adaptively calculates the optical power required to produce sharp images from the prescription of the wearer and object distance range measurements..

4. AUTOFOCUSING SMART EYEGLASSES

The smart autofocusing eyeglasses consists of two tunable-focus eyepieces, a ToF distance sensor, a microcontroller supervisory processing unit, a two-channel microprocessor controlled DC-to-DC high-voltage converter providing actuator voltages, a wireless bluetooth low energy (BLE) module, and a set of LiPo rechargeable batteries, all integrated in a low-weight platform frame. The microcontroller system wirelessly communicates with a mobile app that is used to enter the wearer prescription and other operating parameters. The driving circuits and microcontroller system are powered by 3.7V rechargeable batteries embedded inside the eyeglasses frame temples. The details of the electronics subsystem have been presented elsewhere [9]. Figure 5 shows a photograph of a second generation smart eyeglass set. A time of flight (ToF) distance sensor is embedded above the nose support of the eyeglasses frame to measure the forward distance d to the object in front of the observer. The entire set weighs approximately 120 gr.

The set is controlled by a smartphone application used to set the observer prescription, the type of refractive error and other operating settings. The supervisory board continuously calculates the two-component (one for each eyepiece) optical power vector $\overrightarrow{P}_{lens}$ required to produce sharp images of the object ahead by combining the prescription setting vector $\overrightarrow{S}$, object distance d and accommodative response curves to reproduce the accommodation deficiency curves $\overrightarrow{P}_{lens} = \overrightarrow{AD}(d)$. The supervisory processor maps the required optical deficiency powers into actuator voltages needed for the eyepieces.

5. OPTICAL TEST RESULTS AND DISCUSSION

We have carried out two tests to evaluate the effectiveness of the smart eyeglass eyepieces in the restoration of accommodation.

Image Quality Test:

The first test is designed to test the ability of the liquid tunable eyepieces to produce sharp images under a preset fixed refractive error. This setup demonstrates how our adaptive eyeglasses eyepiece changes optical power as a function of distance restoring accommodation function. To perform this test we constructed the optical camera setup shown in Figure 6 consisting of a 18MP image sensor (MU1803, AMScope) with a fixed power.

lens that mimics the response of a fully presbyopic farsighted eye (focused at infinity) with zero accommodation. The camera lens setup is followed by our tunable lens. To check the feasibility of our lens and control system, we first placed one object in front of our eyepiece and varied the object distance from 28 cm to 1.5 m. The distance sensor measured the distance to the object and varied the eyeglasses optical power as specified in Eq. (1) of [9] for an eye that has zero remnant accommodation. Figures 7(left) and (right) show two photos of far and near objects taken at +0 D and +3.5 D. When the object is at infinity the lens optical power becomes +0 D and when the object is 28 cm away from the eyepiece, the lens optical power becomes +3.5 D.

From the photos it is clear that the eyeglasses eyepiece changes its focal length according to the object distance that the observer wants in focus. We have also measured the MTF of the setup using a standard slanted knife edge target and ImageJ software from NIH. For a modulation factor of 0.5, the resolution was 25 lp/mm.

Restoration of Accommodation Deficiency:

The second test is designed to measure the smart eyeglasses system ability to correct for a pre-programmed accommodation deficiency curve. To do so we replaced the fixed lens in the setup of Figure 6 with a variable lens that follows a prescribed hyperopic (far sighted) accommodative response curve $AR(d)$ at different object distances as shown in Figure 8 below. The AR eye simulator setup was constructed utilizing a stepper motor connected to a single Adlens Hemisphere tunable eyepiece as shown in the photograph of Figure 8.

Our piezoelectric tunable eyepiece was next programmed to produce a power corresponding to the accommodative deficiency $AD(d)=S(d)-AR(d)$ and the total power of the lens combination was measured using a Shack-Hartmann wavefront sensor. Figure 9 (left) shows a model accommodation deficiency curve for hyperopic (farsighted) presbyopia. Figure 9 (right) shows the comparison of the accommodative response without and with the smart eyeglasses tunable eyepiece programmed to compensate for the deficiency. Note that the smart eyeglass eyepiece restores accommodation lost with high fidelity,

6. SUMMARY

We demonstrated an implementation of autofocusing eyeglasses designed to restore accommodation lost by age related presbyopia. The variable power eyepieces are driven by a battery-powered microcontroller system that measures the distance from the observer to the object and combine this with the observer prescription to produce clear images at any object distance. We experimentally measured the image quality through our variable power lenses and demonstrated the ability of the smart eyeglasses algorithm to restore lost accommodation for normal vision restoration.

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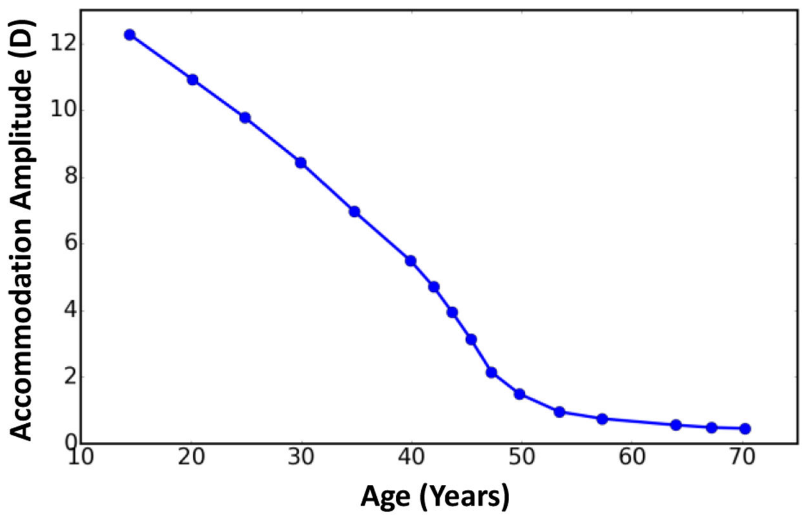

Figure 1.

Illustration of typical Duane's accommodation amplitude vs age curve [4] for the human eye. The accommodation is reduced from roughly 12 D to about 1 D after age 50.

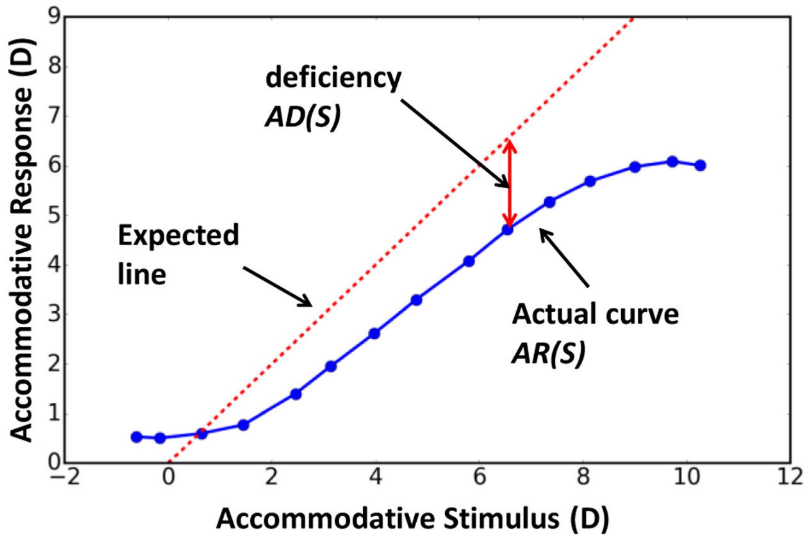

Figure 2.

(a) Example of typical *S-type* accommodative response [5] for the human eye. The curve slope progressively flattens for the high powers with age. Furthermore the curve may exhibit offsets and flat regions at low stimulus.

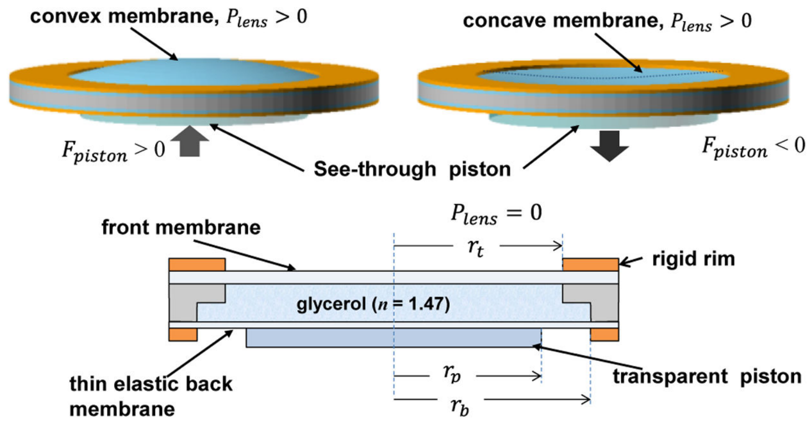

Figure 3.

Simplified schematic of the tunable-focus lens excluding actuators [9]

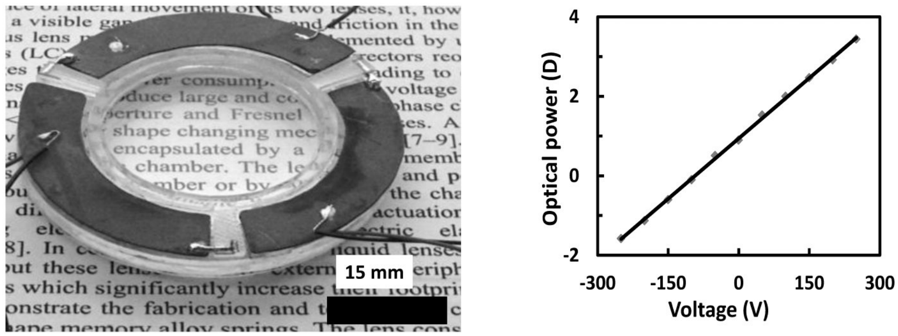

Figure 4.
(left) Photograph of the actual device, and (right) lens optical power as a function of actuator voltage [9].

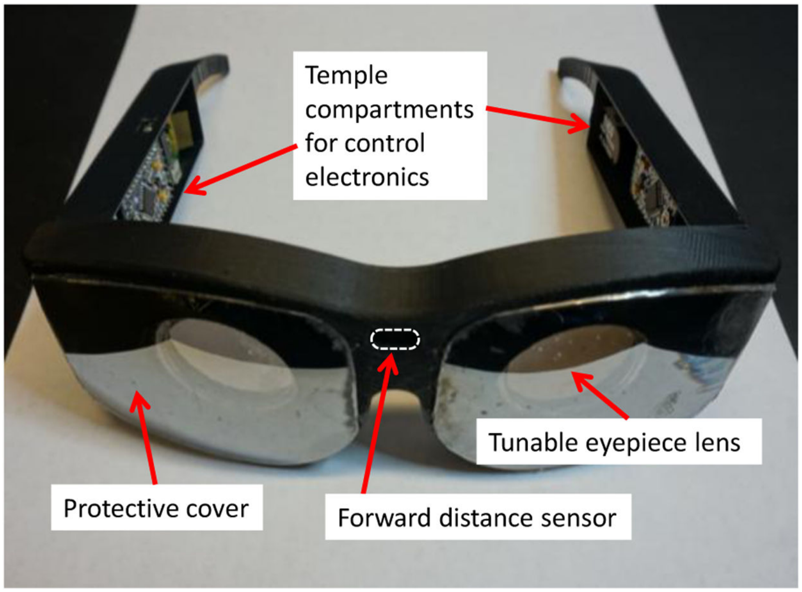

Figure 5.
Photograph of a second generation smart eyeglasses with exposed temple compartments.

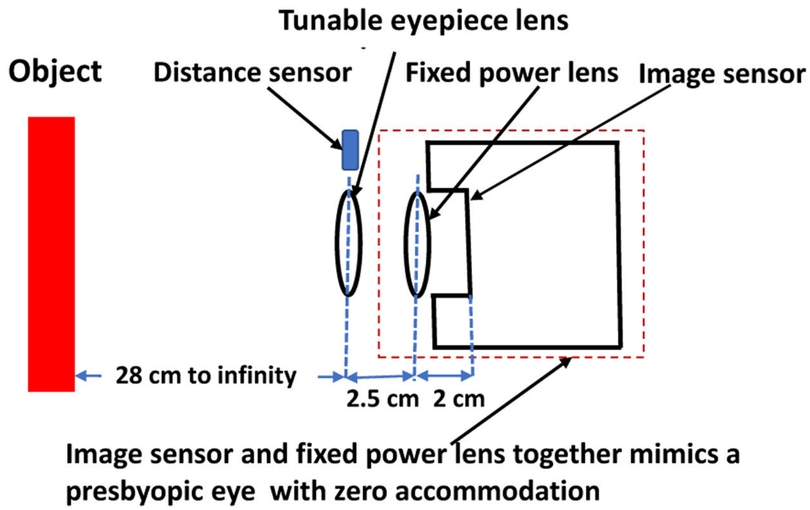

Figure 6.

Optical setup utilized for imaging an object through a tunable lens eyepiece [9]. The fixed lens and camera emulates the response of a fully presbyopic eye with zero accommodation.

Figure 7.
Imaging of objects through optical setup of Figure 6 emulating a fully presbyopic eye with accommodation provided only by the variable power eyepiece. Images were recorded using our test unable focus eyepiece at optical powers of +0 D (left), and at +3.5 D (right)..

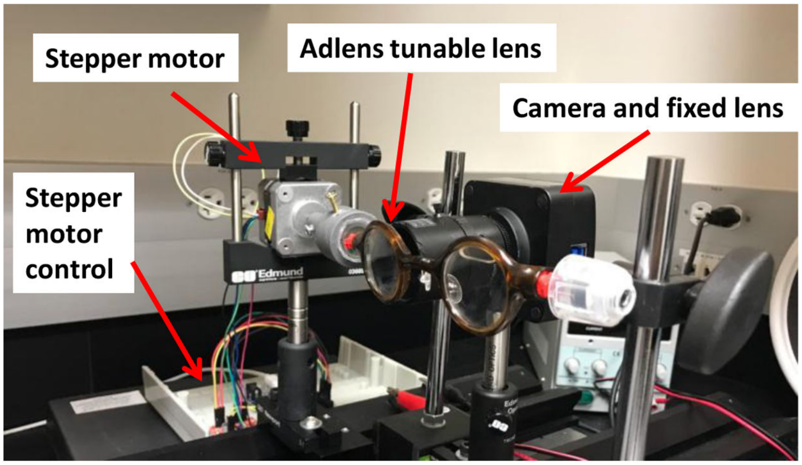

Figure 8.

Variable power setup used to emulate the accommodative response of an eye. The accommodation response is provided by the programmed power of the variable lens as a function of object distance.

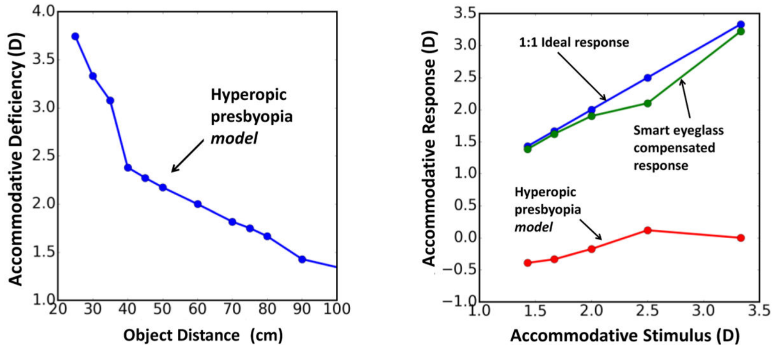

Figure 9.

(left) Example of a model accommodative deficiency response for a hyperopic presbyopia eye. The model curve was programmed in the optical setup shown in Figure 8. (right) Accommodative response versus accommodative stimulus for the model prebyopic eye (red) and compensated by the smart eyeglass (green). Note that the smart eyeglass algorithm restores the lost accommodation with good fidelity.