Development of Wavefront Sensor using Shack-Hartmann Principle

Marie Cattleah D. Atas, Larish Mariam T. Landicho, Abigail D. Lobo, Carla Joy L. Orubia,
Adolph Christian O. Silverio, Aaron U. Aquino, Timothy M. Amado, John Carlo V. Puno, Jay Fel C. Quijano, Nilo M. Arago*
Electronics Engineering Department, College of Engineering
Technological University of the Philippines
Ayala Blvd., Ermita, Manila, Philippines

Email: jcp040195@gmail.com

Abstract*— Over the past years, wavefront technology is used in astronomy because it has better telescopic resolution for examining the universe. Since earth turbulence causes atmospheric aberrations, this technology is the solution compensating it. Human eye also has aberrations, which is divided into two, higher and lower order aberration. In this study, human eye is examined using the wavefront technology. Developing vision correction is the key technique to understand the condition and quality of a human eye. The wavefront sensor is composed of photodetector, visual stimulus, collimating lens and microlens array, which is based on the Shack Hartmann Principle. As the light from the visual stimulus enters the human eye, it is reflected by the retina. The light rays bounce back and will pass through the collimating lens that would make the reflected light parallel to configure illumination. Then, it will enter the microlens array that will divide it into discrete sections, one section for each lenslet. Therefore, each lenslet will focus its part of the incoming wavefront to a spot. It will be captured by the photodetector, which is controlled by a microcontroller. It would take only 5 seconds to capture the wavefront. This sensor creates a raw image showing how the light traveled in the eye and its imperfections. Numerous processing methods can be applied depending on the desired output. This raw image from the wavefront sensor contains information and parameters that can be helpful in detecting the aberrations.

Keywords*— (Wavefront, Shack-Hartmann Wavefront sensor, Wavefront Technology, Refractive Error, Charge Coupled Device (CCD) Camera, Higher-Order Aberrations (HOA), Lower-Order Aberrations (LOA))

I. Introduction

In the late 1960's, the Optical Sciences Center (OSC) at the University of Arizona by the US Air Force wanted to improve images of satellite taken from the earth. The image quality and exposure time of the stars taken by the telescope is limited by the earth's atmosphere [1]. With wavefront technology and adaptive optics, this turbulence was compensated, and astronomers could use their telescopes to discover far-off stars and distant suns in the universe. This technology was also used in astronomical telescopes for military purposes, in antimissile defense systems [2].

Vision impairments are optical imperfections of the eye that prevent light from focusing perfectly on the retina, resulting in flaws in the visual image. These are also called wavefront aberrations. Since the human eye has also aberrations, wavefront technology can be used in studying and examining it. These aberrations are grouped into two, the lower-order aberrations that is consist primarily of nearsightedness, farsightedness and astigmatism, and the higher-order aberrations that is generally associated with double vision, blurriness, ghosts, halos, starbursts, loss of contrast and poor night vision. There are a variety of reasons why most refractive errors are left uncorrected. This includes the lack of awareness regarding the proper eye care and the limited services offered for eye checkups [3]. Up to date, eye clinics in the country use autorefractometers which follows refraction assessment using low vision eye charts and phoropters. All the autorefractometers being used are imported and costs more than half a million pesos. Moreover, the latest statistics says that the ratio of the ophthalmologists in practice and in training to the population in the Philippines is 14: 1,000,000 [4]. This means that there are only around 1,400 ophthalmologists in the country.

II. Theoretical Background

Several technology advancements have been made towards the measurement of refractive errors in the eyes. The early methods used, which are still used in every eye checkup conducted up to date, are the subjective eye examinations. These eye checkups require the feedback of the patient to acquire an accurate result [5]. Typically, optometrists and ophthalmologist utilize the use of specialized low vision eye charts. After asking the patient to read out lines from the chart, the next process will be the refraction assessment. Nowadays, the most common eye checkup device found in eye clinics is the autorefractometer. The autorefractometer estimates the refractive errors in the eyes.

This study will address the problem of the limited availability of the eye checkup services in the Philippines which is one of the main reasons why there are uncorrected refractive errors. Using the latest technology, the wavefront technology, the eye checkups in the country will be more efficient and provide a more accurate result as this eye examination is not subjective. Nowadays, interest in the application of wavefront sensing technologies for visions science and ophthalmology has increased. [6].

A. Microlens Array

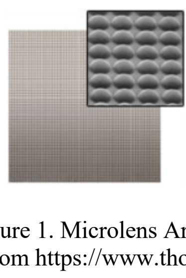

Figure 1. Microlens Array
(adapted from https://www.thorlabs.com/)

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Microlenses, as show in figure 1, are discrete or array-based spheres, aspheres and other optics being used for focusing light inside fibers for optical networking or vision system. In general, microlenses have a diameter between 10µm–5mm and a curvature radius of 0.25—2.5mm [7] [8] [9]. Microlens arrays are used for combining a variety of modern light emitters from line-narrowed excimer lasers to high power LEDs. These lenses are suitable for applications that requires high efficiency and non-gaussian uniformity [10]. Square microlens, which is usually 10mm x 10mm, are usually used in wavefront sensors [11]. The manufacturer, Thorlabs, used fused silica for excellent transmission characteristics from the UV to the IR [10].

B. Wavefront Technology

One of the new technologies used in measuring the refractive errors in the eyes is the wavefront aberrometry. Light travels in flat sheets called wavefront. Undisturbed waves remain parallel. These aberrations and irregularities in in the lenses and cornea of the eye vary the light waves that enters it, which causes wavefront errors or distortions. The interpretation and calculation on how the way a wavefront of light passes through the cornea and crystalline lens, which are the light focusing or refractive components of the eye, is called Wavefront Aberrometry, It examines at the whole eye and the way in which the eye sees the world to develop a raw image [12]. This image has numerous information which is are important in detecting refractive aberrations. Some eye doctors see wavefront analysis as an extension of the principles of corneal topography. It is also an essential method for high-resolution imaging of the retina.

The most commonly used wavefront sensors are the laser ray tracing technique, spatially resolved refractometer, and the Shack–Hartmann wavefront sensor [6]. These wavefront sensors can diagnose both lower order aberrations and the higher order aberrations in the eyes [12][13]. Wavefront analysis focuses on the optical center of the human eye and interprets more detailed evaluation of the visual system. It optimizes any aberrations it detects to create the most accurate vision correction treatment for that every individual. Therefore, these technology does not only provide more accurate knowledge and details for the vision correction plan, but far more information than ever within the central vision area to be handled [2][12].

C. Shack-Hartmann Principle

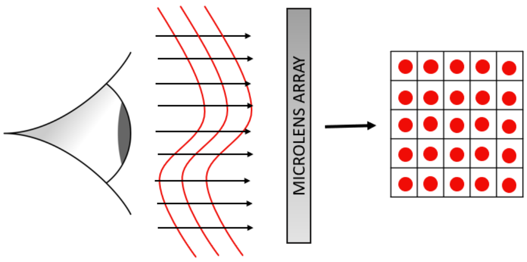


Figure 2. Wavefront from the eyes is spatially sampled by the microlens array forming the red dots

The impairments of an optical system, such as the eye, prevents a spherical wavefront from being spherical once it passes through the system, as shown in Figure 2. When the rays bounce back and show imperfections, the images are called aberrations [15][16][17]. As the light from the visual stimulus enters the eye, it is reflected by the retina. The photodetector captures the wavefront from the reflected light that passed through the microlens array. Each micro-lens concentrates its part of the light on a charge-coupled device (CCD) camera placed on the focal plane of the lenslet array. Raw data containing red dots will be processed by the program to obtain the desired result [15][18][13].

D. Aberrations

Optical aberrations of the eye which inhibits light from focusing completely on the retina, that results in faults in the visual image are called wavefront aberrations or errors. There are two kinds of aberrations, the lower order aberrations (LOA) and the higher order aberrations (HOA) [19][20].

a. Lower-order Aberrations

LOA, which comprises first three order aberrations, define the refractive errors in the eyes which are usually corrected by eyeglasses, contact lenses, or refractive surgery. There are three types of LOA, namely, myopia, hyperopia, and astigmatism [20]. Myopia or nearsightedness occurs when light focuses in front of the retina, which causes far objects to be blurry. It can be caused if the length of the eyeball is long or when the cornea is too curved [21]. Hyperopia or farsightedness occurs when light focuses behind the retina, causing near objects to appear blurred. It can be caused if the eyeball is shorter than normal [22]. Astigmatism, on the other hand, occurs when the cornea of the eye is irregularly shaped, that causes near or far objects to be blurred. In an eye with astigmatism, light rays bent which causes multiple focus points, either in front of the retina or behind it (or both) [23].

b. Higher-order Aberrations

HOA, which comprises the 3rd to nth order aberrations, define optical imperfections such as coma, trefoil, etc. The HOA covers about fifteen percent of the total number of aberrations in the eye [19][24]. HOA is a distortion when the wavefront of light passes through an eye with irregularities in its refractive components (tear film, cornea, aqueous humor, crystalline lens and vitreous humor). Regular eyeglasses and contact lenses cannot correct these kinds of aberrations because these are more complicated refractive errors than nearsightedness, farsightedness and astigmatism. There are many different kinds of higher-order aberrations, but only spherical aberration, coma and trefoil are usually encountered [24][25].

Although these refractive errors in the eyes can be corrected by eyeglasses, contact lenses, or refractive surgeries, it may lead to worse cases or even blindness if not treated immediately.

III. Methodology

This section explains the construction of a wavefront sensor using Shack-Hartmann Principle.

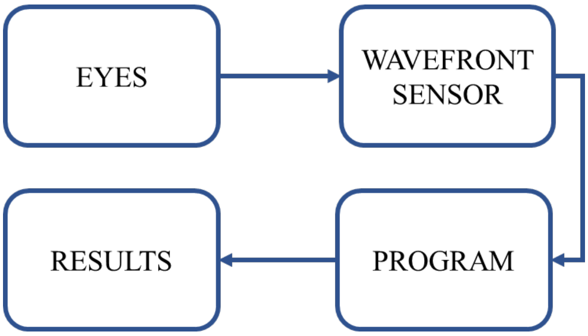


Figure 3. General Block Diagram

Figure 3 shows the general block diagram of the hardware. The wavefront sensor is the one responsible in producing a raw image from the wavefront generated by the eye. It will be then utilized by a program in charge to obtain the desired output. The raw image from the sensor produces information that can be used to determine the LOA and HOA.

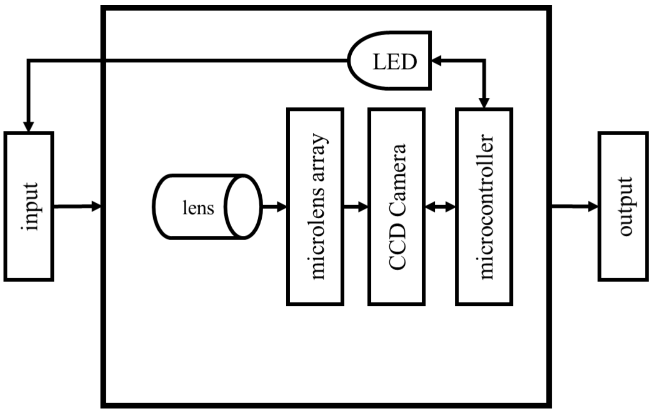
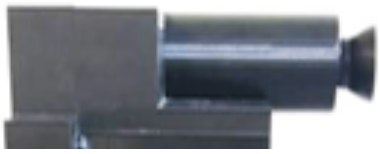


Figure 4. Wavefront Sensor Diagram

Figure 4 shows the block diagram of the wavefront sensor. Human eye being the input, and raw image as the output. As the light from the visual stimulus, enters the eye, it reflects and produces a wavefront. The visual stimulus that is used in this sensor is a red Light-Emitting Diode (LED) that has a wavelength under the group, Retinal thermal-weak visual stimulus. The LED is controlled by the microcontroller. When the wavefront reaches the microlens array, the array will divide it into discrete sections, one section for each lenslet. Therefore, each lenslet will focus its part of the incoming wavefront to a spot on the CCD. A perfect eye wavefront is a plane wavefront which produces a perfect grid on the CCD camera. However, an eye which is aberrated will produce a distorted and complex grid that diverges horizontally, vertically and both from the optical axis of the lenslet. It deviated by an equal proportion that is directly related to the angular ray aberrations of the eye at the corresponding pupil location [26]. With the help of collimating lens, the field of view is controlled for the collection efficiency and spatial resolution of the setup. The CCD Camera, which is also connected to the microcontroller, will capture the wavefront in 5 seconds. This output produces the raw image that will be processed by the program depending which aberration is needed to be detected [13][27][28].

(a)



(b)

(c)

Figure 5. Construction of Wavefront Sensor (a) base, and the components inside (b) top (c) components inside the top

Figure 5 shows the construction of the wavefront sensor. The base, as shown in Figure 5.a, is composed of the screen where the results can be seen, power bank as the power source, circuit for the LED, switch to turn on and off the prototype and the microcontroller. In figure 5.b shows the top part of the prototype, it is designed like a telescope. It has an eyecup where the users can peek for them to be examined. While in Figure 5.c shows what's inside the top part, it is composed of the camera and its ribbon, which is connected to the microcontroller, the collimating lens and microlens array.

IV. RESULTS

This section presents the Shack Hartmann wavefront sensor, its specifications and the sample raw image acquired.

(a)

(b)

(c)

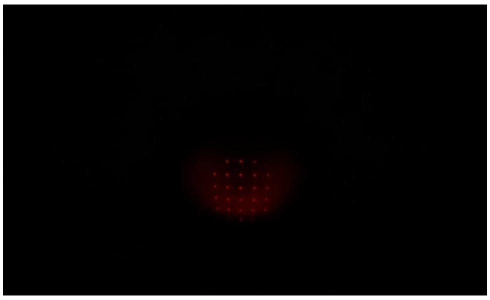
Figure 6. SOLLA Eye Check (a) front view (b) back view (c) side view

Figure 6 shows the final design of the prototype. The 3D printed case is supported by a tripod that can be adjusted depending on the height of the user. The eyecup where the user peeks in, is seen from the front view, shown in Figure 6.a. The screen display is located at the back, shown in Figure 6.b. The ports and the switch are located at the left and right side respectively, as shown in Figure 6.c. In table 1, the specifications of the wavefront sensor is computing or detecting the aberrations.

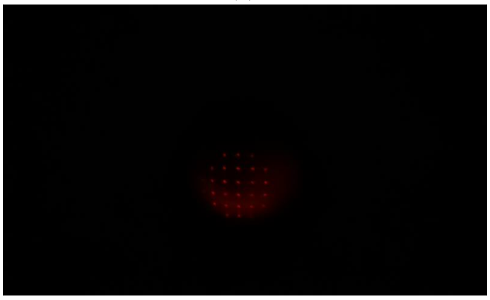
TABLE 1

SPECIFICATIONS OF THE WAVEFRONT SENSOR

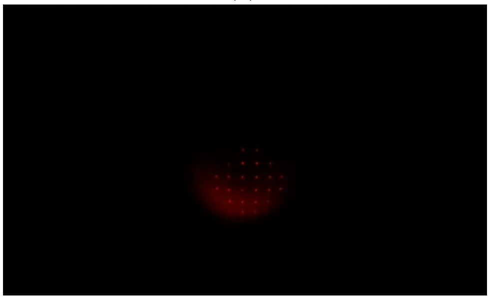
Array Size and Type	10x10mm, square grid
Lens Pitch	150 μm
Lens Diameter	146 μm
Focal Length	5.2mm
Camera Resolution	8megapixel, 3280x2464pixel
LED Wavelength	700nm
Operating Hours	24-30 hours



(a)



(b)



(c)

Figure 7. Raw images obtained from the wavefront sensor (a) sample-1 (b) sample-2 (c) sample-3

Figure 7 shows the sample raw images that was obtained from the wavefront sensor. It is noticeable that each image has differences. The raw image contains spots. Each image has different level of brightness in their own spot. Also, the number of spots, Figure 7.a and Figure 7.b has same number of spots, while Figure 7.c has more. Therefore, each image contains different information. Once processed using different algorithms, data from each image will be very helpful in obtaining the desired output.

V. CONCLUSION

Wavefront technology is very essential in today's generation for it has numerous applications. Wavefront sensing using Shack-Hartmann principle is one of it. The wavefront sensor is composed of a CCD Camera, collimating lens, visual stimulus and microlens array. When the light enters the human eye, it is reflected and will be captured by the wavefront sensor. From the raw data obtained by the sensor, it is can be processed and interpreted by a software. Each spot in the raw image contains relevant information that is useful in detecting the higher and lower order aberrations. With the use of this sensor, early detection of the aberrations in the eyes and the immediate correction using contact lenses, eyeglasses, or refractive surgeries will prevent further complications that may occur.

VI. FUTURE WORKS

The researchers recommend having a faster and easier testing by using binocular lenses where the user will have both eyes to be examined at the same time. Using a high-definition camera is also recommended, it will give better image quality for easier processing. It is suggested to use a better microcontroller for high-speed processing.

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