DEVELOP AND TEST A WEARABLE EYE TRACKER

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Eye tracking is a technology that tracks the pupil of the user's eyes and estimates her/his gaze direction to realize gaze control computer and machine interface. This can be useful for patients with severe motor disabilities to control a motorized wheelchair. However, most of the available wearable eye trackers currently suffer accuracy issue over time of usage due to slippage and drifting problems. These problems are especially significant and critical when it is used with on automated wheelchair moving on uneven surfaces and setting up vibrations. Therefore, a wearable eye tracker with robust frame design is necessary to overcome the challenges. The accuracy of the eye tracker is evaluated and compared before and after a series of designed conditioned that are similar to habitual behaviours of user in real life application which contributes to the slippage of an eye frame. The results of accuracy and precision were obtained in the factor of deviation and RMS (root-mean-square) respectively in regard to the calibrated result. Although it was still suffering from the effect of frame movement especially in the z-direction, the overall improvement on the frame was significant compared to previous research performed with commercial wearable eye tracker.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ ABBREVIATIONS

$\emptyset$	angular offset
x_m	position of marker in x-axis
y_m	position of marker in y-axis
x_e	position of reported gaze in x-axis
y_e	position of reported gaze in y-axis
d	distance between user and calibration screen
POR	point-of-regard
IMU	inertial measurement unit
IR LED	infrared light-emitting diode
USB	universal serial bus
RMS S2S	root-mean-square sample-to-sample

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Eye tracking is a sensor technology that detects the pupil, estimates the gaze of the user and projects the information into the scene or computer screen that the user is looking.

Currently, there are two main applications of this technology that are being widely studied. One of the applications is the study on human behavior which gives us insight into our area of interest and information that we process, which has direct impact on our actions and emotions as well as decision making process. It can be achieved not only by tracking what we are looking, but also what we are not looking and ignoring as well as the how our eyes blink and how pupils react to different stimuli. However, this application is not the subject of interest in this study.

The main topic of this study is to collect data that is able to realize enhancement of human-computer interface by using gaze information as input control for computer or machine. In other words, users who cannot use their hands as input can use their eyes instead as a “pointer” on a to interact with computer and digital device. Such a system enables disabled users who are unable to control their voluntary body movement to gain back their social capability and boost their independency.

There are two main types of eye trackers. The first type is a remote eye tracker that is fixed on a panel at a certain distance and the second type is a wearable eye tracker that can be worn by the user like eye glasses. This project focus is on wearable type eye trackers that allow free head movement of the user as well as to counter the stability problem of a remote eye tracker that is mounted on a wheel chair.

1.2 Importance of the Study

This project is a subpart of a main project of a smart wheelchair that can be controlled by a user with severe motor disabilities. The eye tracking system is crucial for the user using gaze to communicate and to control the wheelchair in an accurate and precise manner with minimum slippage problem caused by the wheelchair as well as user's habitual behavior.

1.3 Problem Statement

For an eye tracker system, it has to be accurate and precise in detecting the gaze for a better user experience and control over the interface. Such device with high accuracy usually comes at a high cost. The main challenge is to build one with such capability with a limited budget as high quality wearable eye tracker available in the market may cost from around RM 10 000 – RM 40 000 (prices of different commercial models are given in Table 4-3). In addition, the frame for an eye tracker has to be not easily slipped from the user's head while being comfortable and not causing any stress on the head or face as much as possible at the same time.

1.4 Aim and Objectives

Aim:
To develop wearable eye tracker and test its performance to know if it sufficient to be used as human-computer interface (HCI).

Objectives:

- Develop wearable eye tracker with gaze estimation of less than one degree error in accuracy and precision.
- Collect data of accuracy and precision and compare it to data from existing research to evaluate its robustness against slippage.

1.5 Scope and Limitation of the Study

A complete system of eye tracking with application should consist of three important aspects as following, however they are not equally prioritized in this study:

- hardware that consist of frame and camera sensor
  - which was the main focus in this project by designing a customized frame for the eye tracker
- software for data acquisition and image processing
  - existing open-source software that has been mature in development and has high reliability had been deployed as it would be time consuming to otherwise self-develop an eye tracking software from scratch
- user interfaces to interact with computer device
  - was not discussed in this study due to time limitation, however can be proposed for further development of this project

Functionality of the wearable eye tracker in terms of accuracy and precision was the main interest of this study, followed by other requirements of a wearable eye tracker such as weight and cost.

1.6 Contribution of Study

Multiple studies have shown that physical activities of the user will cause inaccuracy in eye tracking, even for commercial wearable eye tracker (Nierhoster et al., 2020). Meanwhile, it will be especially troublesome for the eye tracker user with severe motor disabilities that require fine accuracy and precision for both communication and wheelchair control, as adjustment or recalibration of eye tracker will be difficult for them to perform independently.

Therefore, this study was to design a customized frame with wearable eye tracking system that is robust against slippage effect. The prototype is then tested according to experimental steps conducted by Nierhoster, et al., (2020) for a direct comparison between anti-slippage of commercial eye trackers and the prototype.

1.7 Outline of Report

Chapter 1 of this report has been identifying the problem that had been studied in this research. Chapter 2 will be following with research on working principle of eye tracking technology and previous works that had been done by others as well as the gap that this project able to contribute. Chapter 3 have been sectioned into two parts with first part introducing the eye tracking system of the prototype I have built and how it was made while the second part will be the experimental steps that used to test the prototype. Then, Chapter 4 will be discussing the performance of the prototype against slippage and its specifications compared to commercial eye trackers. Lastly, Chapter 5 will be a conclusion on the outcome of this study as well as the improvement that can be made in further development.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Eye tracking is a technology to obtain data regarding the gaze direction or point-of-regard (PoR) of the user on a real time basis. In other words, it detects the position of the point where the user is looking. Eye tracking has been a subject that is undergoing intense research for decades, given its potential over a wide range of applications.

2.2 Eye Movement and Area of Interest

When a ray of light coming from the world is projected onto human eyes, it first passes through a thin layer of protective transparent membrane that sits in front of the iris and pupil before reaching it, called cornea. The pupil then controls the amount of light that will be passed onto the biconvex multi-layered structured eye lens, by changing its size, depending on the light condition of the environment. The eye lens performs deformation to focus on the incoming light depending on differences of its depth. The ray of light will then be casted on a retinal surface that consisted of photoreceptor cells after travelling through the vitreous humour fluid. There are two types of photoreceptor, but gaze tracking will only be concerning on the small portion of area called fovea, that is highly packed with “cones” (which are more sensitive in colour), as the visual acuity (or resolution of eyes in particular) is significantly reduced as the distance from the fovea increases (Kassner and Patera, 2012). The visual axis line that connects the centre of cornea and the fovea has also been suggested as the true eye gaze direction (Hansen and Ji, 2010), which is the component that eye tracker seeks to measure.

Eye movements can be mainly categorized into fixations and saccades. Fixations, which are usually called gaze, happen when the eyes need to rest on a small area to obtain a detailed resolution of an area of focus, usually lasting a hundred to three hundred milliseconds. In contrast, saccades are high frequency rotation of the eye to position the fovea to the area of interest as the effective angle of fovea visual is only one degree in approximately. Both types of eye movements have been investigated in various different area of research, where saccadic eye movements are applied in the study of human vision, sleep disorders and detection of drowsiness (Duchowski, 2003), while fixations are used in studies that require to analyse one's area of interest and level of focus. In this research, fixation is the interest of study as information from gaze input is sufficient to control a wheelchair and typing in a computer interface.

2.3 Eye Tracking Working Principle

In general, there are mainly four types of techniques that have been studied to measure human eye movement throughout the history of eye tracking technology: *Electro-Oculo Graphy (EOG), scleral contact lens, Video-Based (appearance, model and geometry),* and *Video-Based Pupil Centre and Corneal Reflection (PCCR)* (Duchowski, 2003). However, only the last one will be discussed in this section.

Although the other techniques mentioned are all capable of being used to detect eye movement, they generally measure the movement of eyes relative to the head. A person can change the direction of gaze by rotating the pupils and eyeballs while keeping their head straight. Likewise, a person can alter the direction of gaze by merely changing their head pose. In natural sense however, a human's gaze is a combination of both eye orientation and head movement, where a person usually changes the head pose into a comfortable position before adjusting their eyeballs to the point of regard. In another sense, the head movement is a coarse scale adjustment of the gaze while the eye rotation is responsible for the fine scale adjustment. The gaze estimation of eye tracker therefore has to include the model of eye movement as well as the head pose (Hansen and Ji, 2010).

Therefore, in often time, the head movement is tracked by additional hardware like IMU sensor or the head is fixed in certain position, where both methods are not comfortable for the user. Otherwise, multiple features have to be measured to obtain the information regarding position of head thus the computer vision is able to distinguish between head movement and eye rotation. The pertinent features that are commonly used by most modern eye trackers are the corneal reflection and bright/ dark pupils that are initiated by light illumination.

There are two approaches of light illumination used in eye tracking techniques: passive light method that relies on visible ambient light (Li, et al., 2005) (Yuille, et al., 1992) and active light approach that usually use near IR (infra-red) light source which wavelength about 780-880 nm (Hansen and Pece, 2005). The visible light spectrum light is difficult to control due to the reason that the ambient light source might consist of multiple specular and diffuse components. In contrast, a near infrared active light source eliminates the uncontrollable variable. Additionally, although near IR light is not visible to human eyes, it can be easily captured by many commercial cameras that can be acquired in the market nowadays. The invisible property has prevented from distracting the user or causing the contraction of pupils, as well as not causing discomfort to the user's eyes over the time usage. However, the current issue with active IR illumination is that it is prone to inaccuracy in outdoor conditions where the interference from sunlight during daytime will be heavy.

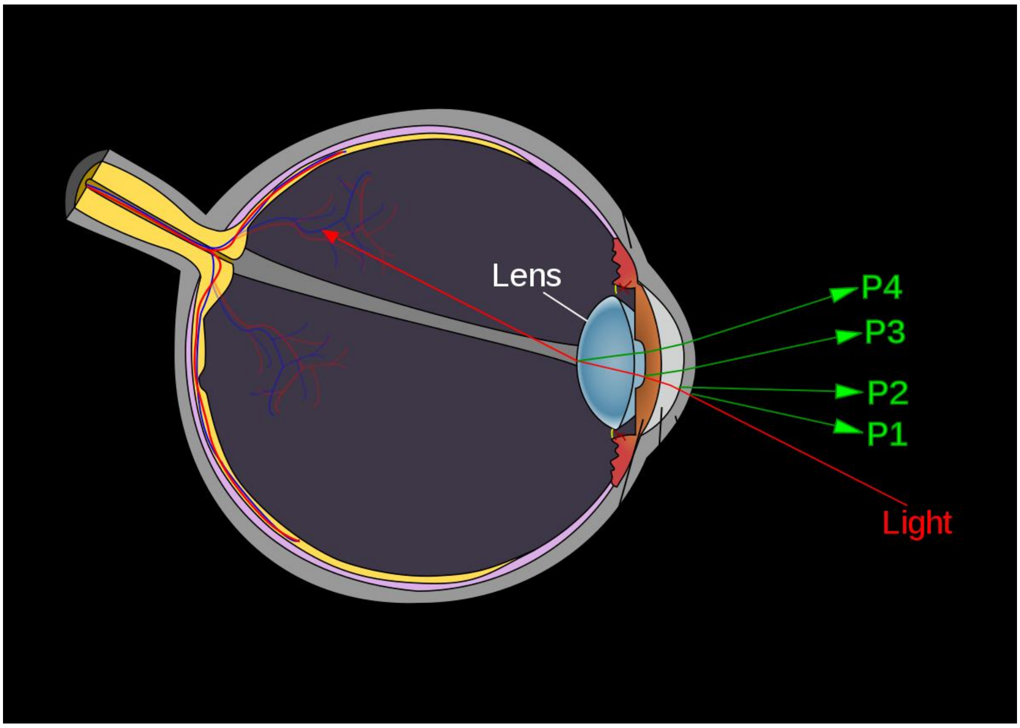

Figure 2-1: Light Reflection in Purkinje Image

Purkinje image is a phenomenon that happens when a handful of light reflections from the boundary between the cornea and the eye lens due to incoming light that projects on the convex-curved cornea of eyes. In Figure 2.1, four Purkinje images that are visible to human eyes are usually reflected when a ray of light is directed into the eyes (Morales, 2017). The first Purkinje image with small but sharp reflection on the eye, which is due to reflection from the front surface of the cornea, is called corneal reflection, generally known as the glint in eye tracking. It is often used for the detection of eye fixation due to its brightness. Fourth Purkinje images are sometimes used together with the first by measuring the space between two images in some older studies (Lewis, 1977), (Crane & Steele, 1995). This is because the spacing between the two images remained constant when during the translation of eyes, but the distance changes during the rotation movement. Thus, the translational and rotational movements of eyes can be detected separately. This technique of tracking works comparatively well and precise in 2D. However, it does not appear to be a reliable method in advanced eye tracking due to the difficulty of implementation where extra work to stabilize the head is necessary. In addition, as the fourth

Purkinje image is weak compared to the first, light conditions have to be tightly controlled.

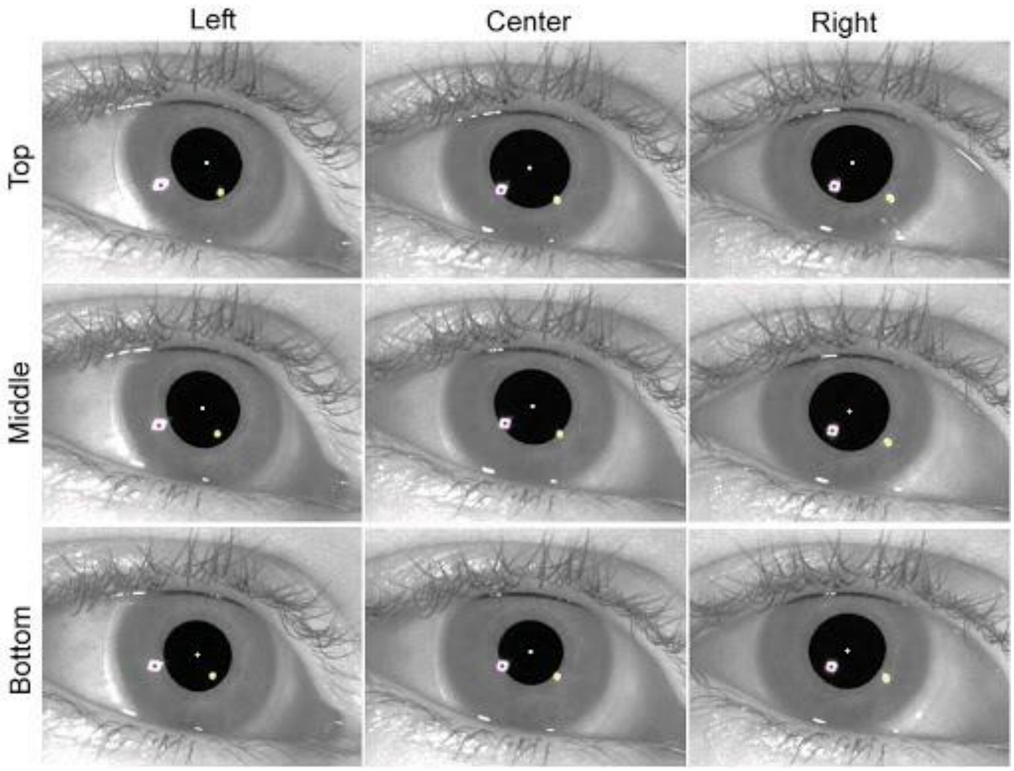

Figure 2-2: Glint and Dark Pupil

(glint remains relatively constant in position in regards of eye movement)

(Source: *http://apps.usd.edu/coglab/schieber/eyetracking/ets/ets-calibration.html)*

Thus, the most advanced commercial eye trackers in recent years usually apply a combination of both bright or dark pupil detection, and corneal reflected glint (Purkinje's image) detection for better accuracy and robustness. Pupil Center Corneal Reflection or PCCR eye tracking uses the bright/ dark pupil to detect the pupil centre and taking the difference with the glint is calculated to obtain the gaze estimation. The glint as an effect of on-axis light source naturally stays at the centre of pupil when the eyes are gazing on the axis of the camera. Meanwhile, as shown in Figure 2.2, it also remains at the original position of eyes even if the gaze changes and the pupil is not anymore at the centre of eyes. In other words, the corneal reflection can act as an absolute centre for the rotation of eyes. Namely, this underlines the approximate proportional relationship between the gaze angle regarding the light source and the distance of corneal reflection and pupil centre. The vector distance between the pupil centre and the glint centre is taken to measure the eye movement. In addition, the position of the glint changes together with the pose and movement of head of the user (Guestrin and Eizenman, 2006). Therefore, it comes to a combination where the changes of bright/ dark pupil centre with respect to the glint is used to eye rotation while the changes of glint position are used to distinguish the eye rotation and the head movement. As such, corneal reflection is an effective approach to compensate for head slippage problems. In addition, it is noteworthy to mention that both the eyes and head detection come from the single component which is the IR illumination and no extra cost of equipment production is needed to detect the head pose.

2.4 Relatable Work

There are already reliable commercial eye trackers available to provide promising data accuracy. However, it is still considered an expensive wearable with a cost of around MYR 2 800 (Gazepoint GP3, which is sold as an affordable one for research). It is one of the reasons why eye tracker is mainly used for research purposes at the current stage and not found ubiquitously yet in daily life application, which it has a lot of potential usage. The reason behind its expensive cost, is mainly due to the cost invested in the research of this developing technology, instead of the hardware price. Otherwise speaking, it is possible to build an alternative eye tracker with low cost off-the-shelf hardware components. Numerous developers and researchers in the eye tracking community have built and published their low cost and open-sourced pervasive eye tracker with the capability matching commercial ones in term of accuracy and precision.

First of all, Babcock and Pelz (2004) provided a practical solution on building wearable IR light based dark pupil eye trackers using micro lens cameras and other commercially available components. In a noteworthy innovative DIY (Do-It-Yourself) approach, the lightweight headgear that it suggested was modified from a safety glass as well. Nevertheless, the off-line processing system approach is a hard limitation to integrate into our eye tracking system that can be applied on HCI purposes. Although there is no evaluation on the reliability of the eye tracker reported, it has however opened the door for open-source development of IR light-based eye tracking.

Ferhat and Vilariño (2016) studied open-source projects alternative to commercial eye trackers which IR light-based approach is widely used and built a low-cost eye tracking project by removing the hardware requirement for IR light eye tracker. The survey is made on the open-source projects that are video-based which included both model, feature and appearance-based approaches. However, the research is more focused on remote eye tracking systems instead of wearable eye trackers, which most of which have the limitation on free head movement.

OpenEyes has built a low-cost wearable with an IR illumination that integrated with corneal reflection approach for the purpose of human-computer interface using webcam cameras. The details work regarding the problems found and recommended solutions that have been reported is laudable and well compatible to be adopted in our system as well. Li, et al. (2006) has suggested the requirement of better resolution and frame rate of cameras, which is much more affordable as of now. In addition, it also suggested the consideration of wireless solution or usage of thin and flexible cable connecting the eye tracker to the computer, for a better noise removal. Besides, the bandwidth limitation of the camera has to be considered when selecting the webcam. On the software side, Starburst algorithm with a combination of feature-based and model-based image processing method has been developed and applied on general hardware with the necessary accuracy that is sufficient for HCI.

Pupil Core is an open source platform for wearable eye tracking that was built in 2014, by Pupil Labs which has since then grown into one of the leaders in the commercial market. On the platform, it has provided a guide and detailed list of commercially available components to build IR light based wearable eye trackers using webcam cameras. Moreover, it has developed free open source software, Pupil Capture for data acquisition and image processing for eye tracking with Pupil algorithm that has been proven with the accuracy of 0.6 ° under ideal condition (Kassner, et al., 2014).

Borsato and Morimoto (2017) has proposed structured light where multiplexed IR light sources are used to project illumination pattern to ease feature extraction when doing image processing, by using a low cost PS3 eye camera. However, although it has proven to be applicable without external synchronisation mechanism, the camera has to be running at a high frame rate of 187 fps, which will cause a low resolution of the image quality. In addition, the extra setup will be an extra cost and not compatible for mobile wearable eye tracker as well.

Arbabi, et al. (2017) has also proposed a low-cost low complexity eye tracker for regular application by using IR light to detect the eye movement and retro-reflective adhesive paper on the user's face to track the head movement. Although it is an innovative solution for simplicity, it is however only suitable for the application of non-wearable eye trackers. It is because this method requires the camera to capture the face of the user instead of the eyes merely. Although it can be solved by using a wide view angle lens on the camera, it will increase the complexity of software in order to minimize the distortion it causes digitally. In addition, comfortability and user experience will be a concern for applying and adhesive paper on face.

2.5 Summary

As a summary, IR illumination eye tracking technique is currently considered the most reliable method and easiest to be implemented in low cost eye tracker. However, distortion from the ambient light shall be taken into account when the method is used. Furthermore, Pupil software that is open-sourced from Pupil Labs is suitable to be integrated in the eye tracking system of the prototype as it is compatible to IR illumination and it does have high reputation of reliability and user-friendly advantage.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

As the commercial wearable eye tracker that is available in the market is too expensive which costs around MYR 2 800, this project will be building a do-it-yourself wearable eye tracker that is assembled from components with a total cost within MYR 500. It is applicable to build a low-cost eye tracker ourselves nowadays due to the three reasons. First, the hardware setup of modern eye tracker with IR illumination technology is relatively simple to build compared to older versions of eye tracker where the intrusiveness is high. Second, the most expensive part of the video-based eye tracker, which is the camera, can be easily obtained from general use webcam cameras nowadays with required specification. This is possible due to the advancement in camera technology where the capability of the camera has largely improved while the cost is significantly. Last but not least is the willingness of the eye tracker community to share their software selflessly and publicly in an open-sourced manner that can be found on the web.

In this Chapter, two parts will be discussed in the coming sections. The foremost one will be the system overview for the eye tracker, including hardware and software components. The second part will be discussing the experiment setup to measure the functionality of the eye tracker that I have built.

3.2 System Overview

The eye tracker that I have built is a head mounted monocular eye tracker, which take information from one eye, together with a world camera that tracks the scene in front of the user. The eye camera and world camera were built using the same model of camera module without other assistance from another device such as glint. The eye contour feature is detected to obtain information of pupil centre and is mapped into the world camera captured scene to obtain the fixation point or direction of gaze.

3.2.1 Hardware

First of all, the hardware components to be used will be listed below and discussed in detail following the sequence.

1. USB camera module
2. Headset and Mountings
3. Computing Device

3.2.1.1 USB camera module

First of all, the most expensive component needed for the building of a wearable eye tracker is the camera. The foremost part of this was to make a decision on the number of cameras that will be used in the system, whether it is a monocular or binocular eye tracker. According to Cui and Hondzinski (2006), two cameras which is the binocular eye tracking system always performs better than eye tracking using a monocular method. In addition, although Hooge, et al. (2018) argued that sometimes it is better to use a single signal (data from only an eye) in eye tracking systems based on the application and the characteristics of the user. It however concluded that it is better to use version signal, which is the mean of the data from both eyes is taken, in general purpose research and application. Nevertheless, monocular eye tracking was implemented in this project after a trade-off between the performance and the cost of camera as the performance difference between binocular and monocular shown in the research was insignificant and acceptable in this project. Therefore, a monocular eye tracking method that uses a single eye signal is chosen in this eye tracking system, which means two webcam cameras will be needed with a camera tracking the eye and another capturing the scene that user is looking at.

Figure 3-1: Sony IMX291 USB Camera Module

The USB camera module product found to be suitable for our eye tracking project was model Sony IMX291 USB camera module shown in Figure 3.1. The camera is chosen based on three criteria, the resolution, frame rate and cost. As a matter of course, both the cameras will be from the same webcam model for easier configuration and consistency in capability. A higher resolution ensures more details of eyes to be captured as more pixels are used to describe the image. A higher frame rate means better responsiveness of the eye tracker, which is helpful in detecting fast movement of saccade. However, as the project is more concerned on the fixation instead of saccade, 60 fps or higher of frame rate is not necessary in our system. Meanwhile the cost for each camera should be around MYR 200 at most as 2 cameras will be used.

As according to the papers regarding low cost self-made eye tracking researches that is discussed in Section 2, the webcam cameras are usually with the specification of 640 x 480 resolution or lower and frame rate that is not over 30 fps. Although there are differences in the technique and model used in the system, the results obtained (according to the papers) however had shown satisfactory capabilities of eye tracking. It indicates that the specification of Sony IMX291 with a resolution of HD 1280 x 720 at 30 fps is more than capable to achieve the accuracy required. Although a finer resolution and faster frame rate that can be found in better models, will certainly achieve a higher accuracy, a trade-off for the cost has been made.

It is important for the camera to be sufficiently lightweight and small in dimension, to have the eye tracker as light as possible and not obstructing vision of the user. Therefore, the module IMX291 as shown in Figure 3.1 chosen was only $26\ mm\ \times 24\ mm\ \times 6.3\ mm$ without including the lens. In addition, the camera was mounted several cm distant from the eyes for getting an image that is sufficiently wide to cover the eyes. Closer position to the eyes will have extra fisheye lens installed on the cameras which will cause distortion to the recorded image and also an extra budget for purchasing.

3.2.1.2 Customized Frame

The design of a customized headset or frame is crucial to build the required robustness against the slippage problem, and it is as well apparently the largest portion of equipment of the device. Therefore, to evaluate the design of frame, several criteria will be set as following, (a) it must be simple and lightweight to not impose any burden on the user's head, (b) it must be robust enough against slippery in order to hold the components in fixed position during the usage, (c) accuracy and precision for the placement of components including cameras and (d) it must be comfortable and not causing any visual obstruction and harm to the user. As the matter of course, the entire frame was basically fabricated by 3d printing to achieve low weight, flexible shape and fast prototyping.

The frame and parts had been printed using PLA filament, which has comparatively high strength and dimensional accuracy as well as competitive in cost and widely available, associated with 0.4 mm diameter nozzle to ensure balancing between fine details and printing duration. Although the strength requirement is low, the parts had been printed with 40 % infill in honeycomb pattern to achieve reliable structure with minimal material and cost. As result, the final 3D printed frame and parts were only 38.03 g in total with an estimation of RM 2.92.

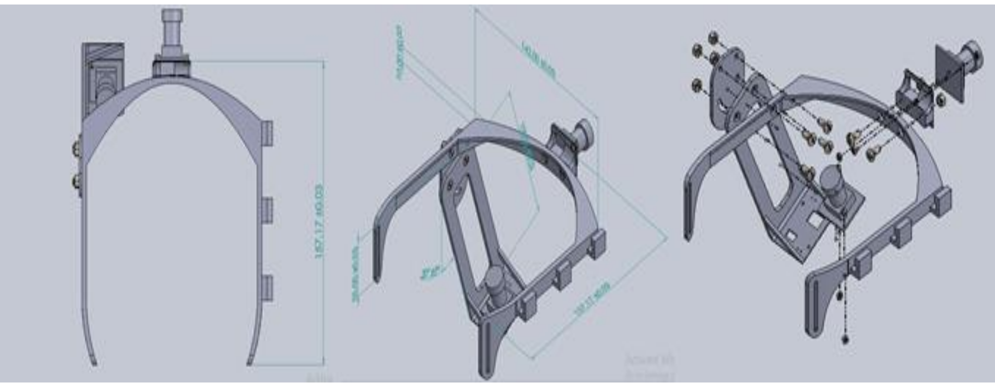

Figure 3-2: Different Views of The Eye Tracker Design

The final frame design shown in Figure 3.2 was drawn in SolidWorks prior to be printed. There are several frame features designed to achieve better eye tracking performance and user experience. First of all, as mentioned above, the eye camera has to be placed certain distance away from the user's eye. Therefore, the arm of the camera holder was made according to the focus distance of the camera module. As in this case, the focus distance of IMX291 is minimum of 50 mm (according to specification), therefore the arm was designed to be more than 50 mm as well. However, it was purposely designed to be as short as possible to prevent slippage issue as larger torque would be needed to hold the moment of longer arm.

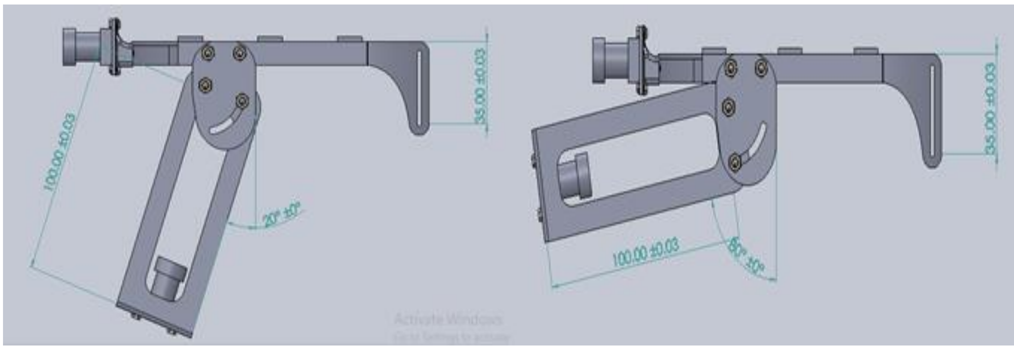

Figure 3-3: Side View of The Eye Tracker Design

Other than that, as every user has different face and eye features, the arm of camera holder was designed to be adjustable in angle to make sure that the camera can be positioned at an angle that is focusing on the user's eye. To ensure that it fits variety of user, it was made to capable of an adjustment of from 20 ° up to 80 °, as shown in Figure 3.3. The eye camera was then able to be adjusted specifically to the user base on the accuracy and precision shown by the calibrated result to obtain the optimal angle and position. However, the optimal angle of camera arm for this eye tracker lies around 70 ° for average user.

Moreover, the tips of the frame were made with slots for headband to slip in as shown in Figure 3.3 and Figure 3.4, in order to tighten the frame according to head feature of the user for the purpose to counter unnecessary horizontal and depth movement of the frame and keep the eye tracker in initial position. To tighten the eye tracker, the frame was designed to be as thin as possible as well to allow flexure of the frame due to lower moment of inertia.

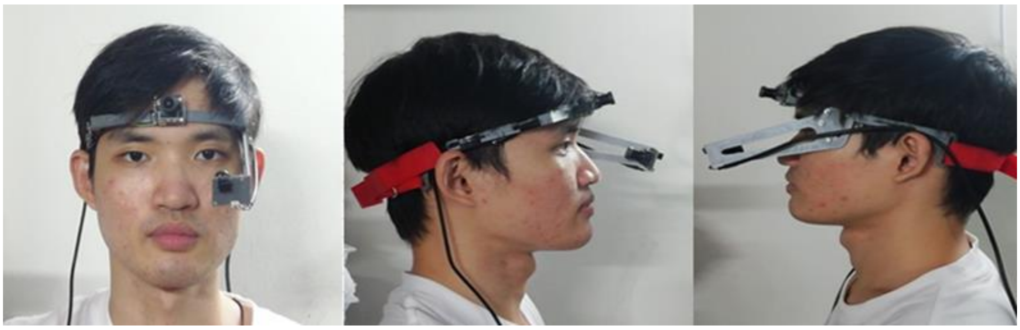

Figure 3-4: Final Prototype of The Eye Tracker

3.2.1.3 Computing Device

The computing device to process the data from both eye and world camera was a laptop with 2.40 GHz processor Intel® Pentium ® CPU 2020M with 4 GB installed RAM. The laptop was operating in 64-bit Windows 10 operating system.

3.2.2 Software

In order to obtain useful data information from the video captured by the eye cameras, a robust software is essential and necessary for the eye tracking system to acquire the data and perform image processing using the video captured by the eye cameras. Most of the promising commercial eye trackers on the market use proprietary software that is bundled with their own hardware selling at a high cost, which is not realistic for this project regarding the budget. Fortunately, self-developed open-sourced software has become available in the eye tracking community in recent years.

Among them, there is a reputable open source software developed by a commercial eye tracker company, Pupil Labs. Pupil has been widely used by researchers and currently still under active development by the developers of open-source community (Kassner, et al., 2014). The software has been claimed explicitly by Pupil Labs for having the ability to compensate for the slippage of hardware. The performance of the open-sourced solution by Pupil had been evaluated with a result of 0.6 ° accuracy and 0.08 ° precision under ideal condition (Pupil 2014).

Figure 3-5: Interface of Pupil Capture Software During Eye Tracking

The software is mainly divided into two applications, Pupil Capture (as shown in Figure 3.3) that captures and performs real time image processing from multiple camera video streams; and Pupil Player that playback the video and visualize gaze data recorded using Pupil Capture.

The eye tracking technique that Pupil software uses is mainly dark pupil eye tracking, it detects the location of dark pupil in eye camera image under illumination of infrared light. However, the software does not rely on the glint feature to detect the eye movement, therefore it can be used by user with eyeglasses as well.

The image processing flow will be briefly explained in the followings. First of all, the image captured from eye camera is converted to grayscale. An initial estimation of eye region is then made by the algorithm using center-surround feature. Contour features of the eyes are then found using edge detection and filtered based on intensity of neighboring pixel. The filtered contours are then split into sub-contours according to continuity of curvature. The pupil ellipse of user is then finally formed using ellipse fitting onto contours subset.

The detected pupil position is then mapped onto the scene captured by world camera using transfer function with two bivariate polynomials which the parameters are acquired in the calibration phase. There are several calibration methods readily available in Pupil Capture, however only “Screen Marker Calibration” (which will be discussed in further details later in evaluation part) was used throughout the evaluation to ensure the consistency of experiment.

3.3 Performance Evaluation

The method and steps used to evaluate this eye tracker follows Nierhoster, et al. (2020), which the accuracy, precision and robustness to hardware slippage of commercial eye trackers were being compared side by side in the same research. This is due to the credible results and data of commercial eye trackers obtained from the paper are easily available to be compared to our eye tracker. Therefore, the eye tracker built had gone through the same process of evaluation as well for the credibility of results. However, with some modification the data loss was not be evaluated as the only concerns are accuracy and precision in this project. Moreover, the fixation data was taken at the point when the gaze is fixated at the marker for a duration of time, instead of going through the recordings manually as the research did.

The eye tracker had been tested repeatedly six times to minimize the error of the evaluation. First of all, the experiment was conducted in a room where the light condition is low and with the windows covered or without a window, to minimize the interference on the image processing. The eye camera holder was adjusted to make sure it was capturing the entire pupil of the user and the headband was adjusted to make sure the world camera was heading towards the front of user as well.

The user sat approximately 0.3 m distant from 17-inch laptop monitor. The calibration session was made using “Screen Marker Calibration” that is built-in in Pupil Capture software. This calibration method uses a standard 5-point animated marker as shown in Figure 3.6. This calibration mode runs in full screen mode with the markers sampled in specific location one after another fixated by the user in for a short duration of 1.5 seconds accumulated to prevent multiple markers existing in the scene image at the same time. The gaze samples and marker’s position in scene image were collected by the algorithm to match and update polynomials parameters required.

In the calibration session, data that were lower than confidence level threshold of 0.80 were dismissed automatically by the software. The confidence level threshold indicates whether the detected ellipse could be defined as contour of pupil, the data sample is dismissed as no pupil was detected by the algorithm if lower than the threshold. The frame was adjusted and the calibration process was repeated until at least 30 % of data samples were accepted. The position of the frame and camera were fixed and the headband was tightened after the calibration.

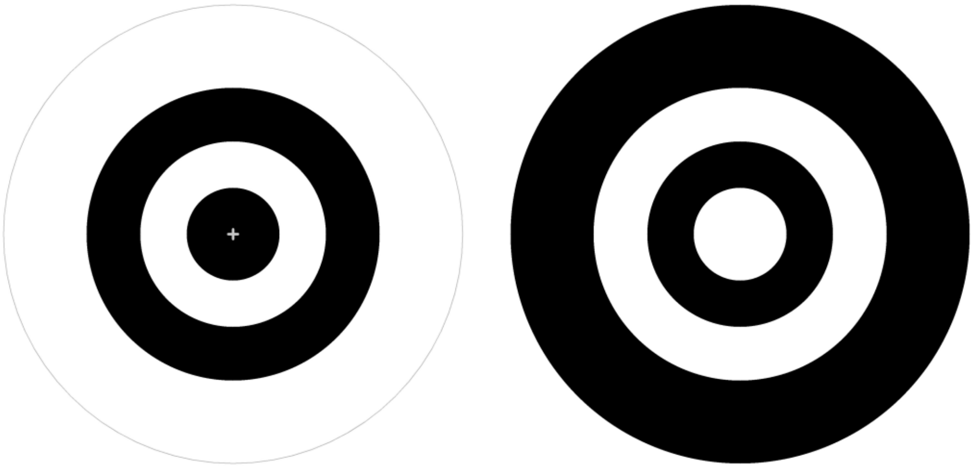

Figure 3-6: Pupil Standard Calibration Marker v1.2 Release

(Source: *https://pupil-labs.com/releases/core/v1.2/*)

Data regarding gaze of the participants had been recorded under eight conditions based on possible habitual behaviour of user when eye tracker is in use. The following steps shown in Figure 3-7 had been performed sequentially in the evaluation:

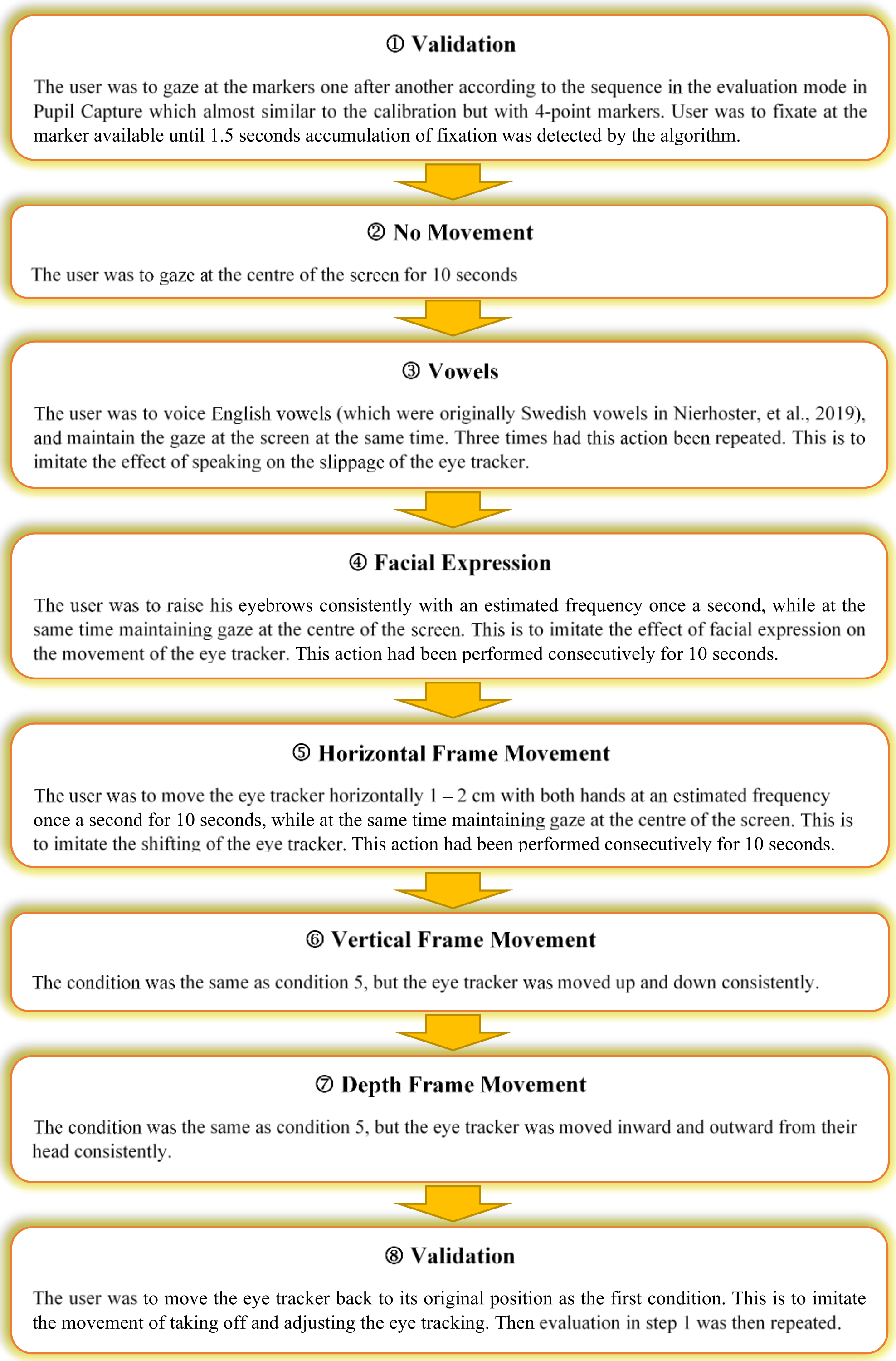

Figure 3-7: Flow Chart of Experiment

The process from calibration to the eight steps above was repeated for each of the samples taken. A total of six samples had been collected and the mean was taken to minimize the systematic and human error.

The steps from voicing vowels (3) to depth movement (7) were then undergone standalone evaluation for further investigation, which evaluation data were taken before and after each condition and the eye tracker would undergo calibration after evaluation on each condition ended. Three samples had collected for each condition and the mean was taken to minimize the error.

The data of minimal temporal distance between gaze point and its corresponding marker in the validation steps were recorded. Data with angular offset more than 10 degrees were considered as outliers and discarded as it most probably associates with human error such as blinking of eye or no fixation on the marker.

The angular offset, $\emptyset$ which indicates discrepancy between geometry position of marker on the grid that the user gaze and the position of fixation point that reported by the eye tracker, was obtained by the algorithm with the following equation:

$$\emptyset = \tan^{-1}\left(\frac{\sqrt{(x_m - x_e)^2 + (y_m - y_e)^2}}{d}\right) \tag{3.1}$$

Where,

(x_m, y_m) are geometry position of marker reported by the eye tracker on the captured scene in x and y axis,

(x_e, y_e) are geometry position of gaze reported by the eye tracker on the captured scene in x and y axis,

d is the distance between user and the calibration screen, which was fixed as 0.3 m in this case.

The samples of angular offset were then evaluated in regard of accuracy and precision (there was data loss in the original research as well). For a quantitative evaluation, the variables were defined into the following measurable factors.

(a) **Deviation** was used to calculate the accuracy. It is calculated as average of angular offset samples that obtained using Equation 3.1.

$$Deviation = \sum_{i=1}^{n} \frac{\emptyset_i}{n} \tag{3.2}$$

Where Σ denotes algebraic summation

(b) **RMS-S2S** will be used to calculate the precision. It is the root mean square of the sample-to-sample displacement between the consecutive fixation point that reported by the eye tracker.

$$RMS - S2S = \sqrt{\sum_{i=1}^{n} \frac{(\emptyset_{i-1} - \emptyset_i)^2}{n}} \tag{3.3}$$

The data were plotted against the time of beginning and finishing the experiment and compared to the results in existing research.

3.4 Summary

As a summary, a wearable eye tracker prototype had been built with monocular eye tracking which a camera tracking one side of the eyes and another tracking the scene that the user is looking. The frame of the wearable eye tracker had been built with 3D printed PLA to ensure that it is light and cheap. The IR illumination technique had been used in this prototype associated with open-source eye tracking software from Pupil Labs.

Testing of the prototype had been following the steps listed in Figure 3-7 which according to research of Nierhoster, et. al. (2020). The obtained data was then compared to commercial eye tracker evaluated in the research.

CHAPTER 4

RESULT AND DISCUSSION

Tests were conducted to validate the accuracy and precision of the wearable eye tracker prototype and results were plotted in Figure 4.1 and Figure 4.2 according to the data collected in Table 4.1 together with performance of commercial eye trackers evaluated in existing study (Nierhoster, et. al, 2020).

4.1 Comparison Between Prototype and Market Product

4.1.1 Comparison of Performance

Examining changes of deviation, Figure 4.1 has shown an increase of deviation which means lower accuracy from an initial average of 3.2536 ° to average of 3.6187 ° after the actions performed. Comparing to performance of commercial eye trackers evaluated in existing research, although the prototype in this project had shown approximately 1 ° higher deviation initially, the changes after the evaluation were rather flat than the slope of commercial products from Tobii, SMI and Pupil Labs with its own bundled software. This result is especially significant comparing Pupil-labs eye tracker that used the similar software.

The graph of precision has shown the similar result as well as it changed from initial average of 0.2075 ° to 0.2298 °. However, although the precision was lower than Pupil-labs eye tracker, its precision error had remained around range of 0.2 ° which appeared to better than most of the commercial eye trackers especially Tobii Pro Glasses 2 and Pupil Headset with EyeRecToo software, in both before and after evaluation.

As a result, both accuracy and precision of the prototype were only affected by 10 % from the slippage effect which was comparatively lower all the commercial eye tracker tested with its own software.

Nevertheless, it can be seen by the error bars that the eye tracker still had consistency issue as the variations were large in both factors comparing to commercial eye tracker. This might be due to movement of user's head during the calibration phase that causing the error in reference data as well as the inconsistency of distance between the user's head and target marker as it was not strictly restricted during the evaluation.

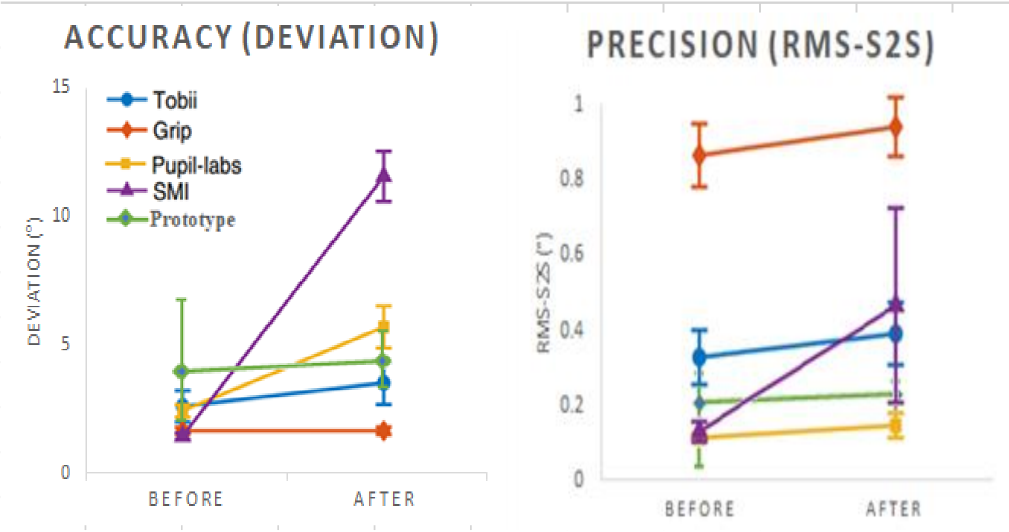

Figure 4-1: Accuracy and Precision Graph of Eye Trackers

(Prototype denotes the eye tracker that I have built in this project; Grip denotes Pupil Headset with EyeRecToo software instead of its own associated software (Nierhoster, et. al., 2020))

	Before		**After**	
	Accuracy (°)	**Precision (°)**	**Accuracy (°)**	**Precision (°)**
Sample 1	3.6937	0.1568	3.8437	0.1463
Sample 2	3.6414	0.2847	3.2831	0.1974
Sample 3	4.6412	0.2561	3.3348	0.2628
Sample 4	3.3099	0.0382	4.0647	0.2537
Sample 5	1.9254	0.2252	3.2590	0.2537
Sample 6	2.3100	0.2837	3.9271	0.2651
Mean	3.2536	0.2075	3.6187	0.2298

Table 4-1: Accuracy and Precision Data of The Prototype

4.1.2 Comparison of Cost and Weight

Materials used to fabricate the prototype has been listed in Table 4-2 with weight and cost shown. As comparison, weight and cost of commercial eye trackers evaluated in the research (Nierhoster et. al., 2020) has been shown in Table 4-3 as well.

Materials	**Weight (g)**	**Cost (RM)**
3D Printed Frame & Parts	38.02	2.92
Scene Camera	50	158.00
Eye Camera	50	158.00
IR LEDs	0.4	1.60
Fasteners & Wires	Negligible	7.96
Total	138.42	328.48

Table 4-2 Material List of The Prototype

Products	**Weight (g)**	**Price (RM)**
Tobii Pro Glasses 2	45	41645.00 (10 000 USD)
SMI Eye Tracking Glasses 2.0	47	49557.55 (11 000 USD)
Pupil Labs Headset	22.75 (only frame)	12150.12 (2490 €)

Table 4-3 Weight and Price of Commercial Eye Trackers

Contrary to expectations, the weight of the prototype was notably higher than both these products. It is possible to assume that the main limitation is on the cameras, as it can be seen in Figure 4- that the customized camera sensors used in these eye trackers are significantly smaller in size and hence lighter as well as the frames can be more compact and lesser materials are required. Further than that, it is possible to speculate by looking at Figure 4- that the required focus distance of their cameras is short as it can be located close to the eyes and thus further reduce the need for any extra extension arm like the prototype did.

Figure 4-2 Commercial Eye Trackers

(Starting from left: Tobii Pro Glasses 2, SMI Eye Tracking Glasses 2.0 and Pupil Headset)

However, it is worth noting that the cost of material for the prototype was remarkably lower with at least 40 times than Pupil Headset and 100 times cheaper than eye trackers from Tobii and SMI, while the performance can be compared to these commercial eye trackers especially in term of precision.

4.2 Comparison Between Activities

To further investigate the effect of each condition on the eye tracker for further improvement, standalone evaluation of actions from voicing vowels to depth movement of frame had been made. Table 4-4 has shown the data collected for this part of evaluation, while comparison of the effects has been plotted in graph and shown in Figure 4-3 and Figure 4-4 for better visual.

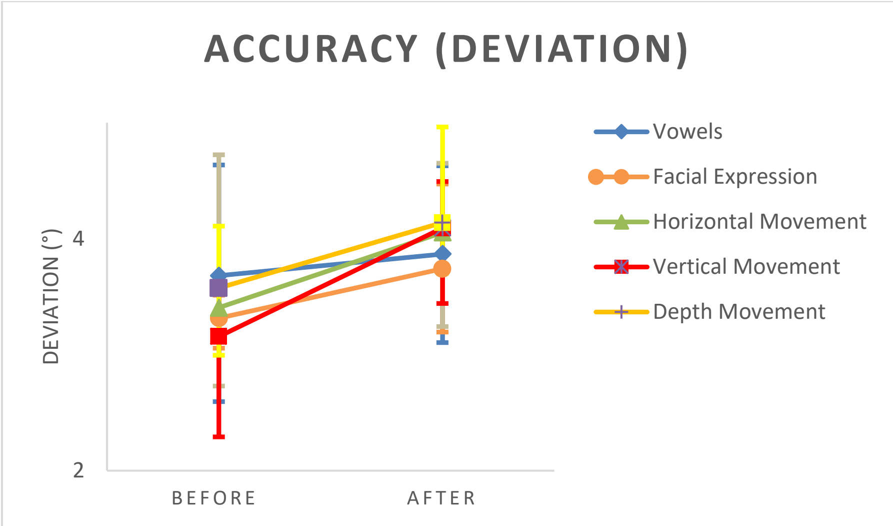

Figure 4-3: Accuracy Graph of Eye Tracker for Each Step

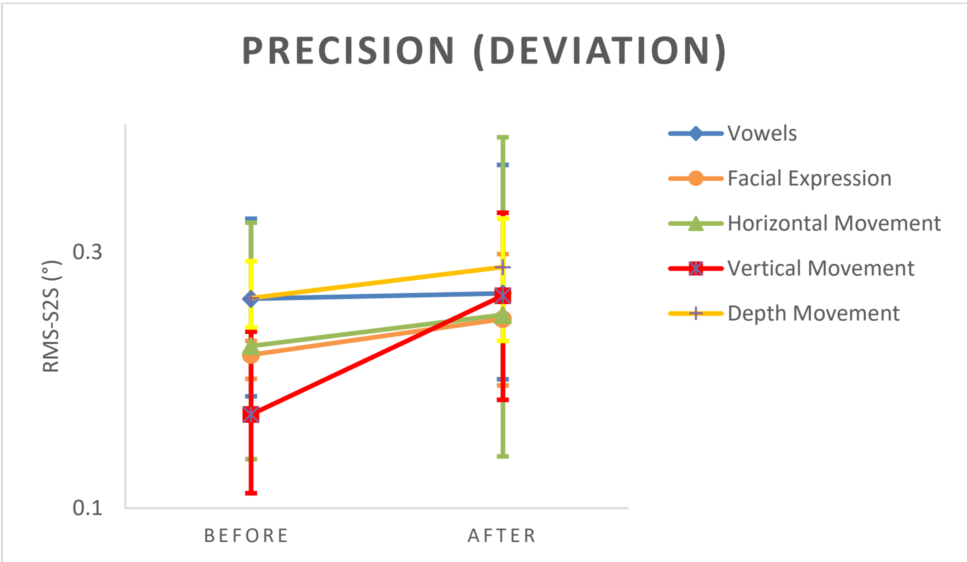

Figure 4-4: Precision Graph of Eye Tracker for Each Step

It can be seen that both conditions of movement had more critical effect on either accuracy or precision of the eye tracker. Furthermore, vertical movement had the steepest slope among them, indicating that the vertical movement had the most influence on the eye tracker with a reduction of 29.62 % in accuracy after this step is performed which other steps had only reduction below 20 %. This can be due to the reason no counter movement or restrain on the vertical movement, unlike the effect of headband on horizontal or depth movement. This can be a critical point to reinforce for further improvement of this eye tracker.

	Before		After	
	Accuracy (°)	**Precision (°)**	**Accuracy (°)**	**Precision (°)**
Vowels				
Sample 1	4.635486	0.187403	4.628042	0.200768
Sample 2	3.812694	0.277518	3.10432	0.234604
Sample 3	2.59548	0.326219	3.869333	0.3683
Mean	3.68122	0.263713	3.867232	0.267891
Facial Expression				
Sample 1	3.375914	0.230765	3.556883	0.248923
Sample 2	3.513128	0.201134	3.195	0.195955
Sample 3	3.056078	0.227896	4.471176	0.29858
Mean	3.31504	0.219932	3.74102	0.247819
Horizontal Movement				
Sample 1	4.723436	0.218752	4.65021	0.389929
Sample 2	2.729576	0.323186	4.266868	0.223131
Sample 3	2.763925	0.138294	3.242564	0.14045
Mean	3.405646	0.226744	4.053214	0.25117
Vertical Movement				
Sample 1	3.545379	0.237965	3.441394	0.242733
Sample 2	3.631947	0.1117	4.49274	0.144696
Sample 3	2.29132	0.169968	4.339778	0.2909
Mean	3.156215	0.173211	4.091304	0.22611
Depth Movement				
Sample 1	2.994998	0.241313	3.754784	0.308157
Sample 2	3.620933	0.258281	4.962779	0.230809
Sample 3	4.108019	0.293058	3.698617	0.326464
Mean	3.57465	0.264217	4.138727	0.288477

Table 4-4: Accuracy and Precision for Each Step

4.3 Summary

As a summary, the prototype was not able to achieve accuracy of 1 ° error, its resistance to slippage impact was significant compared to commercial eye trackers with only 10 % reduction in both accuracy and precision after the steps were performed while commercial eye trackers could have 30 % or more reduction in performance after the steps, which can be seen in Figure 4-1. The weight of the prototype can be part of further improvement as it is notably heavier than all of the evaluated commercial eye tracker. However, the result it is motivating as the specifications of the prototype can be compared to commercial eye trackers with a cost of hundred times lower. The second evaluation had also shown that the prototype is particularly vulnerable against the slippage effect in vertical direction with a reduction of 29.62 % after vertical movement of the frame had been conducted.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A wearable eye tracker was designed and built with an off-shelf camera module and a 3d printed frame associated with commercial open-source software – Pupil Capture. Its accuracy, precision and robustness against slippage and drifting were then tested using built-in evaluation algorithm of Pupil Capture. Although the performance of the prototype was generally lower than the commercial eye trackers and the required 1 ° of error was not achieved, the effect of slippage had been minimal with only 10 % of reduction in both accuracy and precision, which was significantly lower than other eye trackers.

The weight of the prototype however was much higher than the commercial eye tracker which possible due to the limitation of camera modules. The second experiment as well had shown that prototype was especially weak against slippage in the movement of z-direction.

Nevertheless, the performance and robustness against slippage effect of the prototype was significant consider that the cost was 100 times lower than the commercial eye trackers.

5.2 Problems

The built eye tracker showed improvement against slippage problem. However, it had some limitation as well. The effect of vertical movement on accuracy and precision evaluation was especially significant among the actions.

Other than that, although the difference between before and after evaluations is smaller compared to commercial eye tracker, the overall accuracy and precision of regardless of slippage effect is lower than most of the commercial eye trackers.

Moreover, data transmission of the camera is not reliable and convenient to use in practical case as it has to connect an USB cable to the computer, which might be easily disrupted by the user in practical application such as wheelchair controller.

Last but not least, as the size of the camera module was comparatively large and shape was not ideal, it had limited design of the eye tracker to be compact and hence the eye tracker prototype was bulk comparing to commercial eye tracker.

5.3 Recommendation

To solve the vertical movement limitation mentioned in problems and further improve the performance of the wearable eye tracker against slippage, one of the solutions is to extend additional parts from the frame in order to counter or limit the movement in z-direction. It can be either a support with nose pad on the nasal just like on safety glass, or an adjustable fixture that extend to the jaw of user.

The data loss problem can be solved by improving data processing ability of the hardware both in the camera module and the connected computer. Another improvement can be made by applying visible light filter on the camera sensor to reduce noise on IR images.

As the stability problem of the camera data transmission was due to the usage of USB cable, a better solution is to use wireless Bluetooth USB to replace the communication during practical application.

For the headset design to be more compact, the camera module is recommended to be as small as possible and the shape should be rectangular instead of square, hence can have better fitting on the frame. However, it is rare to have such shape in readily available camera module, thus it is suggested to customize the camera module for better overall design.

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APPENDICES

APPENDIX A: Figures

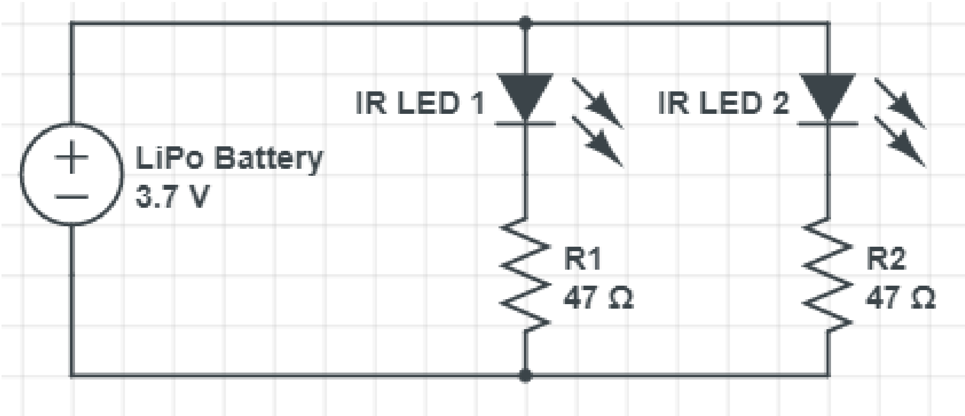
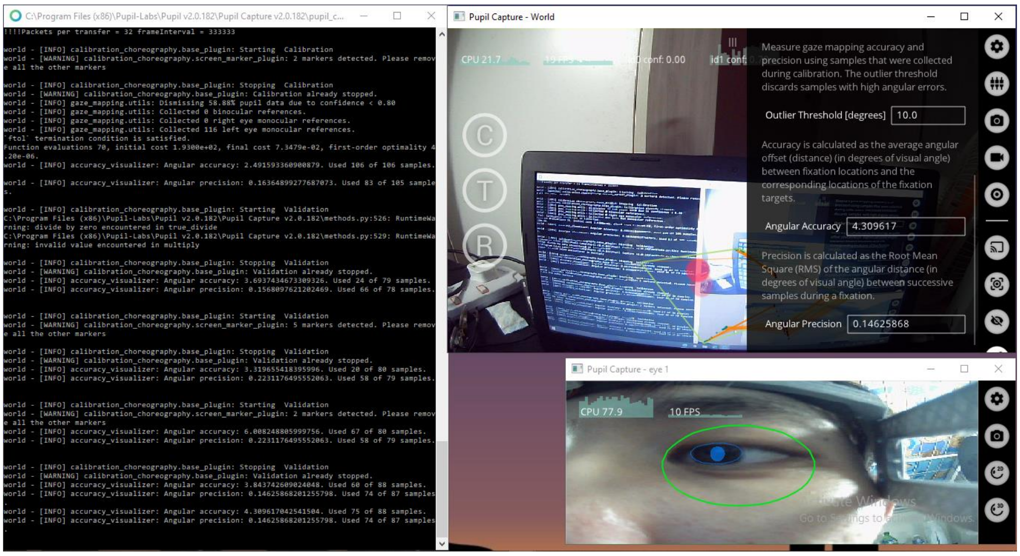


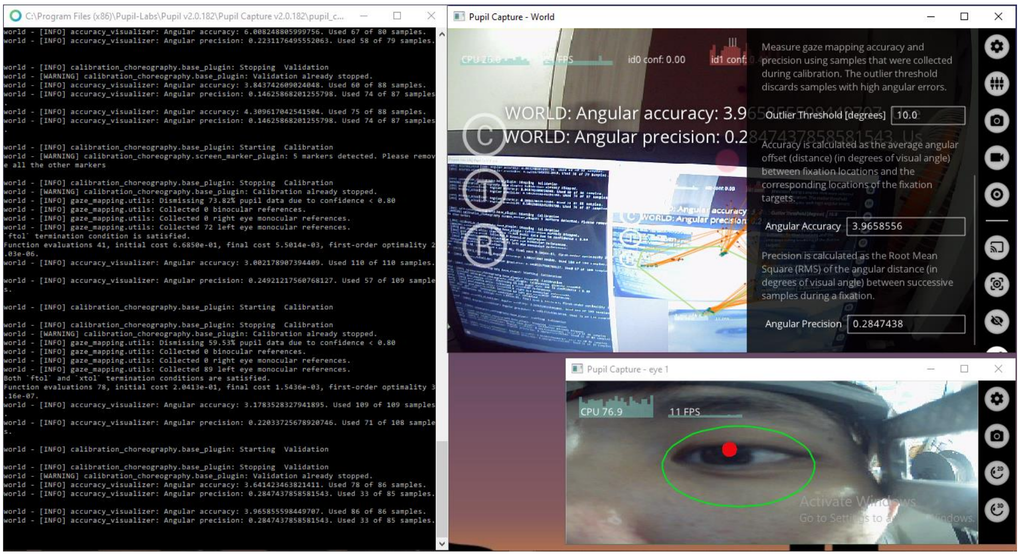
Figure A 1 Circuit Design of IR LED

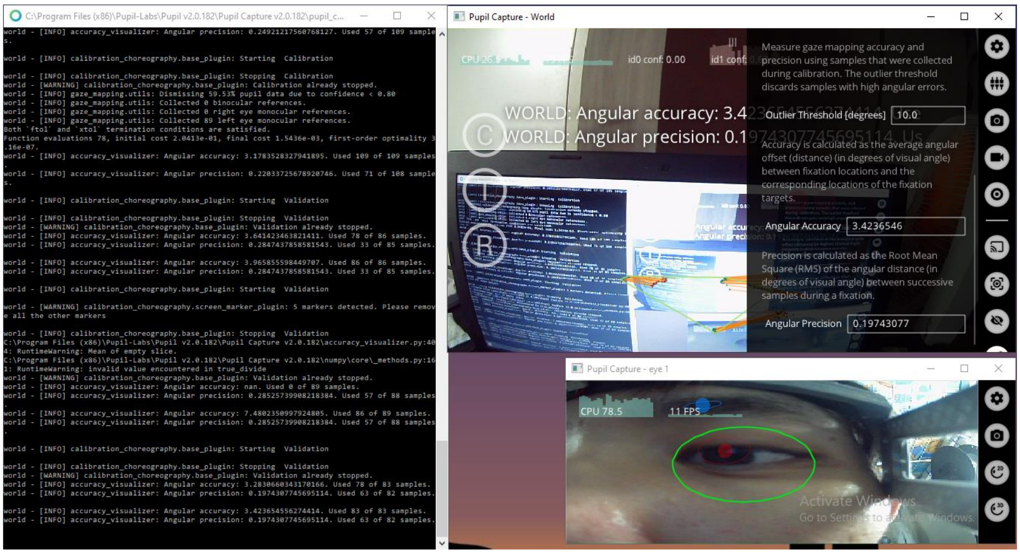
Figure A 2 Illumination of IR LED on Camera Arm

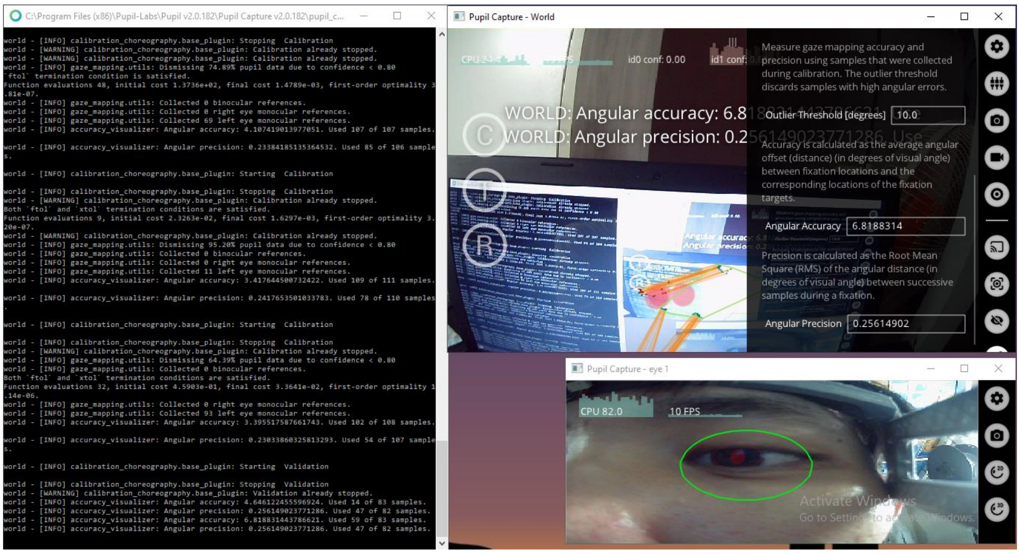
APPENDIX B: Evaluation Data

Figure B 1 Accuracy and Precision Data in Pupil Capture

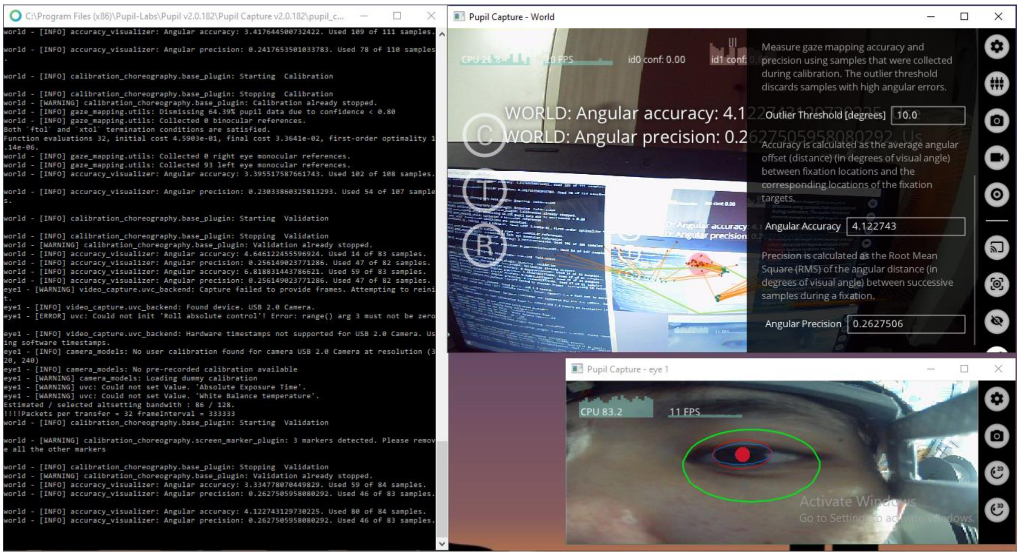

Pupil Capture - World
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees] 10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy 4.309617
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision 0.14625868
Pupil Capture - eye 1
CPU 77.9
10 FPS


Pupil Capture - World
Outlier Threshold [degrees] 10.0
Angular Accuracy 3.9658556
Angular Precision 0.2847438
Pupil Capture - eye 1
CPU 76.9
11 FPS

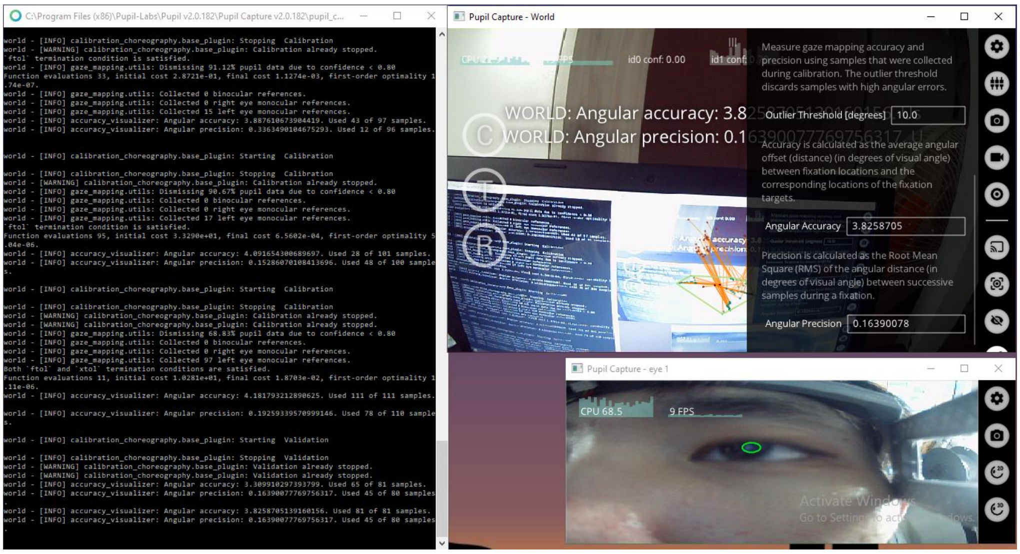

Pupil Capture - World
Outlier Threshold [degrees] 10.0
Angular Accuracy 3.4236546
Angular Precision 0.19743077
Pupil Capture - eye 1
CPU 78.5
11 FPS



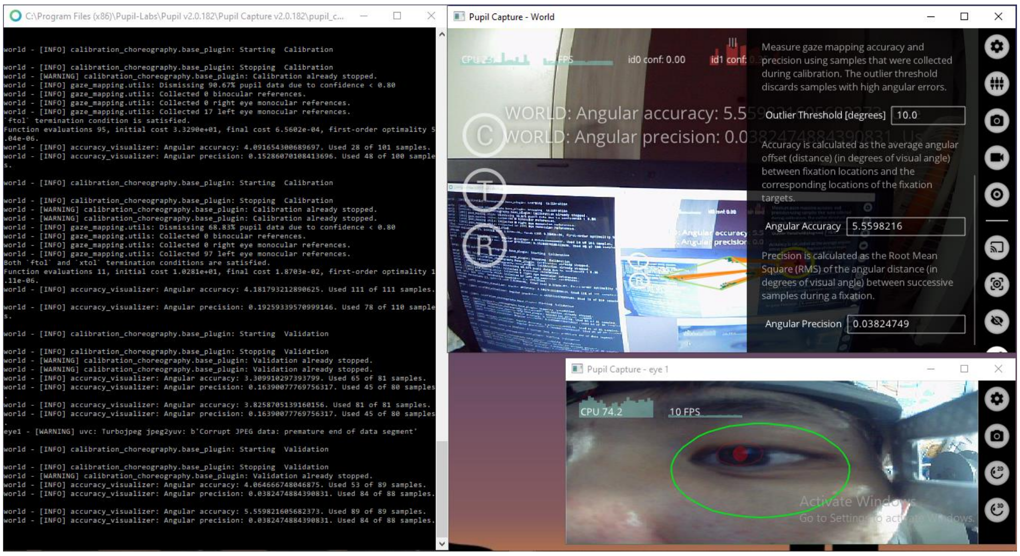
C:\Program Files (x86)\Pupil-Labs\Pupil v2.0.182\Pupil Capture v2.0.182\pupil_c...
Pupil Capture - World
WORLD: Angular accuracy: 6.8
WORLD: Angular precision: 0.2
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees]
10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy
6.8188314
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision
0.25614902
Pupil Capture - eye 1
CPU 82.0
10 FPS

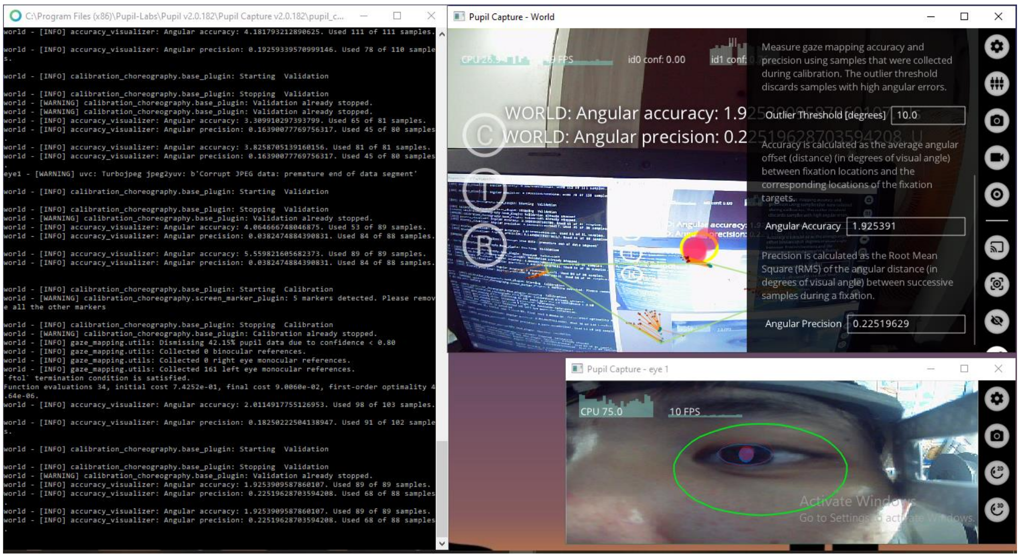


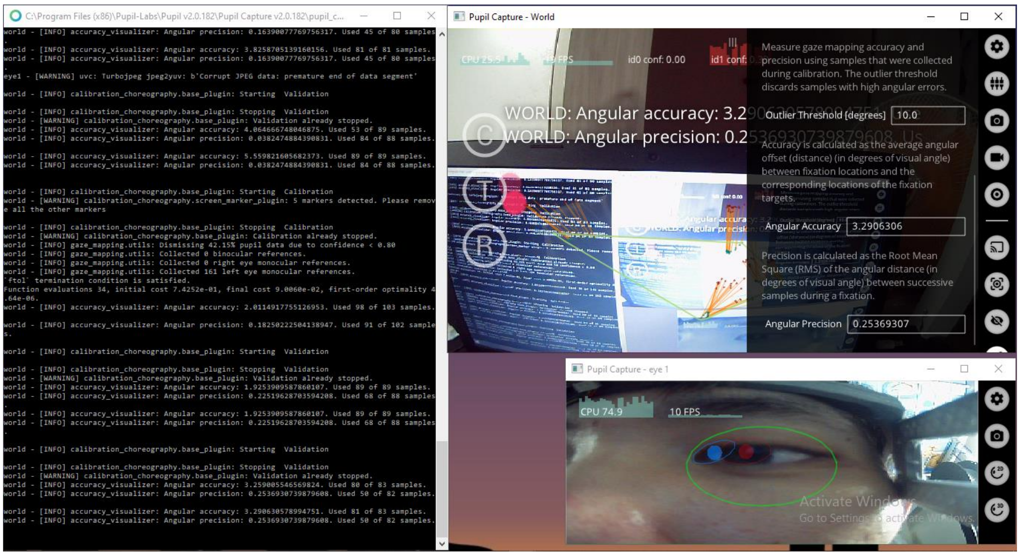
C:\Program Files (x86)\Pupil-Labs\Pupil v2.0.182\Pupil Capture v2.0.182\pupil_c...
Pupil Capture - World
WORLD: Angular accuracy: 4.1
WORLD: Angular precision: 0.2
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees]
10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy
4.122743
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision
0.2627506
Pupil Capture - eye 1
CPU 83.2
11 FPS

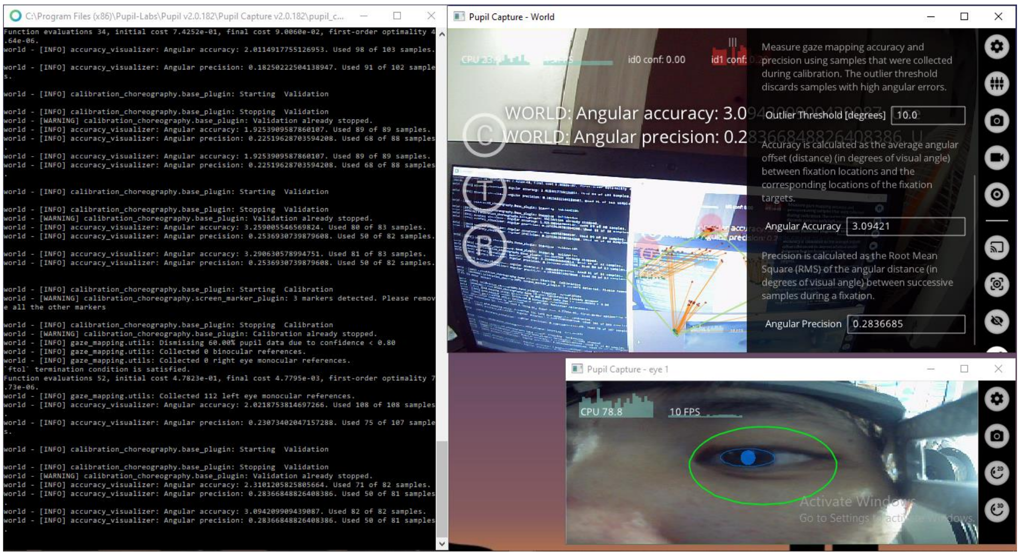


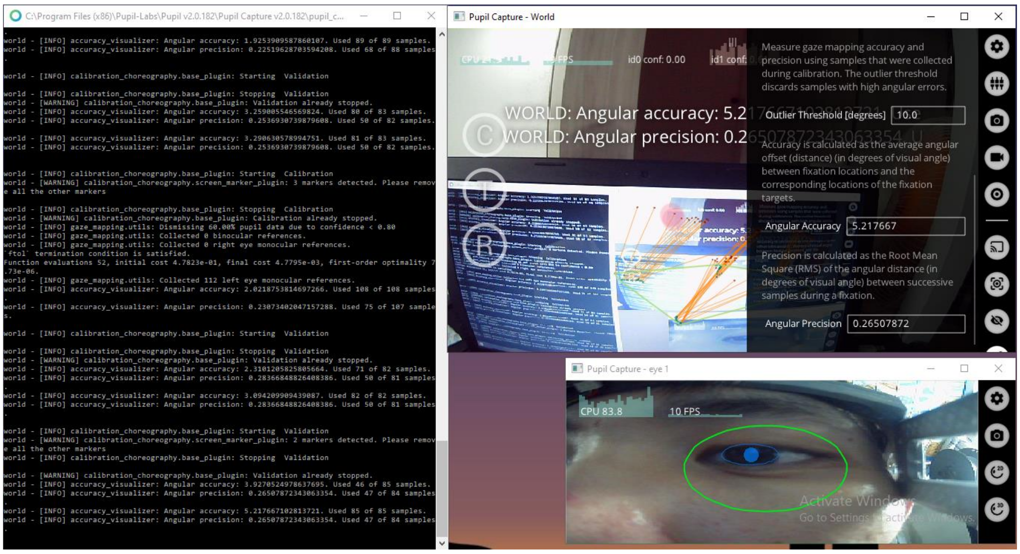
C:\Program Files (x86)\Pupil-Labs\Pupil v2.0.182\Pupil Capture v2.0.182\pupil_c...
Pupil Capture - World
WORLD: Angular accuracy: 3.8
WORLD: Angular precision: 0.1
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees]
10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy
3.8258705
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision
0.16390078
Pupil Capture - eye 1
CPU 68.5
9 FPS


Pupil Capture - World
WORLD: Angular accuracy: 5.5
WORLD: Angular precision: 0.0
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees] 10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy 5.5598216
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision 0.03824749
Pupil Capture - eye 1
CPU 74.2
10 FPS


Pupil Capture - World
WORLD: Angular accuracy: 1.9
WORLD: Angular precision: 0.2
Outlier Threshold [degrees] 10.0
Angular Accuracy 1.925391
Angular Precision 0.22519629
Pupil Capture - eye 1
CPU 75.0
10 FPS


Pupil Capture - World
WORLD: Angular accuracy: 3.2
WORLD: Angular precision: 0.2
Outlier Threshold [degrees] 10.0
Angular Accuracy 3.2906306
Angular Precision 0.25369307
Pupil Capture - eye 1
CPU 74.9
10 FPS


Pupil Capture - World
id0 conf: 0.00
WORLD: Angular accuracy: 3.0
WORLD: Angular precision: 0.2
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees] 10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy 3.09421
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision 0.2836685
Pupil Capture - eye 1
CPU 78.8
10 FPS


Pupil Capture - World
id0 conf: 0.00
WORLD: Angular accuracy: 5.2
WORLD: Angular precision: 0.2
Measure gaze mapping accuracy and precision using samples that were collected during calibration. The outlier threshold discards samples with high angular errors.
Outlier Threshold [degrees] 10.0
Accuracy is calculated as the average angular offset (distance) (in degrees of visual angle) between fixation locations and the corresponding locations of the fixation targets.
Angular Accuracy 5.217667
Precision is calculated as the Root Mean Square (RMS) of the angular distance (in degrees of visual angle) between successive samples during a fixation.
Angular Precision 0.26507872
Pupil Capture - eye 1
CPU 83.8
10 FPS