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A wearable non-contact optical system based on muscle tracking for ultra-long-term and indirect eye-tracking

by

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Statement of authentication

I declare that this thesis is my own work and all the assistance and works received from others have been acknowledged.

Luyao Guo 2 June 2023

Abstract

Eye signals have become popular worldwide due to their potential in multiple fields. Such data can be regarded as indications of diseases such as epilepsy, a sign of fatigue, expression of potential interests during shopping and so on. In this paper, we demonstrate a novel optical eye-tracking system, NIRSense, which is able to track eye activities based on muscle movements, without any touching with the cornea. The NIRSense sensors, six pairs of near-infrared (NIR) light-emitting diodes (LEDs) and photodiodes are emitting 940 nm lights on skins below eyes in a contactless distance, where lights are able to penetrate and be reflected back to photodiodes. These signals are then transmitted into electric currents and processed to build relationships between signals and pupil locations. It is proved that the NIRSense system can track eye activities not only accurately (1.05 degrees) and precisely (0.6 degrees), but also in a safe, long-term used way. Moreover, the hardware design of the NIRSense system allows the assembling easily on diverse near-eye frames, involving Virtual reality (VR) goggles, Augmented reality (AR) headsets and normal glasses frames, via attaching sensors near the bottoms of lenses. In this way, this system has enriched the possibilities of exploring human reactions to virtual or real environments. Functions of accurate and precise eye trace prediction, pupil tracking with eyelids closure, comparison of performances with a commercial eye tracker Tobii Pro Glasses 3 and clinical application on the concussion assessment are presented in this paper.

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Chapter 1

Introduction

Virtual reality (VR) and Augmented reality (AR) glasses have shown increasing demands in recent decades, which allow people to interact with the virtual environment. While VR headsets provide an enclosed environment to promote users' perception of the fully virtual environment, AR glasses enable interactions of virtual subjects with real three-dimensional (3D) surroundings via see-through lenses (Hou et al., 2013; X. Li et al., 2018; Xiong et al., 2021).

On the other hand, eye signals have been regarded as important information in the AR/ VR application, since such signals explore functionalities of AR/ VR systems in various scenarios (Adhanom et al., 2023). Gaze tracking in virtual environment not only enables eye movement-based interactions and controls, but also allows to track the user's attention, points of interest and emotional responses (Tabbaa et al., 2021; Adhanom et al., 2023). Furthermore, eye tracking is widely applied to analyse human interactions in real life, which has shown successes in brain-computer interface (BCI), seizure detection, smart home devices, distraction detection, advertisement, entertainment and many other applications (Zou and Zhang, 2021).

In order to achieve long-term and valuable monitoring on eye activities, diverse innovations have been sought to deliver precise and efficient technologies. Such technologies include cameras, contact electrodes, ultrasonic sensing, and laser or optical sensors (*Tobii Pro Nano product description* n.d.; Plöchl et al., 2012; Sun et al., 2021; Meyer et al., 2020; R. Li et al., 2020). All techniques have shown success in gaze mapping. The most commonly applied methods are camera-based eye trackers, types of video oculography (VOG), which track pupils based on analysing videos of the eyes (*Tobii Pro Nano product description* n.d.). Contacted electrode-based eye tracking systems such as electro-oculography (EOG) are also popular in the field, where the electrodes next to the eye sockets can detect the potential changes around the eyes (Acuña et al., 2014; Plöchl et al., 2012; Rasch et al., 2015; Yamagishi et al., 2006). Ultrasound is another direction of eye-tracking technology. The ultrasound beams are emitted from the glass frame, touch the eyeball and then are reflected and received by the receiver. The duration of the whole process indicates the pupil location as the duration of the ultrasound to reach the cornea is shorter than other parts of the eye surface due to the convex shape of the cornea (Sun et al., 2021). This system has only proved the ability to distinguish the gaze direction, rather than providing results of precise pupil location. In recent decades, optical eye trackers have became popular. With a wide range of optical lights in diverse wavelengths or laser beams available, the engineers track pupil locations based on optical scanning and reflection of the cornea (R. Li et al., 2020; T. Li and Zhou, 2018; Meyer et al., 2020).

Furthermore, it is proved that eye activities are connected with and controlled by different neural systems and brain regions (Anderson and MacAskill, 2013). Therefore, abnormal visual performances can assist the diagnosis of neurodegenerative disorders in clinical fields (e.g., Parkinson disease and concussion disease) (Anderson and MacAskill, 2013; Mucha et al., 2014). In this paper, the relationships between eye movements and concussion disease have brought interests of research. Concussion is a common damage on brain, which can trigger problems such as memory disability, physical unbalance, visual abnormality and cognitive difficulty (Mucha et al., 2014; McCrory et al., 2017; Ferris et al., 2022). Diverse approaches are introduced to this market aiming to diagnose concussion at early stage, such as Vestibular/Ocular-Motor Screening (VOMS) test and Sport Concussion Assessment Tool (SCAT), in which the medical professionals follow these standardized tools step by step to assess (Mucha et al., 2014; *SCAT5 SPORT CONCUSSION ASSESSMENT TOOL - 5TH EDITION* n.d.). While these tools show different focus points of assessment, the VOMS test mainly aims to examine the patient's visual performances in several scenario, but the SCAT form tests aspects such as memory and cognition (Mucha et al., 2014; *SCAT5 SPORT CONCUSSION ASSESSMENT TOOL - 5TH EDITION* n.d.). However, the decisions of these tools largely depend on the medical professionals' knowledge, observations, experiences. In recent decades, gaze tracking is applied in concussion assessment as well, in which researchers use camera-based eye tracking devices to value and compare eye tracking metrics among concussed patients and healthy groups (Mucha et al., 2014; Samadani et al., 2015; Jain et al., 2022).

1.1 Research motivation

Various eye tracking technologies are brought up in this field, but there are still concerns on accuracy, precision, cost and safety. Therefore, we aim to propose a system with high accuracy and precision, which can be used safely and be manufactured in a low cost. Furthermore, we want to bring this system to the VOMS tool in the concussion assessment, to discover the visual responses corresponding to the VOMS test in a numeric way. Below we list the points of motivations that we aim to achieve in this paper:

1) Accuracy and precision improvements: The accurate and precise eye tracking capacity is always the primary concern. We propose our system, which is not only proved with great results in gaze tracking experiment, but also is tested and compared with a leading commercial eye tracking technology.

2) Cost efficiency: Currently, commercial eye trackers are costly, and these high prices limit the possibilities to be applied in wider fields and purchased by more people. In this paper, we propose our system in a low manufacturing cost.

3) Safety: Comparing optical eye tracking technologies published in recent years, a finding can be noted that the way of shining optical lights into the cornea can be risky. Therefore, our system tracks gaze based on muscle movements and avoid any optical contact with the cornea to ensure safety.

4) Clinical application: One of the main approaches accepted in the clinical field to diagnosis concussion is examining eye tracking capacities in the VOMS test, which is currently relied on medical staff's observation and decision. Therefore, we bring new insights to this field, introducing our eye tracking technology to the concussion assessment. Relevant eye signals all along the VOMS test are plotted and analysed in variables.

1.2 Problem statements

Diverse eye tracking technologies show their achievements in many aspects, but gaps still exist to overcome, involving the accuracy, precision, safety, privacy as well as price. Moreover, the combination of eye tracking system to the concussion assessment is almost blank. Challenges are listed below:

1) One eye tracking technology that shows integrated advantages still awaits to be achieved, which is expected to show great accuracy and precision, to be safe for long-term use and privacy guaranteeing, and with an affordable price.

2) Traditional VOMS assessment, as an essential tool in concussion diagnosis, assists decision making based on the medical professional's observation. No eye tracking technology has been introduced into the concussion assessment to provide numeric evidence.

3) Although it is commonly acknowledged that concussed patient's visual abilities are different to the healthy people. The specific relationships between the eye signals and the concussion disease have not been discovered at this stage.

To address these challenges, first of all, we aim to improve the hardware design of the eye tracking technology and certify its functions. After that, we plan to introduce this technology to the VOMS test regarding to assess the concussion, aiming to numerically prove the impacts of the concussion to eye activities.

1.3 Research questions

With the understandings of challenges we are facing in fields of eye tracking technologies and concussion assessment, the research questions of this thesis can be concluded as below:

1. How can we monitor muscle contractions to capture eye activities?

2. How can we process these eye signals to map the gaze directions?

3. How can we apply the eye tracking technology to the concussion assessment?

1.4 Thesis organization

This thesis is structured into five chapters: introduction, literature review, methodology of gaze mapping, technology of concussion assessment, statement of contribution and conclusion.

In the first chapter, introduction, we start with the application of eye signals in fields, a brief introduction of technologies developed to track eye activities, along with the symptoms triggered by the concussion and corresponding diagnosis approaches. In the chapter of literature review, we discuss the advantages and disadvantages of eye tracking systems that are classified based on their technologies. In addition, we explained the concussion assessment tools. Among these tools, the VOMS test, as one of the most important topics in this paper, is discussed in details.

Followed two chapters introduce achievements in this paper, which focus on the gaze mapping and the concussion assessment separately. In the third chapter, the hardware and software designs of the NIRSense system are explained. Not only its performance in terms of accuracy and precision is tested, also a comparison with a commercial eye tracker is conducted. The concussion assessment is discussed in the fourth chapter. The method of conducting the VOMS test when wearing the NIRSense system on is introduced, and data are processed and illustrated. We make statement of contributions in the final chapter.

1.5 List of publications

1.5.1 Conference publications

- Luyao Guo*, Daniel Babekul*, Rhonda Orr, Omid Kavehei (2023). A wearable non-contact optical system based on muscle tracking for ultra-long-term and indirect eye-tracking Under review with *IEEE VR 2024*.

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Chapter 2

Literature review

2.1 Camera-based eye tracking technologies

The most commonly applied methods are camera-based eye trackers, types of video oculography (VOG), which track pupils based on analysing videos of the pupils (*Tobii Pro Nano product description* n.d.). In current market, camera-based eye trackers are reported as the most developed and practical devices with the highest accuracy and precision, assisting users to achieve multiple functions, such as controlling screens with eye activities (*Tobii Pro Nano product description* n.d.). The camera eye trackers can be classified into two types: remote or close-to-eye.

Tobii pro nano, as a typical example of remote eye trackers, is the device developed from the Tobii company, which is designed to track pupils remotely, usually next to a screen. In this way, this eye tracking device enables the user to control the screen by eye movements (blinks etc.) instead of manually controlling a mouse. This device analyses pupil and cornea reflections in different illumination conditions, which achieves the gaze prediction as well as measurement of pupil diameter. This product is reported with accuracy of 0.3 degrees and precision of 0.1 degrees at optimal conditions (*Tobii Pro Nano product description* n.d.; *Tobii Pro Nano Enter the world of eye tracking research* n.d.).

Beside the remote eye trackers, close-to-eye eye tracking technologies are popular as well. Products Tobii pro grasses 3 and SMI eye tracking glasses 2 are discussed here as examples. As claimed in their documents, both of them mount cameras on the glasses frames, with additional scene cameras that facing outwards to the environment. The accuracy values of these two products are both 0.5 degrees (*SMI Eye Tracking Glasses 2 Wireless* n.d.; *Tobii Pro Glasses 3 product description* n.d.). The Tobii pro glasses 3 is also evaluated in this paper, and it will be discussed in details based on its hardware, data recording and extraction, as well as its practical performance.

Overall, the camera eye tracking technologies show great potential to be applied in real life. However, such technologies can bring problems involving privacy concerns, high prices and unsustainability when considering their energy consumption during video processing.

2.2 Electrodes-based and ultrasonic eye tracking technologies

Contacted electrode-based eye tracking systems, such as EOG, are also widely accepted in the field, where the electrodes next to the eye sockets can detect the potential changes around the eyes (Acuña et al., 2014; Plöchl et al., 2012; Rasch et al., 2015; Yamagishi et al., 2006). Although such electrode-related systems show more applicability in the clinical field because the attachment of electrodes to the skin significantly limits its practicality in daily life (Acuña et al., 2014; Plöchl et al., 2012; Rasch et al., 2015; Yamagishi et al., 2006). For instance, placing electrodes next to the eye can interrupt the dynamic of eye muscles. The conductive gel applied between electrodes and skin for high electric conductivity can bring risks of allergic reaction (Golparvar and Yapici, 2017). Additionally, attaching several electrodes on the user's face leads to less practicality in daily life.

Ultrasound is another direction of eye-tracking technology, which is proposed most recently. The ultrasound beams are emitted from the glass frame, touch the eyeball, and are reflected and received. The duration of the whole process indicates the pupil location as the duration of the ultrasound to reach the cornea is shorter than other parts of the eye surface due to the convex shape of the cornea (Sun et al., 2021). This system has only proved the ability to distinguish the gaze direction rather than providing results of precise pupil location.

2.3 Optical eye tracking technologies

Emerging optical eye-tracking technologies show the most recent growth. The beams of light shine directly into or pass through the cornea, i.e., delivering energy to the cornea. Nevertheless, optics is a popular concept applied to track eye signals via optical light reflections. Generally, optical emitters and receivers are applied together as the beginnings and endings separately in optical paths, where the light beams touch the eye halfway. Optical changes are triggered when eye activities are performed, simultaneously transferring into electricity oscillation by optical receivers (R. Li et al., 2020). Several papers have been published to prove the capability of optic lights in eye monitoring, such as (R. Li et al., 2020; T. Li and Zhou, 2018). Although system designs vary, they share a similar concept of combining light-emitting diodes (LEDs) and photodiodes to generate light paths and touch the cornea with the light beams to track eye activities. They illustrate accuracy results as 2.67 *degrees*, 1.57 *degrees* and 92.1 % respectively (R. Li et al., 2020; T. Li and Zhou, 2018). Besides the application of pairs of LEDs and photodiodes, another optics-related work from (Meyer et al., 2020) certifies laser beam is also a valid approach to track the eye position based on scanning and reflection, where the laser beam touches the cornea before eventually reaching the receiver. The pupil direction is measured based on the changing angle of the laser beam, where the final resolution is 1.31 *degrees* while the precision is 0.01 *degrees* (Meyer et al., 2020). All eye-tracking systems mentioned above have highlighted the potential of optics in gaze tracking. However, designs from these systems rely on cornea reflection or scanning, which can cause dry eyes, especially in long-term use or pose rare but real induced seizures in people who are living with photosensitive epilepsy disease (Yamagishi et al., 2006; *Tobii Pro Glasses 3 product description* n.d.). Also, LEDs and photodiodes from (R. Li et al., 2020) and (T. Li and Zhou, 2018) are displayed all around the eye, unavoidably blocking the view of sight. Furthermore, some designs of light paths are complicated, following multiple reflections and scanning. The more complex the design, the less robust this system is to any changes. In this paper, We propose a robust optical pupil tracking system, termed NIRSense, as a camera-free, low-cost, relatively safe, non-contact approach to achieving accurate gaze mapping and ultra-long-term monitoring capability.

2.4 Concussion and diagnosis

Concussion, is a sport triggered brain disease, which results into cognitive, somatic, behavioral, vestibular and visual-oculomotor impairments (Mucha et al., 2014; McCrory et al., 2017; Ferris et al., 2022). Accurate and acute concussion diagnosis is therefore essential. In current market, assessments involving Vestibular/Ocular-Motor Screening (VOMS) test and Sport Concussion Assessment Tool (SCAT) are commonly accepted in this field. Such assessments are tools administered by medical professionals (Ferris et al., 2022). Besides, due to the fact that ocular motor dysfunctions are common among concussed patients, eye trackers have been introduced to assess concussion (Mucha et al., 2014; Samadani et al., 2015; Jain et al., 2022). For instance, studies from Samadani et al., 2015; Jain et al., 2022 have applied camera-based eye tracking devices, to assess the severity of concussion by analysing eye tracking metrics among concussed patients and healthy groups. These variables include gaze disconjugacy between two eyes, saccadic performances, pupillary dynamics and so on (Samadani et al., 2015; Jain et al., 2022).

According to Guskiewicz et al., 2001 and Mucha et al., 2014, patients suffered from concussions have high possibilities to report vestibular impairments or ocular motor impairments. The VOMS test, as indicated in the name, focuses on the assessments of the vestibular system and ocular motor. The vestibular system is located at the inner ear and combined with visual sensing to play important roles in the sense of motion, especially in motion steadiness, physical balance and eye movement stabilization, where injuries can lead to the disability of balance (Cullen, 2012; Mucha et al., 2014). Ocular motor impairments, on the other hand, happen frequently to the concussed athletes with symptoms of double vision, dizziness, gaze distraction, disability of visual focus, inattention to visual reading and headaches (Ciuffreda et al., 2011; Mucha et al., 2014). Therefore, the VOMS test designs five independent tests: smooth pursuit, horizontal and vertical saccades, convergence, horizontal and vertical vestibular ocular reflex (VOR) and visual motion sensitivity (VMS) to examine corresponding eye activities (Mucha et al., 2014). At the beginning and after each assessment, the patient rate symptoms in terms of headache, dizziness, nausea and fogginess from 0 to 10, in which a larger number indicates a higher severity (Mucha et al., 2014).

As described in the supplementary material from Mucha et al., 2014, the whole VOMS assessment is conducted as follows. First of all, the patient is asked to rate their symptoms on headache, dizziness, nausea and fogginess as the baseline symptoms, followed by the smooth pursuit test, which aims to test the patient's ability on tracking a moving object in a slow speed. While the participant keeps still, the medical professional holds the object that is 3 ft away from the participant, moving the target horizontally to the right direction up to 1.5 ft, back to the midline, and then moving oppositely 1.5 ft to the left until return to the starting point. During this process, the participant is asked to follow the moving object with eyes. The process is regarded as one loop. Two repeated loops are required to finish the horizontal pursuits. Similarly, vertical pursuits are conducted via moving up and down both 1.5 ft, repeating two times. The speed of pursuit is controlled by the examiner, approximately 4 s is taken to complete a loop. After both horizontal and vertical pursuits, the patient rates symptoms based on feelings again (Mucha et al., 2014).

The second test, saccades, is carried on to examine the patient's capacity on quick movements between two targets. The staff put two targets 3 ft away from the patient, which are both 1.5 ft away from the midline. The patient will move eyes as fast as possible between two points and repeat 10 times. Saccades are also tested horizontally and vertically. Symptoms rating after the test is required as well (Mucha et al., 2014).

Furthermore, convergence test is brought up, in which the medical professional aims to calculate the visual ability of staring at a close object without double vision. When the test starts, the participant holds and visually focus on a target and move it towards himself. The participant is required to stop once a double vision is noticed. The distance between the object and the participant is measured by the specialist, in which any value larger than 6 cm is regarded as abnormal. The participant is asked to rate the symptoms again (Mucha et al., 2014). The fourth test is the VOR test, which is designed to assess the ability to stabilise the vision when the head is moving. In the horizontal VOR test, the patient is asked to turn the head 20 *degrees* to the right and 20 *degrees* to the left. During the process of head movement, the patient is expected to star at the object in front of him. A metronome is included at the speed of 180 beats per minute, in which the patient changes to the other direction every beat. One loop is completed when the patient finishes one left and one right movements. Ten loops are conducted repeatedly. Similarly, the patient follows vertical VOR test by turning the head up and down 20 *degrees* separately for ten times. Rating symptoms is required after that (Mucha et al., 2014). The last test is the VMS test, aiming to check the patient's visual sensitivity to motions as well as whether the patient can resist the vestibular-induced eye activities. The experimenter keeps the arm outstretched while staring at the thumb, and then rotates the body, head and arm as the unit 80 *degrees* to the left and 80 *degrees* to the right. One metronome is set to 50 $beats/minute$ to remind the patient change the direction every beat. Five repeats are conducted before the symptoms rating (Mucha et al., 2014). Overall, the VOMS assessment is ran under the supervision of a medical professional, and the result of concussion diagnosis is generated based on the professional's observation, experience, knowledge as well as the changes in symptoms reported from the patient all over the assessment.

On the other hand, SCAT assessment is also a document-based concussion test. Based on *SCAT5 SPORT CONCUSSION ASSESSMENT TOOL - 5TH EDITION* n.d., SCAT $5th$ edition, SCAT5, aims to evaluate the patient's concussion under the assessment of medical professionals. The SCAT5 tool can be used under two conditions: on-site assessment and off-site assessment. As described in the form, the on-site SCAT5 assessment should be conducted immediately after injuries, but the first aid is still the priority. Five steps are taken by the medical professionals, while the first step is checking red flags (unconsciousness, pain on head or neck, blurring vision etc.), followed by observable signs such as physical unbalance. After that, memory will be tested by answering some basic questions. The patient's visual, verbal and motor performances are examined in the fourth step, and the condition of cervical spine is recorded in the last step (*SCAT5 SPORT CONCUSSION ASSESSMENT TOOL - 5TH EDITION* n.d.).

Furthermore, the SCAT5 tool provides off-field assessment to evaluate concussion in another way, focusing on symptom evaluation, cognitive screening, neurological screen, delayed recall and decision. Although both the VOMS tool and the SCAT5 tool measure concussion-related symptoms based on the patient's feeling, the SCAT5 tool lists these symptoms in more detailed ways. 22 symptoms are provided and rated from 0 to 6. These severity values are summed up to get the total value, which the highest score is 132. In addition, cognitive screening is examined by testing the orientation (such as the awareness of date or month) along with the immediate memory of recalling 5 and 10 word lists. Moreover, concentration capacity is tested in the cognitive screening, by examining whether the patient can recall lists of numbers as well as the list of months backwards. Performances are recorded in scores. The SCAT5 tool also test the neurology (physical balance etc.). Finally, a delayed recall is examined 5 minutes after the immediate recall, which asks the patient to repeat the lists of words again. Decision is made based on scores obtained above by the medical professionals (*SCAT5 SPORT CONCUSSION ASSESSMENT TOOL - 5TH EDITION* n.d.).

It can concluded that both the VOMS assessment and the SCAT assessment are standardized documents that are supervised by the medical professionals. However, the VOMS assessment focuses on the evaluation on the vestibular system and ocular motor, and therefore the main target is monitoring eye performances in different tasks. On the other hand, the SCAT tool is a score-based test, concentrating on rating various perspectives, involving symptoms, cognition, concentration, memory as well as neurology. In addition, eye tracking technologies have been developed in recent decades, to assist the assessment of concussion. Different visual variables can build up eye tracking metrics, while the differences of these metrics between concussed patients and healthy groups can indicate the severity of concussion. However, the fact that eye tracking technologies haven't been applied and combined in regularized assessments attracts interests of research. Therefore, we aim to propose an idea, combining an accurate and safe eye tracking device with the VOMS test to assess the concussion.

2.5 Discussion

As reviewed, camera-based eye trackers show the most developed technologies in the current market, but expensive prices along with privacy concerns are always the issues (Klaib et al., 2021). Optical eye tracking systems, are increasingly published in decades. However, the way of exposing the cornea directly to optical lights or laser beams can be risky, especially in a long term (Yamagishi et al., 2006). Other eye trackers such as electrodes-based and ultrasonic eye tracking systemS can be less applicable in daily life or be lack of further experiments to prove the ability of tracking gaze accurately (Acuña et al., 2014; Plöchl et al., 2012; Rasch et al., 2015; Yamagishi et al., 2006; Sun et al., 2021). Therefore, it can be concluded that an eye tracking system that not only achieves gaze tracking accurately and precisely, but also ensures the safety, privacy and low cost is still expected to be developed.

In terms of the concussion assessment, both VOMS and SCAT5 tools are document-based tests that depend on the medical professionals' decisions. With the desire of providing numeric evidence that concussion has influences on eye performances, we bring the NIRSense system into the VOMS assessment.

Chapter 3

Capacities of NIRSense eye tracking system in gaze mapping

The content presented in this chapter is published as:

- Luyao Guo*, Daniel Babekul*, Rhonda Orr, Omid Kavehei (2023). A wearable non-contact optical system based on muscle tracking for ultra-long-term and indirect eye-tracking Under review with *IEEE VR 2024*.

Statement of Contributions of Joint Authorship

- Luyao Guo (Candidate): Hardware design, Software, Methodology, Experiment design, Data collection, Data analysis, Writing - drafting the article.
- Daneil Babekul (Co-author): Hardware design, Software, Data collection, Writing - Application to the VOMS concussion test section.
- Rhonda Orr (Co-Supervisor): Application to the VOMS concussion test, Review & Editing.
- Omid Kavehei (Principle Supervisor): Project administration, Writing - Review & Editing.

In addition to the statements above, in cases where I am not the corresponding author of a published item, permission to include the published material has been granted by the corresponding author.

Luyao Guo   Date: 02 June 2023

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

A/Prof. Omid Kavehei   Date: 02 June 2023

In this chapter, we discuss the hardware design and primary functions of the NIRSense eye tracking system. The issue of safety is carefully measured. The muscle source that NIRSense system is monitoring on is also considered. The capacity of gaze tracking is compared with a developed camera-based eye tracker as well.

3.1 Methods

3.1.1 System Description

The NIRSense system uses a glasses mount, applied with six near-infrared sensors in total to detect movement in the tissue below the eyes. Each pair of sensors involves one 940nm LED and one phototransistor. Relevant characteristics of the NIR LED and phototransistors can be found in the supplementary material. A beam of near-infrared (NIR) invisible light is emitted from the LED, reaching the skin below the eye. The distance between the sensor to the skin is approximately 8 mm to 2.5 cm away depending on the contours of different faces. Continuously, the NIR light penetrates the skin, touching the tissue behind it, then being reflected back and received by the phototransistor. As displayed in figure 3.4(a), these six sensors are named based on their locations: left eye left (LL), left eye centre (LC), left eye right (LR), right eye left (RL), right eye centre (RC) and right eye right (RR) from left to right, three sensors on each side. The optimal regions of detection (determined empirically) are shown in figure 3.4 as well. These signals are then used to model gaze location in 2-dimensional space. There are no cameras involved, making the system very privacy-friendly. The NIRSense glasses can also detect eye movements when the eyelids are closed, enhancing their capability.

Because no image processing is required, sample rates of up to 255 Hz are currently achievable with a relatively basic microcontroller (ATmega328P/Arduino Nano), requiring a total power consumption of approximately 0.67 W.

3.1.2 Safety

Eye-safe, as the priority of the eye-tracking system, is considered carefully in this experiment. NIR lights, especially light in 940 nm, are widely used in optical eye-tracking designs. However, all of them shine near-infrared LEDs directly into or pass through the eye. With long-term exposure, the potential risks of dry and fatigued eyes, retinal thermal burns as well as delayed lens injury such as cataracts are noted (Yamagishi et al., 2006). In order to prevent such potential hazards, related standards have been proposed,

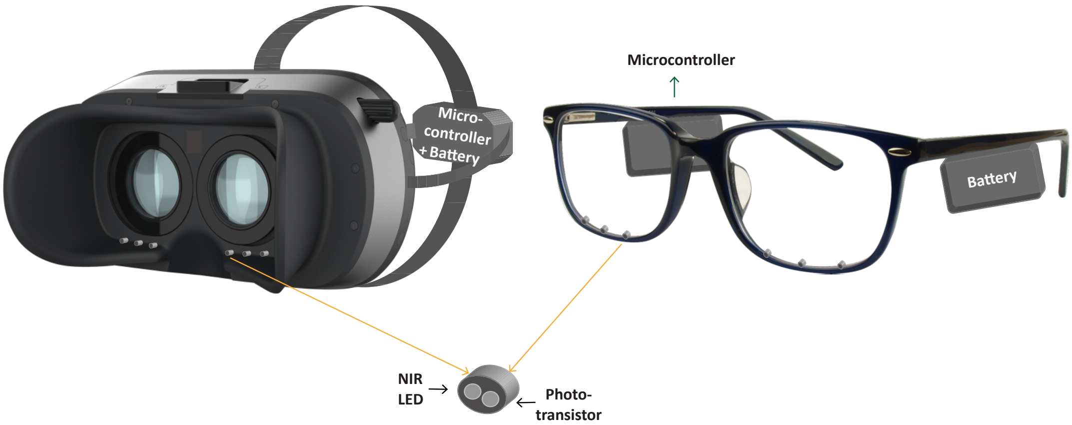


Figure 3.1: The hardware design of NIRSense eye tracking system with microcontroller and battery. Our system can be mounted on VR goggles (left) and Augmented reality (AR) headsets or other glasses frames (right) (the goggles images are adopted from Google Image Oh, 2017; n.d.).

involving ACGIH, ICNIRP, IEC 62471/ CIE S 009, ANSI/IESNA RP-27 Series as well as European Directive 2006/25/EC, in which thresholds of radiance ($W \cdot m^{-2} \cdot sr^{-1}$) and irradiance ($W \cdot m^{-2}$) are limited to protect retina and cornea, within 600 $W \cdot m^{-2} \cdot sr^{-1}$ and 10 $W \cdot m^{-2}$ respectively. To meet these exposure limits, multiple parameters matter, including the radiant intensity emitted from the LED, the distance between the LED with the eye, along with the diameter of the LED. However, such values or calculations are barely reported in most papers where their NIR LEDs are shining into the cornea directly (*D5.4 Exploration of safety issues in Eyetracking* n.d.; Levin, 1998; Ziegelberger, 2013; Weber and Schulmeister, 2003; Mulvey et al., 2014; Yamagishi et al., 2006).

In the NIRSense system, the design of the system avoids touch with the cornea, consequently preventing the potential thermal damage to both the cornea and retina. Nevertheless, radiant exposure ($J \cdot m^{-2}$) is still measured to evaluate the hazard of skin thermal burn, according to the safety standards above, where the radiant exposure should be less than the threshold value of based on IEC and ICNIRP standards:

$$20000 \times t^{0.25} Jm^{-2}, \quad \text{when} \quad t \leq 10s$$

or based on ANSI/IESNA criteria:

$$20000 \times t^{0.35} Jm^{-2}, \quad \text{when} \quad t \leq 10s$$

No specific thresholds are stated for exposure longer than 10 s, due to the fact that the exposure will trigger pain before the thermal burn. The maximum radiant exposure is 1560 $J{\cdot}m^{-2}$ within 10 s, while the change of radiant exposure over time is plotted in figure 3.2 (Weber and Schulmeister, 2003; *Reflective photosensor (photoreflector) RPR-220 datasheet* n.d.; *Everlight Americas Infrared Emitting Diode (EAILP05RDDB1)* n.d.). Furthermore, a logarithmic plot showing the change of NIRSense's radiant exposure is introduced in the appendix.

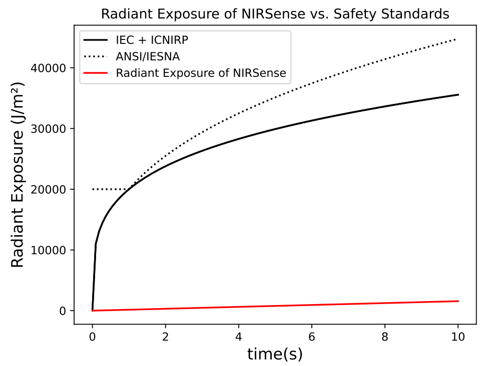


Figure 3.2: The Change of radiant exposure generated from NIRSense system over time.

3.1.3 Muscle Source

The sources of tissues that the NIRSense system is tracking are explored. First and foremost, the valid area that is able to track eye activities is tested. Blinking signal, as an example, is monitored on the changes when the sensor moves position from a place in front of the cornea to 0.5 cm down away from the eye until 2.5 cm far away. It can be observed in figure 3.3 that the trend of signal when light is shone into the eye varies from the trend of signal when light is emitted into the tissue. When the sensor is placed in front of the cornea, the signal fluctuates following eyelid opening and closure. On the other hand, the sensor tracks the contraction and relaxation of tissues. It is also tested that approximately 2 cm is the fastest distance the sensor can be placed below the eye, where the optimal range can be from 0.5 cm to 1.5 cm in order to achieve strong and distinct signals (figure 3.3). To explain it, the orbicularis oculi muscle (OOM) is brought up, which is the muscle distributed all around the eye to control eye movements. OOM can be divided into palpebral and orbital areas from eyelids area to outer area (Costin et al., 2014). The palpebral OOM is located inside the eye orbit, while the orbital OOM is part of the muscle outside the orbital margin. The inferior distances between the eyeball and eye socket as well as the one between the OOM margin with the eye socket rim are examined as 1.2 *cm* and 1.2 *cm* respectively (Costin et al., 2014; Shin et al., 2017). It can be then concluded that the inferior dimension of a whole OOM is around 2.4 *cm*, which explains well why the NIRSense can capture eye signals 2 *cm* below the eye, but signals can be largely reduced when the sensor is approaching the OOM margin.

In addition, signals from sensors in different placements are observed in different sensitivities, in which sensors LL, LC, RC along with RR have all performed in more obvious signal fluctuations, while sensors LR and RR have shown slighter signal changes in a same condition (figure 3.7). By examining the anatomy of facial muscles, the reason that causes such distinction in voltages is also due to OOM. The anatomy of OOM determines the fact that medial sensors will capture slighter signals in less distance range since the width of OOM on the medial line is smaller than the lateral OOM. Therefore, the sensors placed closest to the nasal side are always less sensitive especially when sensors are further away from the orbital rim (Costin et al., 2014).

The penetrating capacity of NIRSense is also considered. As mentioned above, the NIRSense capture eye signals by shining light into the tissue behind the skin. Based on research, the sensor can penetrate a maximum of 2.4 *mm* to the skin (Muhammed and Jammalamadaka, 2016). Depending on variations in facial structure and anatomy, NIR light shining from the NIRSense system may reach the muscle layer but also has the possibility to end at the subcutaneous fat layer (Ha et al., 2005; Kim et al., 2019). In the case that the light only reaches the fat payer, signal fluctuations still occur since both fat and skin layers will stretch with the muscle layer's contraction.

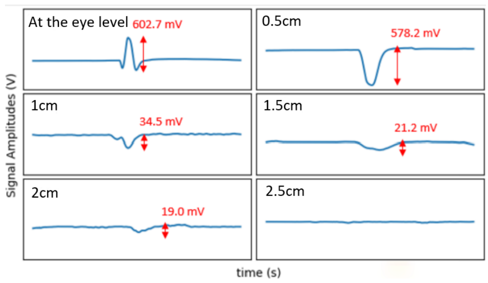


Figure 3.3: The eye signals vary in conditions where the NIRSense sensor shines at different positions. The sensor is placed 2 *cm* away from the face, moving from the position at the eye level, down to a few center meters away below the eye (0.5 *cm*, 1 *cm*, 1.5 *cm*, 2 *cm* and 2.5 *cm* separately). The blinking signals as an example change in amplitudes and patterns over distances.

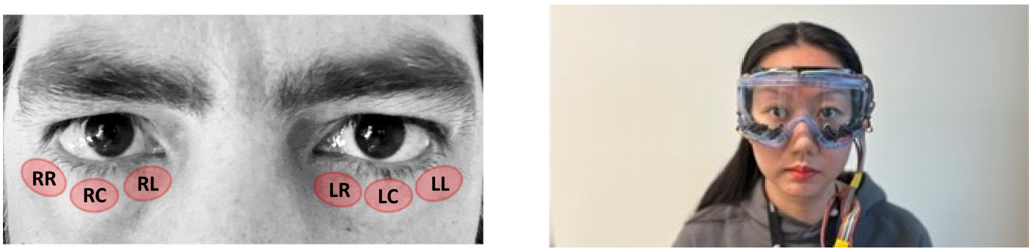


Figure 3.4: (a) The placements of NIRSense sensors under the eyes, 3 sensors on each side from left to right and are named as LL, LC, LR, RL, RC, RL based on their locations. (b) The photo of the participant wearing the NIRSense glasses on (The image is cropped to meet the anonymous review policy because an author's face is included.

3.2 Experiment

3.2.1 Experiment setup

In the experiment, two participants wear the same NIRsense glasses. Spectacles must be removed, while contact lenses are allowed. Participants will be required to sit 120 *cm* away from the screen (154×87 cm^2), facing the middle of the screen, and head on the chin rest to keep still. Two experiments, the gaze test and pursuit test are conducted to assess the NIRsense capability of tracking diverse eye activities. The pursuit test aims to locate the pupil when the eyes are chasing a moving dot, while the gaze test examines NIRsense performance during staring. The procedures follow 2 stages: calibration and test. Each type of experiment is repeated three times, with two loops as the calibration and the other– loop serving as the test.

Besides, this experiment is conducted under ideal conditions, i.e., assuming the surrounding variables, such as ambient light, have minimal effects on the result and the experimenter conducts the experiment smoothly. When the experiment started, all surrounding lights are turned off. Besides, user control is added to the experiment, in which the dot waits for the experimenter input to move, providing rest time during gaps. The recording is conducted simultaneously and automatically during the pursuit experiment, while an additional recording button needs to be pressed during the gaze experiment. Figure 3.5 (a) and (b) show baselines provided during the experiment.

In both tests, eye blink is avoided during recording, i.e., when the record control button is pressed, the eye will follow the baseline only without blinking, which can be achieved easily and comfortably with the support of user control. Therefore, the experimenters can relax when the control button is released, and start recording whenever they are ready.

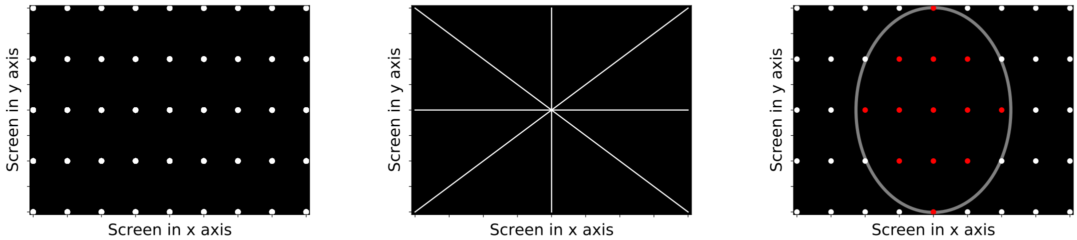


Figure 3.5: (a) Baseline dots during the gaze experiment. Only one baseline dot will appear at one time. (b) Baseline Paths during the pursuit experiment. 4 paths in total, vertical, horizontal, right diagonal and left diagonal, in which breaks are allowed between 2 paths. (c) Dots highlighted in red are dots regarded as valid points in Accuracy Evaluation.

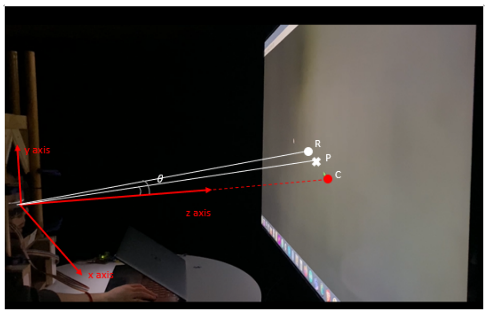


Figure 3.6: The method to calculate the visual angle difference θ. As highlighted, point R is the baseline, P is the predicted dot, and C is the center point of the screen. Angle difference θ is measured as the result of the calculation of the angles between R and C as well as P and C. All the data are vectored into a 3D coordinate, in which the origin starts from the middle of the participant's eyes.

3.2.2 Pupil Mapping Algorithms

The algorithms for tracking pupil location on screen are based on the correlation between baseline data and the NIRSense system's eye signals. In the baseline data, the dot location in terms of the x and y axes as well as real-time timestamps are saved. At the same time, the participant follows the baseline, where all eye signals from NIRSense are recorded in the form of 6 sensors and relative timestamps.

In order to combine these two datasets, a pre-processing technique is applied to compare the two databases with timestamps, binding sensor signals with the baseline data which share the same timestamp, followed by signal normalisation as well as signal smoothing utilising Savitzky Golay filters with a window length of 31 and poly order of

2. Next, nonlinear relationships are computed to the output via curve fitting to build polynomial equations with a degree of 2. The polynomial model can then be applied to test groups for accuracy evaluation.

The performance of NIRSense is presented in ways involving accuracy in percentage, accuracy in degree as well as precision in degree. Accuracy is a common numeric criterion in the market to certify how well this eye-tracking system can predict pupil location on screen compared with the real baseline point. Precision, as another essential parameter for evaluation, aims to assess the position variance of prediction points. The smaller value of precision indicates a denser distribution of the prediction points for each baseline dot, which is an expected result.

To calculate the accuracy in percentage, explained variance score (EVS) is a common method for accuracy evaluation in terms of percentage in supervised learning:

$$\text{EVS} = \frac{1 - \text{Var}(y_{\text{predict}} - y_{\text{true}})}{\text{Var}(y_{\text{true}})}$$

$$\text{Var}(y_{\text{predict}} - y_{\text{true}}) = \frac{1}{n}\sum(\text{error} - \text{mean}(\text{error}))^2$$

On the other hand, the accuracy is evaluated in terms of degree. Based on research from Tobii, the degree calculation should be under ideal conditions, i.e., the situation when the gaze angle is within 20 degrees (*Accuracy and precision test method for remote eye trackers* 2011). Regarding the participant's eyes as the centres, the area within ± 20 scattering degrees on the screen is the valid area. All baseline dots inside this area are considered to evaluate accuracy (*Accuracy and precision test method for remote eye trackers* 2011). For the dots to match the evaluation criteria, all dot positions as well as the participant's position are transformed into 3d vectors. As indicated in figure 3.6, assuming the dot P as the prediction point, the dot R as the baseline dot and the dot C as the centre of the screen, the angle difference between dot P to C and dot R to C is regarded as the accuracy in degree at the point R. The final result is the mean value of results for all the points within 20 degrees gaze angles (figure 3.5(c)).

Precision, as another essential parameter for evaluation, aims to assess the position variance of prediction points. Based on Tobii, the precision is calculated based on the Root Mean Square (RMS) algorithm from the visual angle differences among the successive prediction points (*Accuracy and precision test method for remote eye trackers* 2011). Instead of finding the angle difference between the prediction with the baseline dot during the accuracy evaluation, the angle difference of predictions next to each other is calculated as θ. The final precision value follows the Root Mean Square (RMS) algorithm:

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\theta_i^2)}$$

Where θ is the difference in visual angles between two predictions, and n represents the number of prediction dots in total.

3.3 Results

3.3.1 Eye Activities Distinguish

Due to the six different placements of sensors in the NIRSense system, signals vary from sensors to sensors when the pupil location changes. Based on signal fluctuations, the gazing direction can be localised. Figure 3.7 shows signal fluctuations in 6 sensors when conducting different eye activities. The sensor LL, as an example, increases proportional to baseline upward movement and decreases when the baseline dot moving diagonally downward. Based on the diverse reactions from sensors, the gazing location can be thus specified.

3.3.2 Pupil Mapping on Screen

The NIRsense has been proved with its capability of tracking the pupil location on the screen accurately and precisely. As shown in figure 3.8(a), the image shows the fixation points over the screen in the form of heatmap. Figure 3.8(b) displays the pursuit outcome, in which the participant followed 4 paths of dot movements with moving forward and backward 3 times.

Numerically, the NIRSense model has achieved accuracy of 99.3% and 99.2%, accuracy in terms of degree of 1.05 *degrees* and 1.75 *degrees*, precision of 0.6 *degrees* and 0.91 *degrees* in gaze and pursuit experiments separately.

3.3.3 Comparison with commercial eye tracker

A commercial eye tracker, Tobii pro glasses 3, which is developed and manufactured by Tobii from Swedish, is applied in the same condition to compare its performance with NIRSense glasses. On each side of the Tobii glasses, two cameras and eight infrared (IR)

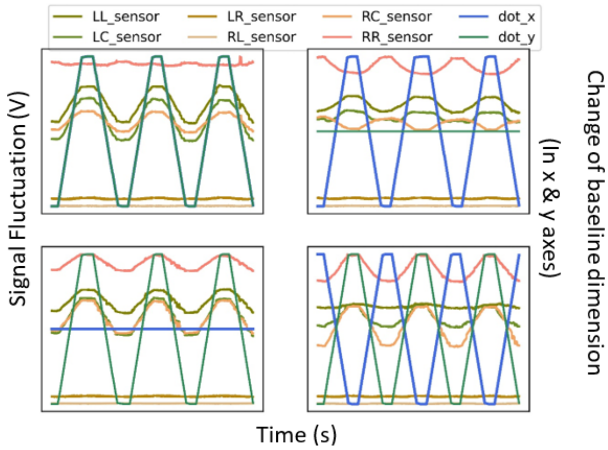


Figure 3.7: Six sensors signal changes following four different pursuit paths.

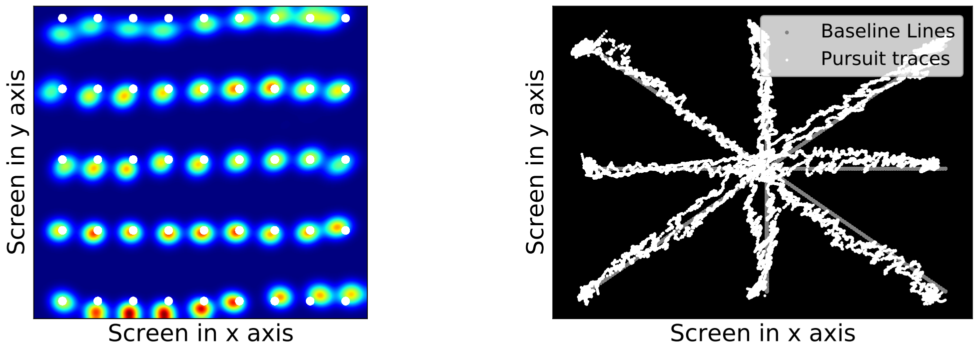


Figure 3.8: (a): The result of pupil paths in gaze test. The heatmap indicates the gazing predictions provided from the NIRSense glasses and the white dots show the real locations of baseline dots. (b): The result of pupil paths in pursuit test. The white lines show the traces of eye movements.

illuminations are integrated into the lens all around the eye (*Tobii Pro Glasses 3 product description* n.d.). Between two lenses, one scene camera is built and placed facing toward to the outside environment. While the glasses are connected to a recording unit which contains battery and SD card, the world scene generated from the scene camera can be visualised and recorded. Calibration is completed based on staring at a pre-printed marker in front of the eyes. After that, the trace of pupil direction is activated and plotted over the map of world scene (*Tobii Pro Glasses 3 product description* n.d.). The baseline experiment starts after the recording button is pressed. The participant tracks the baseline dot on the screen with the head stabled on the chin rest and the eyes facing to the middle of the screen, where the process of the test is the same as the NIRSense gaze tracking experiment. On completion of the experiment, Tobii data is read from the SD card. The 'gaze2d' data extracted from the 'gazedata' file is applied as the eye trace on the screen in the two-dimension way. The world scene from the scene camera is normalised from 0 to 1 in both x and y axes, in which the origin (0, 0) locates at the top-left corner and (1, 1) at the bottom-right corner of the scene. The 'gaze2d' data is then re-scaled ranging from 0 to 1 based on their coordinates in the world scene. As illustrated in figure 3.9(b) , the world scene does not fully cover the screen. Therefore, the baseline dots are re-scaled to Tobii's coordinates based on pixels. Due to the distortion scene camera, small error of the baseline position is unavoidable when the screen is considered as a parallelogram. The accuracy and precision of Tobii glasses are calculated following the same methods which applied in the NIRSense glasses, in which only baseline dots located within 20 *degrees* of the view are counted, as indicated in figure 3.10(a). The accuracy is shown to be 2.55 *degrees*, and the precision is measured to be 1.02 *degrees*. Figure 3.10(b) displays the outcome of eye activities predicted from Tobii. It is also demonstrated that Tobii performs better when the surrounding light is on rather than off, this may due to stronger light contributing to better video processing on pupils.

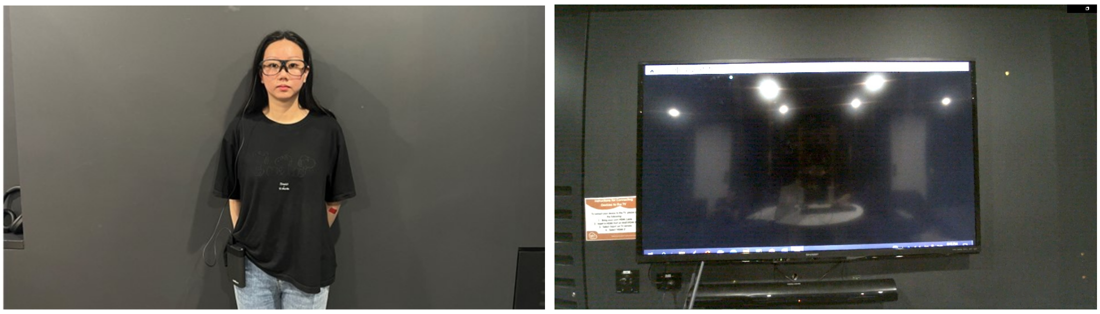


Figure 3.9: (a) Photo of the participant wearing the Tobii pro glasses 3 on. (b) The scene generated from the Tobii scene camera, i.e., the scene where the Tobii user is staring at.

Table 3.1: Accuracy

	Accuracy $EVS(\%)$	**Accuracy** *degree*	**Precision** *degree*
Gaze	99.3	1.05	0.6
Pursuit	99.2	1.75	0.91

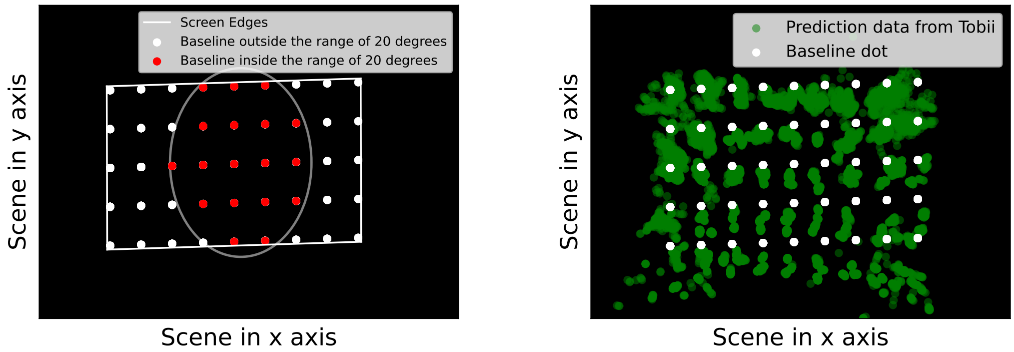


Figure 3.10: (a) A reconstruction of scene from Tobii scene camera to 2D images. (b) The 2D map of Tobii's predictions of gaze and the baseline data.

3.3.4 Eye Tracking with Eyelids Closed

Because this system does not use standard techniques that require direct images of or reflections from the eye, it is one of a very small number of systems that is capable of tracking eye movements when the eyes are closed. Although precise eye direction calibration is difficult with the eyes closed, the amplitude of the eye moment can be clearly detected, the same as the signals when the eyelids are open. This ability show the great potential of the NIRSense glasses in monitoring sleep.

3.4 Conclusion

The NIRSense system has five notable features that differentiate it from a large number of existing eye-tracking hardware products: high accuracy, low-cost construction using off-the-shelf components, the ability to detect eye movement while the eyes are closed, camera-free privacy, suitability for chronic long-term use, especially for users who have trouble blinking, or have conditions that make their eyes especially sensitive.

Accuracy is always the main concern in the field of eye tracking. Up to now, although diverse techniques have been proposed over decades, the most developed eye tracking systems are still camera-based, which are expensive and risky to privacy. Other techniques show less accurate results, bringing challenge to wider application. However, in this paper, we have demonstrated the potential of optics eye tracking system with competitive accuracy as well as precision in the market.

Besides, this system shows great benefit in financial terms The total cost of the hardware components in our current prototype is approximately \$40 USD. As a point of reference, "low-cost" eye tracking products have been described as between $100-1000 *USD* (*Tobii Pro Nano product description* n.d.; *SMI Eye Tracking Glasses 2 Wireless* n.d.). All software used is entirely open-source: various python modules and the Arduino IDE.

While this system can be used in most current applications of eye tracking technology it further offers the possibility for new applications, such analysing sleep states and extended use by patients with increased eye sensitivity or issues blinking (Yamagishi et al., 2006). It further increases the opportunity to use eye-tracking where cost has so far been prohibitive, such as large studies across different locations, or studies requiring multiple devices to simultaneous track subject's eyes. Examples of such applications include sports science research, team training, marketing research etc.

Further investigation is needed however to determine exactly what tissue movement the system is measuring. Based on this hypothesis of the orbicularis oculi muscle, a further experiment is anticipated to determine the exact muscles this system is tracking.

3.5 Appendix

Beside the results presented in the main text, another participant also contributes to test the performance of NIRSense glasses, which are shown below.

Table 3.2: Outcomes generated from another participant

	Accuracy $EVS(\%)$	**Accuracy** *degree*	**Precision** *degree*
Gaze	99.3	1.24	0.83
Pursuit	98.9	2.14	0.93

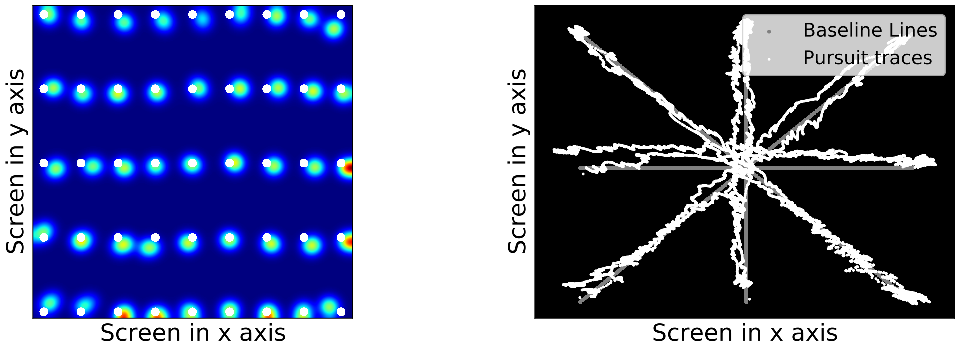


Figure 3.11: (a): The result of pupil paths in gaze test. The heatmap indicates the gazing predictions provided from the NIRSense glasses and the white dots show the real locations of baseline dots. (b): The result of pupil paths in pursuit test. The white lines show the traces of eyes movements.

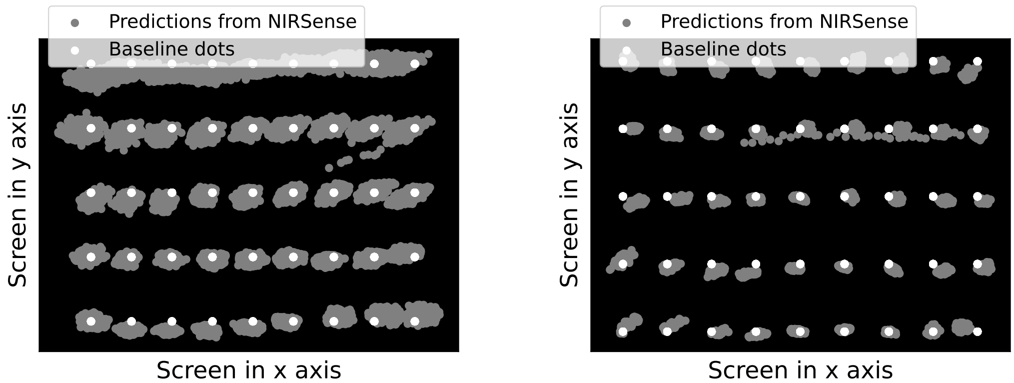


Figure 3.12: The results of gaze experiment in terms of gaze traces. The gray dots are predictions of staring positions, while the white dots are baseline data. (a) Data generated from the participant 1. (b) Data generated from the participant 2.

Chapter 4

The involvement of NIRSense eye tracking system in the concussion assessment

The content presented in this chapter is published as:

- Luyao Guo*, Daniel Babekul*, Rhonda Orr, Omid Kavehei (2023). A wearable non-contact optical system based on muscle tracking for ultra-long-term and indirect eye-tracking Under review with *IEEE VR 2024*.

Statement of Contributions of Joint Authorship

- Luyao Guo (Candidate): Data collection, Data analysis, Writing - drafting the whole article.
- Daneil Babekul (Co-author): Software design, Data collection, Writing - Application to the VOMS concussion test sections.
- Rhonda Orr (Co-Supervisor): Application to the VOMS concussion test, Review & Editing.
- Omid Kavehei (Principle Supervisor): Project administration, Writing - Review & Editing.

In addition to the statements above, in cases where I am not the corresponding author of a published item, permission to include the published material has been granted by the corresponding author.

Luyao Guo Date: 02 June 2023

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

A/Prof. Omid Kavehei Date: 02 June 2023

4.1 INTRODUCTION

Concussion, is a common brain disease, most frequently happened among athletes. Patients suffered from the concussion generally show abnormal signs on physical balance, neurocognition or severe symptoms (headaches etc.) (Mucha et al., 2014). Thus, multiple diagnosis methods are brought up, aiming to assess at the early stage.

VOMS assessment, as one of the most widely applied tool, is a standardised document that allows the medical professional to test the patient's capacities of eyes in different tasks. The VOMS assessment shows its advantages as it brings new insights on the relationship between eye activities and the concussion injury, while other approaches mainly measure the patient's cognitive conditions, such as memory, balance stability, verbal expression and symptoms (Mucha et al., 2014).

However, current VOMS assessment is largely dependant on the medical professional's knowledge, observation and experience, as well as the patient's symptoms rating. Therefore, we want to introduce a new idea, which combines the VOMS assessment with a safe and valid eye tracking system, to further explore the differences of eye activities between concussed people and healthy people, in numeric and signal ways.

4.2 METHODS

A software is designed to imitate the traditional VOMS assessment, in a computerised way. The software mimics whole steps of the VOMS assessment, with instructions to allow the participant follows step by step. At the same time, the participant wears the NIRSense eye tracking system on, with one knob and one button to put in user controls during the experiment.

At the initial time of the experiment, the participant is asked to rate the symptoms in terms of headache, dizziness, nausea and fogginess from 0 to 10, which 0 means none and 10 means the highest severity. The knob can be rotated to change the value of symptom and the button can be pressed to move to the next step. Description of above information is provided on the screen. The initial symptom ratings are regarded as the baseline. After that, the smooth pursuits are tested, where the experimenter is asked to follow a moving dot on the screen with eyes both horizontally and vertically. The data of dot positions, eye signals and the timestamps are recorded. The symptoms are rated again after that. Following test is the saccades. Two dots are plotted at edges of the screen, and the experimenter is instructed to saccade between these two points as quick as possible and repeat 10 times. Both horizontal and vertical saccades are examined, followed by the symptoms rating. Thirdly, the convergence test is conducted. The volunteer holds and stars at the finger, and moves the finger towards to himself. When a double vision occurs, the volunteer presses the button. The timestamp when the button is pressed is recorded and plotted with the eye signals after the experiment. Also, the volunteer rates the symptoms. Furthermore, the horizontal VOR test is carried on. An instruction is shown to the participant on how to rotate their head 20 *degrees* to the right and left sides separately, following the metronome with speed of 180 $beats/minute$ while keeping eyes on the dot in the centre of the screen. Similarly, the participant completes the vertical VOR test by turning the head up and down 20 *degrees*. Symptoms are rated as well. The last step is the VMS step, where requirements of outstretching the arm and staring at the thumb and then moving the body with the head and the arm as a unit to 80 *degrees* are illustrated to the participant. The participant is required to rate symptoms again.

4.2.1 Data Processing

Eye signals all over the VOMS assessment are recorded and saved to a excel file. Within the same file, the signal frequencies, dot positions, test names as well as symptoms are recorded as well. In each test, numeric data are extracted to process separately.

The list of timestamps is firstly converted from the list of frequencies. In the recorded excel file, the frequency per sample is saved. Converting it to the list of seconds, the second consumed at each sample is $second_{per\ sample} = \frac{1}{frequency_{per\ sample}}$, and the second in total at this sample is the sum of all points before this sample, where the i is the number of sample:

$$second_i = \sum_{1}^{i-1}(second_{per\ sample})$$

Besides, all signals are applied with the Savitzky Golay filter with the window length of 31 and the poly order of 2.

In the pursuit test, the performances of horizontal and vertical pursuits are measured separately. Outcomes including consistency, response time as well as signal patterns are analysed. In details, the variable consistency represents the average percentage of voltage consistencies on peaks and bottoms between two repeating loops. As shown in the figure 4.1, 6 sensors are calculated separately, where the consistency of each sensor is:

$$consistency_m = \frac{1}{2n}\sum_{i=1}^{n-1}\left(\frac{voltage_{P_n}}{voltage_{P_{n+1}}} + \frac{voltage_{D_n}}{voltage_{D_{n+1}}}\right)$$

Where n is the number of repeating times, P_n is the peak point of the sensor values in the n^{th} loop, and D_n is the bottom point of the sensor values in the n^{th} loop. The value

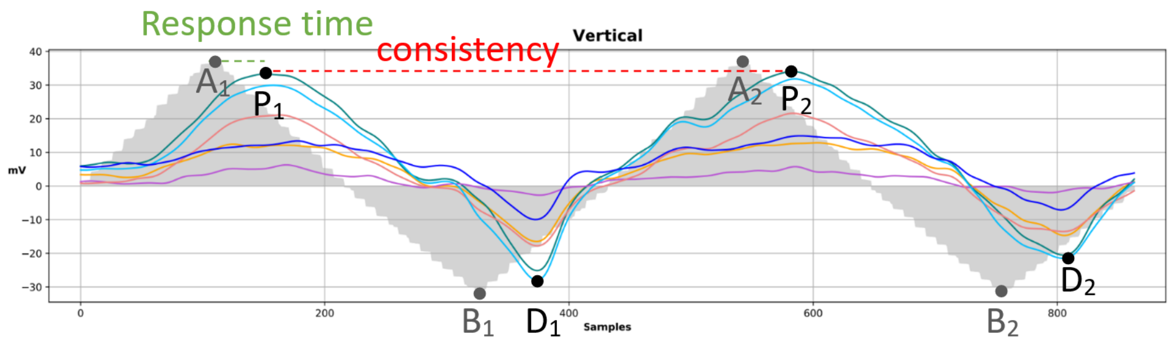


Figure 4.1: Signals generated from pursuit test in the VOMS assessment as an example to illustrate numerical values

m is the number of sensors in total. The average consistency ratio is then:

$$consistency\ ratio = \frac{1}{m}\sum_{i=1}^{m}(consistency_m)$$

Another value, response time is evaluated, which indicates the time consumed by the participant to react to the baseline movement. As shown in the figure 4.1, one example of the response time is the period between the points A_1 and P_1, and the overall response time is the average value of time differences at peaks and bottoms, as listed below:

$$response\ time_{sensor_m} = \tfrac{1}{2n}\textstyle\sum_{i=1}^{n}$$
$$(|timestamp_{sensor_m\ at\ P_n} - timestamp_{baseline\ at\ A_n}|$$
$$+|timestamp_{sensor_m\ at\ D_n} - timestamp_{baseline\ at\ B_n}|)$$

$$response\ time = \frac{1}{m}\sum_{i=1}^{m}(response\ time_{sensor_m})$$

Similarly, the m shows the number of the sensors ($m = 6$ in this paper), and n represents the repeating times of pursuit movements. Furthermore, signal patterns are essential in the pursuit test, due to the fact that the shape of signal is supposed to be sine or cosine waveform when the eye moves in a horizontal or vertical line. Therefore, any abnormal waveform will be labeled.

Similarly, the horizontal and vertical saccades are tested individually. In each saccade test, we focus on two variables, duration and consistency. As illustrated in the figure 4.2, the duration is the time consumed in average to complete one loop, such as the period

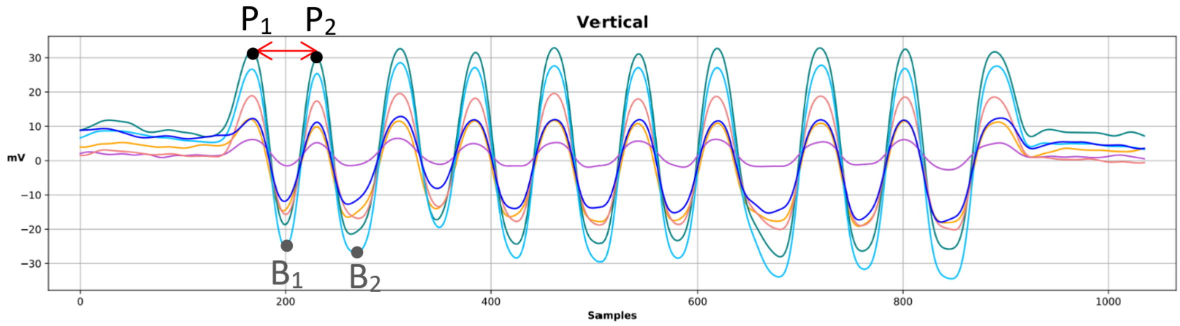


Figure 4.2: Signals generated from saccade test in the VOMS assessment as an example to illustrate numerical values

between P_1 and P_2:

$$duration_m = \frac{1}{n}\sum_{i=1}^{n-1}(timestamp_{P_{n+1}} - timestamp_{P_n})$$

$$duration = \frac{1}{m}\sum_{i=1}^{m}(duration_m)$$

The consistency ratio is then calculated by:

$$consistency_m = \frac{1}{2n}\sum_{i=1}^{n-1}(\frac{voltage_{P_n}}{voltage_{P_{n+1}}} + \frac{voltage_{B_n}}{voltage_{B_{n+1}}})$$

$$consistency\,ratio = \frac{1}{m}\sum_{i=1}^{m}(consistency_m)$$

In the equations above, the variable n equals to the number of repeating times, which is 10. The value m, is the number of sensors. The consistency per sensor $consistency_m$ is calculated firstly, and then the consistency in average consistency is measured. The value of consistency shows the stability of signals, and the value that is closer to 1 represents higher stability.

Following is the convergence test, in which we examine the visual ability of following a object moving towards to eyes, i.e., the distance between the object and the participant when a double vision occurs. The physical distance between the finger and the participant is measured manually. The plot of signal fluctuations versus the moment when the double vision appears is also available.

The fourth test is the VOR test, in which the measurements are similar to the saccades test. First and foremost, the horizontal and vertical VOR tests are evaluated separately.

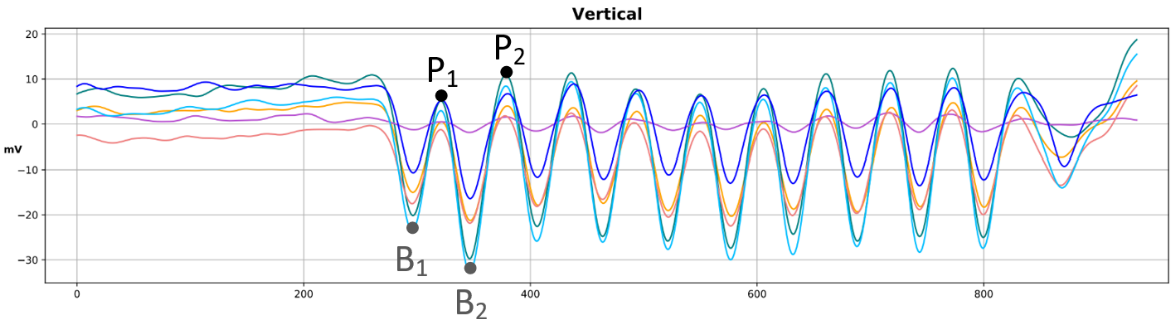


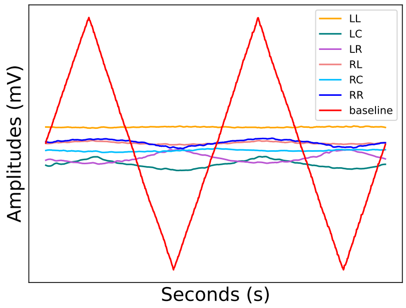
Figure 4.3: Signals generated from VOR test in the VOMS assessment as an example to illustrate numerical values

In each single test, the duration and consistency are calculated. The measurements of consistency and duration are as same as the calculations shown in the saccade test.

4.3 RESULTS AND DISCUSSIONS

The outcomes assessed below are generated from the author, as an example of healthy participants. The capabilities of slow pursuits both horizontally and vertically are evaluated in forms of consistency ratio and response time. The consistency ratio is the proportional ratio in average on signal voltages between the two repeating loops. In addition, the response time represents the period of time in average took by the participant to move eyes following the baseline. In the horizontal pursuit test, the consistency ratio shows to be 0.98 and the response time is 0.38 s. The performances of the vertical pursuit test result into 1.0005 consistency ratio and 0.31 s response time.

The abilities of saccades, on the other hand, are processed numerically based on the consistency ratio along with the duration. More specifically, when the author moving both eyes rapidly between two fixed targets in ten repeating times, the participant's visual stability and reactivity can be reflected on the signals. Steady signals in short duration with sine or cosine waveforms are expected among healthy participants. Therefore, the consistency ratio is brought up to measure the percentage of voltage differences on peaks and bottoms between the following loop and the previous loop. Consistency values with the total number of 108 are gained with six sensors repeating ten times, and the average consistency is calculated as the result of consistency ratio. Furthermore, the duration is regarded as the indicator of the participant's reactivity, which is the average time in seconds that consumed each cycle. As results, the consistency ratios are shown to be 1.0002 and 0.999, while the average durations are 0.76 s and 0.73 s respectively in the horizontal and vertical saccade experiments.



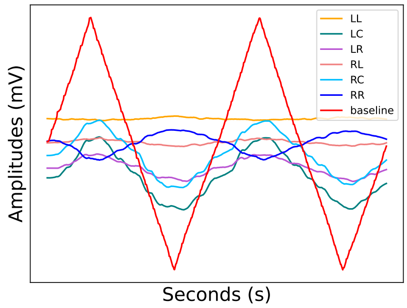
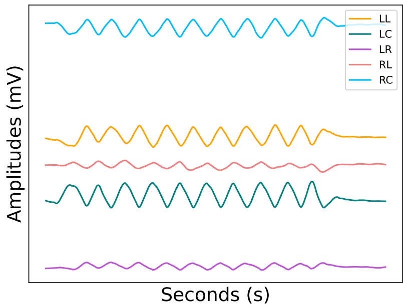


Figure 4.4: The eye signals generated from pursuit tests following the baseline dot movement. (a) Signals generated in the horizontal pursuit test. (b) Signals generated in the vertical pursuit test.



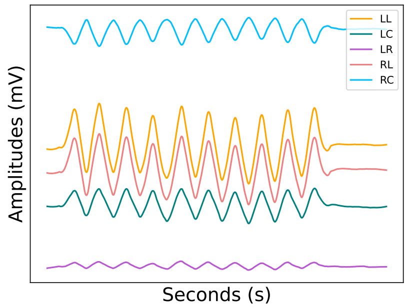


Figure 4.5: The eye signals generated from saccade tests with ten repeating movements. (a) Signals generated in the horizontal saccade test. (b) Signals generated in the vertical saccade test.

Convergence is also an essential part in the VOMS assessment, in order to examine the participant's ability to star at a near-eye target. During the experiment, the physical distance in average between the visually blurred object and the participant is measured to be 3.5 *cm*. Moreover, the relationship between the position when the double vision happens and the eye signals are plotted in the figure 4.6, where the gray vertical lines indicate the moments when double visions happen.

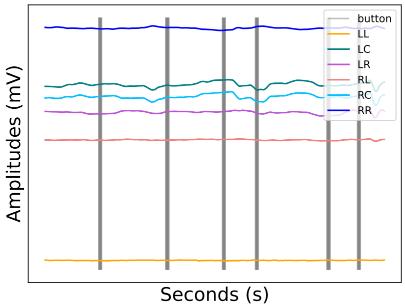


Figure 4.6: The participant presses the button when the double vision appears. The plot shows the moments when the button is pressed, i.e., when the double visions happen, along with corresponding eye signals.

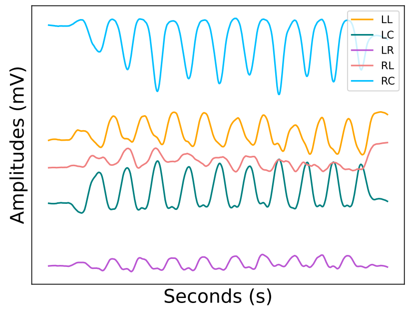
The assessments in the VOR tests are similar to the saccade tests, where two variables: consistency ratio and duration are analysed based on signal fluctuations. Results from the horizontal VOR experiment show the consistency ratio of 1.0001 and the duration of 1.24 s. Based on the vertical VOR test, the consistency ratio is proved to be 0.9997 and the duration to be 1.1 s. All the data are illustrated in the table 4.1 as well.

Recordings of symptoms are enabled at different stages along the experiment: at the beginning of the assessment and after each single test. The values of symptoms rated at the start of the experiment are regarded as the baseline, while symptoms reported after each test are subtracted by the baseline to observe changes. These data are saved in the document.

Above, we have shown the outcomes in pursuit, saccade, convergence and VOR tests. However, we still look for solutions to map the relationship between eye signals with 3D activities. The data analysis in the VMS test is not explained, as the algorithms to track gaze in 3D environment are unclear at this stage. Additionally, this technology is expected to be applied to concussed patients, in order to explore more on the relationship of concussion to eye signals. The ethics are still in the process of application.

Table 4.1: Numeric results of VOMS assessment

Variables	**Horizontal pursuit**	**Vertical pursuit**	**Horizontal pursuit**	**Vertical pursuit**	**Horizontal VOR**	**Vertical VOR**
Response time (s)	0.38	0.31	—	—	—	—
Consistency ratio	0.98	1.0005	1.0002	0.999	1.00008	0.9997
Duration (s)	—	—	0.76	0.73	1.24	1.10



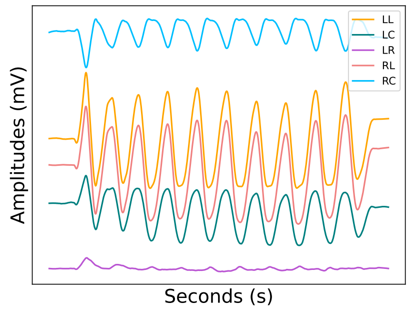


Figure 4.7: The eye signals generated from VOR tests. (a) Signals generated in the in horizontal VOR test. (b) Signals generated in the vertical VOR test.

4.4 CONCLUSIONS

We have proved the potentials of the NIRSense system in the concussion assessment, by combining the VOMS assessment with the eye tracking technology. Overall, we demonstrate the designed software that enables participants to conduct the VOMS assessment while their eye signals are monitored in a safe and long-term way. We also introduce algorithms we applied to process the relative eye signals and show the results. Although further work is still required, involving the signal process in the VMS test of the VOMS assessment and further application to target patients with concussion.

Chapter 5

Concluding Remarks

5.1 Thesis contribution

This thesis has made contributions in several aspects. First and foremost, this thesis proposes an innovative design of the eye tracking system that monitors muscle movements to track eye activities, and avoids optical contacts with the cornea. The way of preventing energy from being delivered to the cornea can largely improve the safety and comfort compared with other traditional optical eye tracking technologies. Thus, it is expected to benefit patients with light sensitivity or fatigue eyes. This thesis also proves achievements of gaze tracking in accuracy of 1.05 *degrees* and precision of 0.6 *degrees*. Under the same circumstances, one commercial camera eye tracker reported with high accuracy is tested, in order to compare with and prove the capabilities of the NIRSense eye tracking system. Another important contribution is that we propose new insights of bringing eye tracking technologies to the concussion assessment, and try to overcome the gap of the traditional VOMS diagnosis method. We not only provide a computerised way to combine the VOMS test with the NIRSense eye tracking system, but also certify our system can extract numeric variables from these eye signals to analyse the relationships between eye signals and the concussion injury. AS a summary, our main contributions are listed:

- We have designed a novel system that can track muscle movements to predict locations of pupils in a safe and long-term way.
- We have certified this system with accuracy of 1.05 *degrees* and precision of 0.6 *degrees*.
- We have designed a experiment that allows the participant to conduct the VOMS

assessment while wearing the NIRSense system on, and we have analysed these eye signals to generate numeric evidence.

5.2 Future research directions

In the future, we need to explore further on the source of muscle that we are tracking. With the understanding of targeted muscle, we can improve our eye tracking system to a higher level. For instance, the anatomy of the muscle can assist us to understand relationships between the muscle and eye activities. It will also help us determine the positions of sensors better. The placements of sensors can affect strength of signals captured, and therefore have impacts on accuracy and precision of gaze tracking.

In addition, we are going to test the eye tracking system to the concussed patients, in order to explore the differences of eye activities responding to the VOMS assessment between the healthy group and the concussed group. Our application of ethics is in progress at this stage.

Furthermore, the ability of mapping gaze in 3D environment is expected to explore. Currently, our system has played great in 2D gaze mapping. However, considering applications such as signal processing of the VMS test in the VOMS assessment or gaze tracking in a 3D environment, the ability of tracking the depth of gaze matters. In this way, our system can be applied to wider fields.

Overall, we have presented properties of the NIRSense system in this paper, and have presented applications achieved in multiple fields. Further work will be conducted to overcome gaps and explore more potentials.

APPENDICES

.1 Gaze Mapping

Beside the results presented in the main text, another participant also contributes to test the performance of NIRSense glasses, which are shown below.

Table 1: Outcomes generated from another participant

	Accuracy $EVS(\%)$	**Accuracy** *degree*	**Precision** *degree*
Gaze	99.3	1.24	0.83
Pursuit	98.9	2.14	0.93

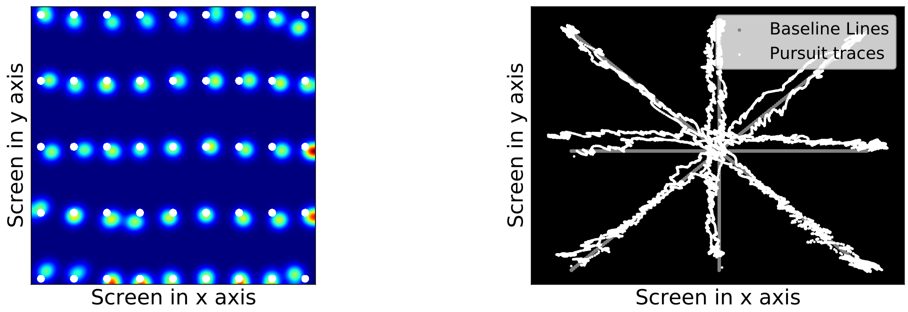


Figure 1: (a): The result of pupil paths in gaze test. The heatmap indicates the gazing predictions provided from the NIRSense glasses and the white dots show the real locations of baseline dots. (b): The result of pupil paths in pursuit test. The white lines show the traces of eyes movements.

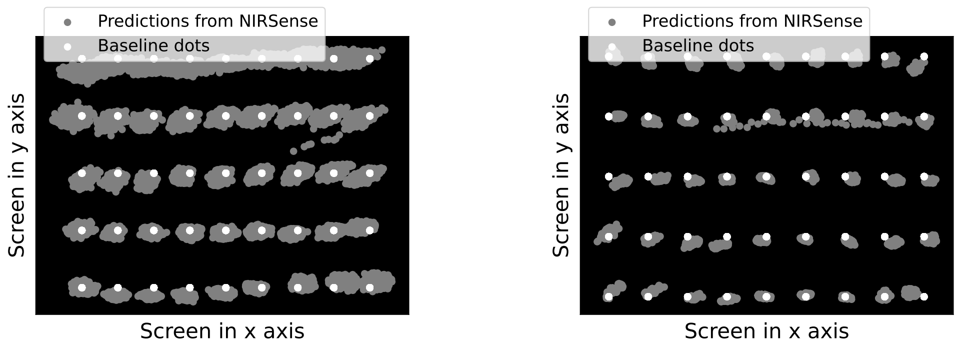


Figure 2: The results of gaze experiment in terms of gaze traces. The gray dots are predictions of staring positions, while the white dots are baseline data. (a) Data generated from the participant 1. (b) Data generated from the participant 2.

.2 Hardware Characterises

The LED that applied in the NIRSense system is from RPR220 sensor, in which the datasheet of RPR220 sensor can be found from *Reflective photosensor (photoreflector) RPR-220 datasheet* n.d. The phototransistor used in the NIRSense system, is WP3DP3BT/BD-P22 phototransistor (*WP3DP3BT/BD-P22 Phototransistor* n.d.).

.3 Safety

Figure 3 shows the logarithmic plot of NIRSense's radiant exposure over time compared with safety standards (e.g., IEC, ICNIRP and ANSI/IESNA).

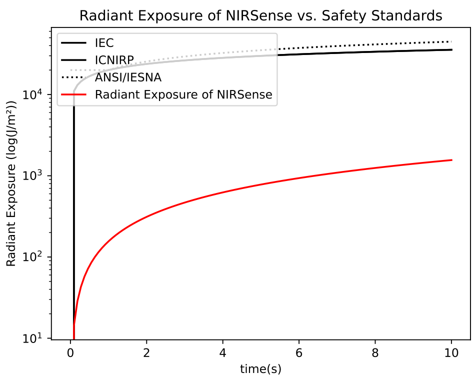


Figure 3: The Change of radiant exposure generated from NIRSense system over time.

.4 Existing Eye Tracking Technologies

Several cutting edge eye tracking technologies are shown in figure 4, aiming to supplement the literature review. Tobii Pro Glasses 3 is displayed as a representative of camera-based eye tracking device, in which cameras are amounted on a glasses frame (*Tobii Pro Glasses 3 product description* n.d.). Tobii Pro Nano is another type of camera-based eye tracking device, monitoring eye movements remotely (*Tobii Pro Nano Enter the world of eye tracking research* n.d.).

Figure 4: Photos of cutting edge Eye tracking systems. (a): Tobii Pro Glasses 3 (*Tobii Pro Glasses 3 product description* n.d.). (b): Tobii Pro Nano (*Tobii Pro Nano Enter the world of eye tracking research* n.d.)

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