ULTRALOW POWER FLEXIBLE OCULAR MICROSYSTEM FOR VERGENCE AND DISTANCE SENSING BASED ON PASSIVE DIFFERENTIAL MAGNETOMETRY

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ABSTRACT

We report the theory, construction, and testing of a flexible ocular, on-the-eye microsystem used for ultra-low power object distance sensing suitable for smart adaptive contact lenses. The microsystem determines object distance by vergence angle triangulation. Vergence angle is determined from passive measurements of the earth's magnetic field at each eye. Vergence measurements were performed every 5-degree interval over 35 degrees in total for each eye to accommodate the entire human visual range. Vergence angle measurements had an RMS error of 1.74 degrees and a distance ranging RMS error of 14.04 mm. The energy requirement per magnetic field measurement was estimated to be approximately 2 μJ per eye.

KEYWORDS

Object distance sensing, vergence angle triangulation, magnetometry, smart contact lens.

INTRODUCTION

As the human eye ages, the crystalline lens within the eye loses its flexibility which leads to a persistent refractive error called presbyopia. More than 1.8 billion people around the globe suffer from this refractive error [1]. Presbyopia manifests itself as an inability of the human ocular system to focus on objects at different distances, near and far. This condition leads to visual impairment, blurred vision, and reduced quality of life. To date, corrective eyewear technologies that consist of bifocal, trifocal, or progressive lens designs have been extensively used for managing and mitigating the effects of presbyopia. A fundamental drawback of such lenses is that they severely reduce the field of view and partition the user's vision into areas of different refractive indices and magnifications. Such division of the field of view has been known to cause accidents in the elderly. Additionally, users are also subject to a false perception of depth, image jumps, and the inherent optical aberrations induced during the manufacturing of such lenses [2].

A better approach for vision correction is the use of smart eyeglasses or smart contact lenses embedded with user-specific power-vs-distance models [3], [4]. The smart contacts adaptively change the optical power of the lens depending on the distance of the object. This results in sharp object images in the user's field of view. The realization of smart contacts require many innovative technologies and subsystems such flexible wiring [5], energy harvesters [6], [7], power storage [8], eye tracking sensors [9], tunable focus lenses [10], supporting circuitry, and soft packaging integration. [11]

The practical realization of this autofocusing system requires the determination of the object distance from the user and the vergence angle between the user's eyes with a very low power consumption. In this work, we make use of MEMS magnetometers, one on each eye, to sense the geomagnetic field. The vergence angle is calculated from this differentially sensed magnetic field. We achieve vergence angle determination with an RMS error of 1.74 degrees and object distance determination with an RMS error of 14.04 mm with an ultra-compact and ultralow-power approach.

DISTANCE RANGING METHODS

Both active and passive distance ranging methods have been previously used to determine object distance. In the case of active ranging, a beam of light is emitted from the user and it is returned back after reflecting from the object. The range is determined by the reflected signal angle or time of flight. The power consumption of this method depends on the object distance. The further the object is, the more powerful beam is required. Such systems are power-hungry and may require battery packs or need to be constantly plugged in. This makes them unsuitable for mobile applications like standalone smart contact lenses where limited energy is available. Passive ranging is more energy-efficient and hence desirable [12].

The most commonly used mobile eye-tracking method utilizes camera-based image processing techniques. Here, the face is lit with multiple IR LEDs, the cameras take multiple pictures, and a powerful computer processes them to determine the gaze direction [13]–[15]. This technique, again, is power inefficient and cannot be used for contact lenses. More recently, VCSEL pairs were used for eye-tracking with an IR camera [16]. Camera-less approaches are desirable to reduce power consumption. IR LEDs and photodiodes-based camera-less eye trackers were implemented in a standalone smart eyeglasses system [17] and in a contact lens system (with photodiodes) paired with eyeglasses (with IR LEDs) [18], a system where light from VCSELs is directed with a micromirror onto the eye and detected with photodiodes is also used for gaze tracking in smart eyeglasses [19]. Purkinje reflections have also been used in literature for eye tracking [20]. Another approach involves using scleral coils, which require a headgear to be worn. This headgear has large, power-hungry, external AC-driven electromagnets. An eye-angle-dependent EMF is induced in the scleral coils, which behave like the secondary windings of a transformer [21], [22]. Though this method is highly accurate, the continuous requirement of wearing bulky headgear is undesirable and may cause the user some discomfort.

Recently, a low-power, low-profile quad scleral coil-based approach was developed for vergence angle detection [12]. In this approach, two sets of coils were placed on each eye. One set of coils generates a magnetic field, and emf is induced on the other set of coils on the other eye. The vergence angle can be determined from the amount of emf induced. This approach completely eliminates the need for any external emf-generating circuitry and hence, any bulky headgear involved. Further improvements were made to this system to drastically reduce the energy consumption to just 340 nJ per measurement [23].

In this paper we discuss a method of determination of object distance that does not require any radiating energy emissions; hence ultimately requiring less power. The method is based on the measurement of a vector field that is uniform on both eyes.

WORKING PRINCIPLE

The magnetic field generated by the quad coil setup in [23] is unnecessary if another external field exists in the space between the two eyes. Two types of such fields exist. One is the Earth's gravitational field, and the other is the magnetic field of the Earth. The gravitational field can be measured with the help of an accelerometer. However, the the downward facing gravitational field is stronger than its horizontal component which are parallel to the ground. The other field i.e., the Earth's magnetic field points downward and to the north. This field can be affected by nearby magnetic materials and can be measured using tiny magneto-resistive sensors. Such magnetic field sensors can be routinely found as a digital compass in consumer electronics.

To determine the vergence angle between the eyes, the magnetic field should roughly point along the same direction on both the eyes. The interpupillary distance (IPD) of human eyes is approximately 60 mm. It can be safely assumed that no other magnetic object will come in close proximity to the eyeballs, lower than the IPD. In such a case the magnetic field will be equal at both eyeballs. If there exists a magnetic object in the vicinity of the eyes, lesser than 60 mm in distance, it will distort the surrounding magnetic field. Also, this method of vergence triangulation does not depend on the direction of the magnetic field.

In this work, we place the magnetometers at a 45-degree angle from the pupil, on the side of the nose bridge. This angle placement is arbitrary and does not affect the field measured. The vergence triangulation approach can be understood from Figure 1. Here it can be seen that, if the vergence angle is θ_V, then the angle between the magnetometers is given by $\theta_V + \pi/2$. When the eyes focus on an object, the eyes rotate about the z-axis. However, the magnetometers are placed such that the reference z-axis is mapped as magnetometer x-axis. The vergence angle can be calculated using (1) if object distance (d) is considered much greater than the IPD, and the object distance can be triangulated using (2).

$$d = \frac{IPD}{2\tan\frac{\theta_V}{2}} \approx \frac{IPD}{\theta_V} \quad (1)$$

$$\theta_V = -\frac{\operatorname{asin}\left((b_{yl}.b_{yr}+b_{zl}.b_{zr}\right)}{\sqrt{b_{yl}^2+b_{zl}^2}.\sqrt{b_{yr}^2+b_{zr}^2}} \quad (2)$$

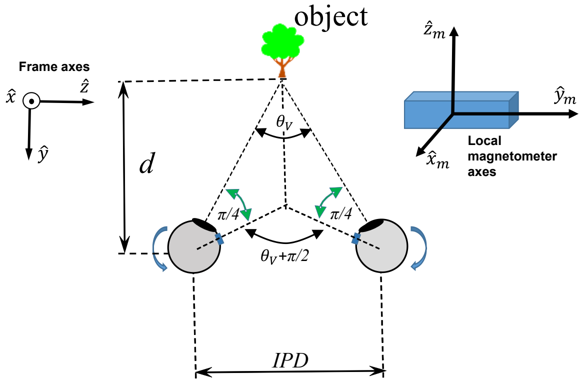

Figure 1: Vergence angle and distance ranging measurement using magnetometers placed at 45 degrees from the pupil.

EXPERIMENTAL

Magnetometer on Flexible Smart Contacts

A contact lens needs to withstand the bending it experiences while a user puts it on and takes it off. It also needs to accommodate appropriate circuit components. Also, attaching components to a curved substrate is difficult. Hence a special origami-based approach was adapted for the substrate of the smart contact lens (SCL) which involved fabricating a polyimide-based flex-PCB, populating it with components and then folding and joining it such that it resembles a dome-shaped contact lens.

A flex-PCB for assembling the magnetometer with the SCL platform was designed using EAGLE (Autodesk). The thickness of the flex-PCB was 80 µm, including a copper trace thickness of 18 µm. Supporting circuit components as shown in Figure 2 were then mounted on the PCB using reflow soldering. The magnetometer used is HMC5883L (Honeywell) and the microcontroller used is the ultralow-power, 32-bit Cortex-M4 MAX32660. The assembled, folded and joined PCB is shown in Figure 3.

A Goldberg polyhedron shell was selected as the base shape and then sliced, from top to have a flat area for the lens and from the bottom to define the SCL size, in Rhino 6. Then using simple cut and unfold origami techniques, this shell was flattened in JavaView. Next a 2D projection of this flattened shell was taken in OpenSCAD. A 4 mm aperture was added to this design, for the lens, at the center of the top sliced face. For permanent folding of the faces, small protrusions or tabs were designed in AutoCAD (Autodesk) to be added to the edge of the cut faces which sported copper pads, designed in EAGLE (Autodesk). Similar pads were also present on the opposite face sharing the edge with the faces with tabs, but with tiny 200 µm holes. Copper pads were also placed on the bottom side of this face, under the holes to allow for proper adhesion with solder. Solder was reflowed on the copper pads of the tabs. The two opposite edge sharing faces were brought together such that the tabs were directly underneath the holes. Heat was applied through the holes and the tab was soldered to the opposite face. All such tabs were joined which resulted in a curved, dome-shaped PCB in the shape of a scleral contact lens.

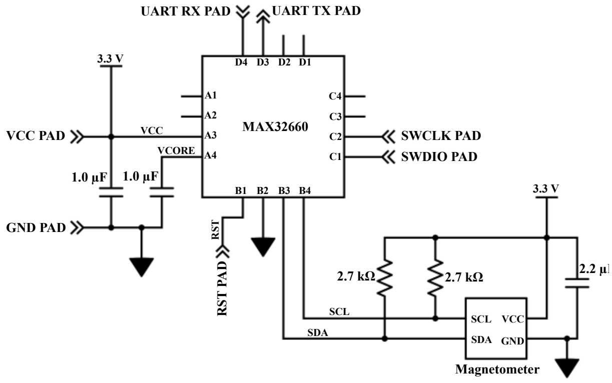

Figure 2: Circuit diagram of magnetic field measurement circuit on the smart contact lens.s

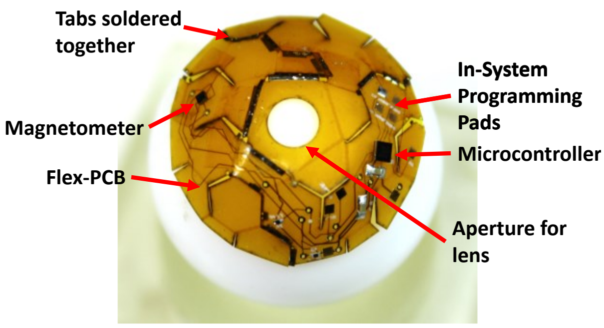

Figure 3: HMC 5883L magnetometer on flexible PCB for smart contact lens.

Data Collection

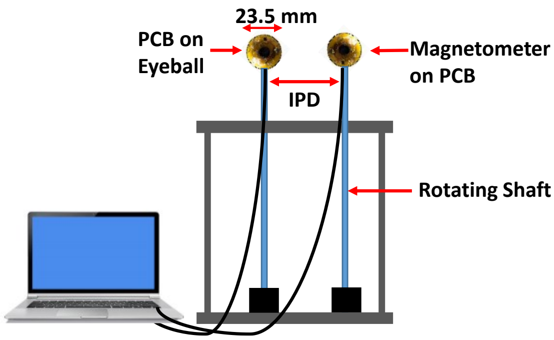

Figure 4: Rotatory experimental setup for measuring magnetic field components from magnetometers on each eye.

The folded flex-PCB was mounted on rubber balls. These balls were attached to a plastic shaft, which in turn was attached to a rotating setup. Embedded C program was written in Maxim Integrated Eclipse IDE. The program was uploaded to the microcontroller through the extra pads designed on the flex-PCB for In-System Programming (ISP). The microcontroller used I2C communication to obtain magnetic field data from the magnetometer. The microcontroller was also externally wired so that data could be stored using UART on a computer for further analysis. The magnetometers need to be calibrated before use to account for hard-iron and soft-iron offsets. These offsets were added to the program uploaded to the microcontroller. The human eye can converge up to 35 degrees on each eye to focus on an object. Hence, individual eyes were rotated inwards at an interval of 5 degrees and data was recorded. Figure 4 shows the measurement setup. The measurements were repeated three times.

RESULTS AND DISCUSSION

Figure 5 shows the plot of measured vergence angles vs ideal vergence angles. It can be observed that the RMS error was 1.74 degrees. Apart from the data point at 60 degrees, most angles were within 1 degree of the ideal value. Table 1 compares the predicted object distance with the expected object distance. The RMS error was 14.04 mm. At smaller distances, the error was less than 1.5 mm. The magnetometer consumes 100 µA at 3.3V at an output data rate of 160 Hz, thus consuming approximately 2 µJ of energy per magnetic field measurement per eye. This energy consumption is magnetometer dependent and dominated by the magnetometer internal circuitry and operating modes.

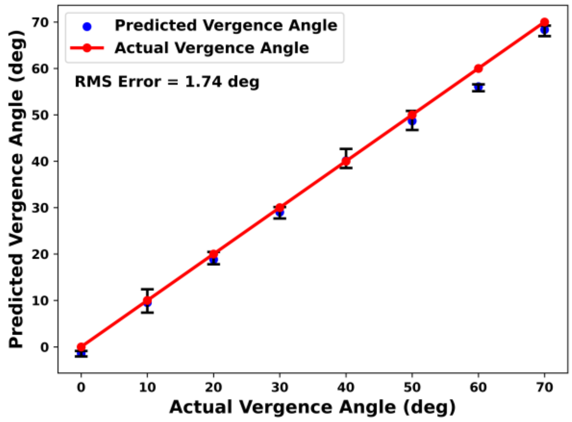

Figure 5: Predicted vergence angles calculated from magnetometers vs expected vergence angles.

Table 1. Expected vs Predicted Object Distance.

Expected Object Distance (mm)	Predicted Object Distance (mm)
342.9	377.57
170.1	181.67
111.9	116.1
82.4	82.3
64.3	66.39
51.9	56.33
42.8	44.21
	RMSE = 14.04 mm

SUMMARY

A novel approach for eye tracking was developed which measured the eye vergence angle and object distance by sensing Earth's magnetic field with the help of magnetometers. This was achieved with and RMSE of 1.74 degrees. The total energy consumption per reading per eye is 2 µJ.

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