DEVELOPMENT OF A WEARABLE EYE TRACKER TO CONTROL AN AUTONOMOUS WHEELCHAIR

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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

In this study, a low-cost wearable eye-tracking system was developed to capture gaze information of the user and used to navigate an autonomous wheelchair. The eye-tracking system utilizes the video oculography method to record movements of the eye and to determine points of interest of the user. The development of this Human-computer-interface between the eye-tracker and the wheelchair would help people with severe motor disabilities to control the wheelchair and regain certain degrees of autonomy in locomotion. Existing research on low-cost wearable eye trackers lacks attention on the product design, which contributes to slippage effects and causes discomfort for the user. This study aims to redesign and optimize an existing eye-tracker developed the previous year by another student for greater cost efficiency, higher robustness, and to achieve deviation of angular accuracy within 1°. The prototype would be evaluated using the Pupil Capture software where parameters of accuracy, precision and data loss can be obtained. The developed eye-tracker is lighter and cheaper (69.5 gms and RM132.00) compared to an earlier model (138.4 gms and RM330.00). The deviation in angular accuracy and angular precision of the developed eye-tracker system was within the 1.5° to 2.5° range that was slightly higher than that of commercially available eye-trackers of within 1^o which costs more than RM10,000.00 each. However, further developments of the prototype are required for its intended application of controlling an autonomous wheelchair.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Eye-tracking is a sensor technology that measures pupil size, eye movement and eye position to detect points whereby the user has particular interest at a specific time. For example, measurement data such as eye rotation are typically detected by reflecting an infrared light from the eye and is sensed by a camera or specially designed optical sensor.

This technology is widely used and studied across various research fields and for several different applications in the commercial realm. Information obtained from other people's gazes can be helpful in a range of contexts, from medical diagnosis, psychological research, and many more. For instance, in the context of neuromarketing, researchers can understand the decision-making process by measuring how an individual's pupil reacts to different stimuli versus the outcome of the decision-making process. However, this study's primary focus is to use eye-tracking technology with an autonomous wheelchair to enhance human-computer interaction.

An eight-year follow-up study shows that older people's mobility problems increase the risk of developing depressive symptoms (Lampinen and Heikkinen, 2003). Furthermore, the gradual or sudden loss of mobility impacts a person's quality of life. The subject of interest in this study would be to develop and improvise wearable eye-tracker will be compared with an existing prototype, prototype v1 from Ong (2020). The intended use of the eye tracker would be to collect data as inputs for an autonomous wheelchair to form a human-computer interface (HCI). The HCI controlled wheelchair aims to allow an individual with severe motor disabilities to control a wheelchair by gaze, thus improving the user's quality of life.

1.2 Importance of the Study

This project is a subpart of the leading project to create an HCI integrated autonomous wheelchair that allows users with severe motor disabilities to communicate with and control the wheelchair by gaze. It may lay the foundation for improving the quality of life for individuals with severe motor disabilities. It is also a continuation of improvising an existing wearable eye tracker prototype and studying the HCI compatibility between the eye tracker and the autonomous wheelchair.

1.3 Problem Statement

For the HCI between the eye tracker and the autonomous wheelchair to be well synchronized and well-executed, the eye tracker system must be precise and accurate in detecting gaze for proper information collection as input data for the autonomous wheelchair. Most commercial eye-trackers available have prices that start from Rm 10,000 and beyond.

The previous wearable eye tracker prototype has certain flaws that need to be addressed, such as the frame design that is prone to slippage and has limited customizability for pupil detection. The key challenges here are improvising the existing eye tracker prototype in terms of compactness, comfort, and accuracy within a limited.

1.4 Aim and Objectives

Aim:

- To improve an existing eye-tracking prototype in terms of cost, accuracy and design.

Objectives:

- Redesign and optimize the eye-tracker for greater cost efficiency, higher robustness against hardware and input data slippage due to movements, and to achieve deviation of accuracy and precision of less than one degree.
- Collect data of accuracy and precision, compare it with the previous prototype and evaluate the feasibility of using the current eye tracker to control an autonomous wheelchair.

1.5 Scope and Limitation of the Study

Due to the limited budget allocated for the project and the lack of expertise in specific technology fields, there are limitations to the development of the eye tracker and the specific wheelchair navigation modalities. Due to the lack of expertise in augmented reality technology, the eye-tracker is limited to using 2-dimensional grids for gaze detection and determining the direction of wheelchair movements.

While the accuracy of the eye-tracking device and the user experience parameters such as comfort and robustness of design of the eye tracking frame will be the main focus of this research, there are certain limitations on hardware and material selection as the prototype developed adheres to a low-cost approach to ensure the affordability of the product.

1.6 Contribution of Study

As the current prototype is developed to use it as a controller to drive an autonomous wheelchair, the targeted users with severe motor disabilities may be prone to the involuntary head or facial movements. Therefore, this study addresses certain shortcomings of the previous prototype, prototype v1, fabricated in Ong (2020), which was not entirely to the slippage effect due to head movements and the lack of customizability of the eye camera angle.

This study was to design and fabricate an improved eye-tracking frame that compensates for shortcomings of the previous design, primarily the lack of customizability for the eye camera angle for optimal pupil detection. The cost efficiency and the accuracy of the eye tracker shall also be prioritized parameters throughout the study. The performance of the eye tracker will be tested according to similar experimental steps conducted by Nierhoster et al. (2020) as referenced in Ong (2020) for direct comparison of the performance of commercial eye trackers, prototype v1 and the current prototype.

1.7 Outline of Report

Chapter 1 of this report identifies the problem statement, aim and objective of this research. Chapter 2 reviews similar research on the working principles of eye-tracking, design approaches and methods. Chapter 3 discusses the design and fabrication process of the prototype, the gaze data acquisition process and the experimental method to evaluate the performance of the eye tracker quantitatively. Chapter 4 discusses the prototype's performance against different experimental tasks. The cost, design, and performance parameters of the current prototype will be compared to prototype v1 from Ong (2020) and commercial eye trackers. Lastly, Chapter 5 will present the conclusion on the outcome of this study and recommendations for improvements that can be made in further development.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Human-computer interaction is a multidisciplinary field of study focusing on designing the interactions and the relationships between humans and computers, HCI has expanded over the years to cover almost all forms of information technology design and no longer makes sense to regard HCI as a specialty of computer science ("Interaction Design Foundation," n.d.).

2.2 User-Centred Design

User-centered design (UCD) is an iterative design approach that revolves around improving the understanding of the user and task requirements, needs of the user are the focus during each phase of the design process. The UCD is the main approach that will be adapted throughout this study to develop the wearable eye tracker to ensure the usability of the product. There are generally four distinct phases involved in each iteration of the UCD approach, to effectively understand the user and their needs in all stages of designing and developing the product.

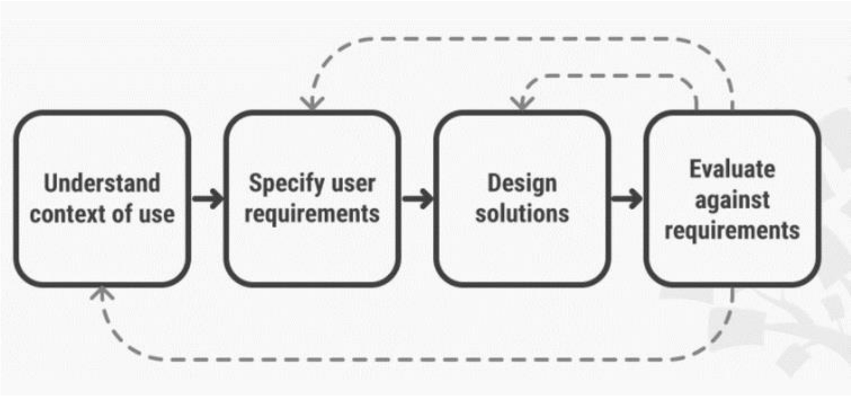

Figure 2-1: Flowchart for UCD approach (Source: Interaction Design Foundation, n.d.).

2.3 Eye tracking technology

2.3.1 Introduction

Eye-tracking is the process of determining the coordinates of the gaze of the user, with the device used to determine the position of the optical axis of the eyeball. Early use of the technology was mainly for psychophysics, cognitive development, and disease diagnosis. Over the past several decades there has been a huge increase in the quantity and variety of studies involving eye tracking technology. The rapid growth in this field is due to the development of an increasing number of software and hardware tools that allows both expert and novice users be involved in eye tracking research activities. Due to the development of deep learning in the field of machine vision throughout the last decade from year 2010 to 2020, it made the development of low-cost eye tracking devices possible (Ildar,2020). In recent years, eye-tracking is used to support multimedia learning and interaction, real-time graphic systems such as video games and in education research.

2.3.2 Eye Movement Measures and Applications

In general, eye movements consist of fixations and saccades while processing information or viewing scenes. Fixations are a relatively stable state of eye movement as defined by HCI and psychological studies, while saccades are rapid eye movements between consecutive fixations (Rayner, 2009). A person's visual perception typically consists of the foveal, parafoveal and peripheral vision. The fovea being the central area of the retina, the parafovea being the region surrounding the fovea and the periphery refers to the region outside the parafovea as shown in figure 2.2. To see things clearly, people often move their eyes to locate objects of interest in the region of highest visual resolution, the fovea (Liversedge et al, 2011) which is the basis of the eye-tracking approach.

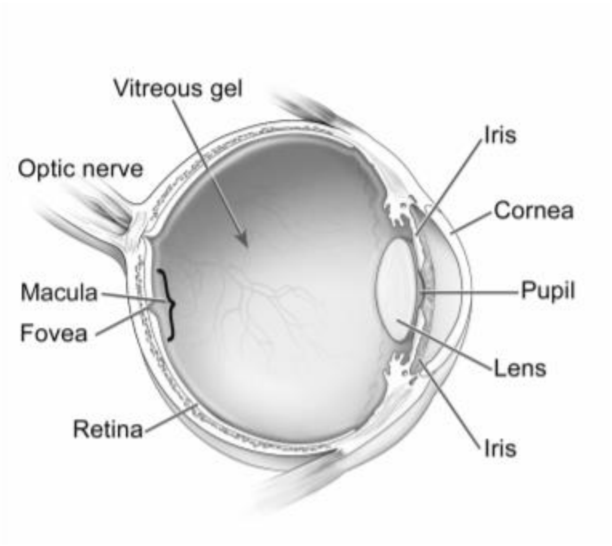

Figure 2-2: The anatomy of the human eye (Source: Dahlberg, 2010).

Eye movement research have shown that different perceptual spans and fixation spans of people indicates areas of interest that generates information that are not acquired during saccades (Duchowski, 2007). Rayner (2009) proposed that a fixation generally ranges from 100 to 500ms depending on the material of interest, while a 2-degree saccade usually lats about 30ms in a typical reading task, and a 5-degree saccade usually takes about 40-50ms. Both types of eye movements have been investigated in different areas of research, where fixations are used in studies that analyze peoples are of interest and attention while saccades are usually studied in sleep state research (Duchowski ,2003). The eye-tracking method is basically developed based on the characteristics of eye movements suggesting that fixations provide a dynamic projection of where a person’s attention is being directed. It is widely agreed that eye-movements and gaze can be measured to reveal the cognitive processes and information processing of an individual and thus is widely accepted as a viable communication mechanism for people with severe motor disabilities.

2.3.3 Eye Tracking Algorithm and Working Principles

Eye-tracking is the process of determining the coordinates of the gaze of the user, with the device used to determine the position of the optical axis of the eyeball (Ildar, 2020). In the past, there were huge numbers of eye tracking methods throughout the history of eye tracking technology, while most of these methods were capable in detecting eye movement, only one method of eye-tracking is still relevant currently and is widely used for commercial and research purposes – video oculography.

The most common distance eye-trackers uses Pupil Centre and Corneal Reflection (PCCR) method (Duchowski, 2003). Corneal reflection is detected where the eyes are exposed to direct invisible infrared (IR) light, which leads to the appearance of reflection in the cornea (Hari, 2012). While the pupil center method uses cameras and algorithms to detect the position of the pupil to determine the gaze position of the user, however the pupil center method on its own may also move in the eye-image when the eye translates due to head movement relative to the camera (Merchant, 1974). To compensate for the effects of inaccuracy due to small relative eye camera movements, the PCCR method is used whereby the pupil center and center of corneal reflection are measures and subtracted from each other (Hutchinson, 1989).

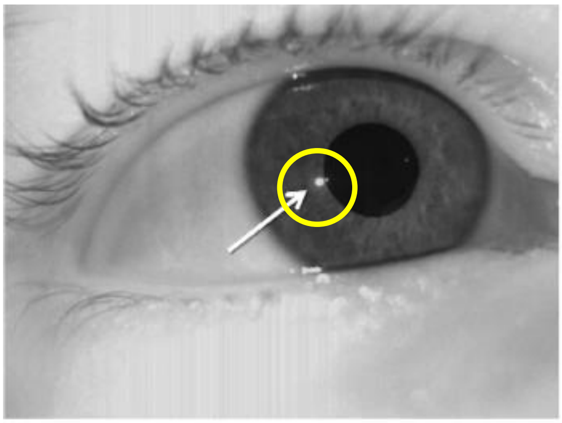

Figure 2-3: The bright white spot marked with a white arrow left of the pupil is the corneal reflection (glint) (Source: Hooge et al, 2016).

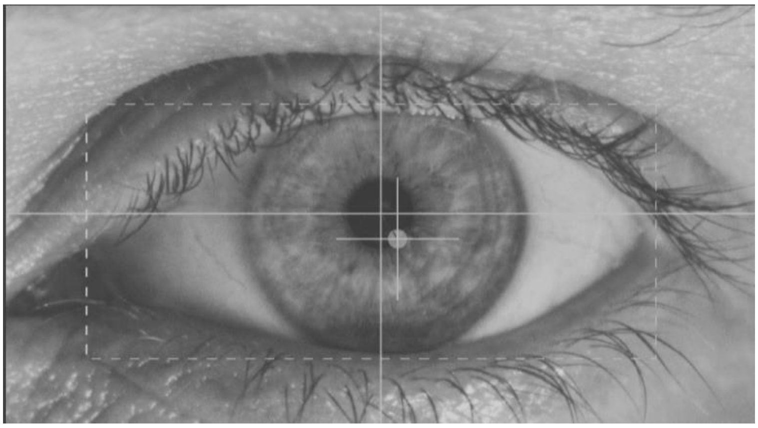

Figure 2-4: Pupil Centre detecting algorithm process (Source: Farnsworth, 2019).

By utilizing the PCCR method, the relative difference in location of the pupil center and corneal reflection allows for deduction of the gaze direction of the user. In commercial research involving the eye tracker, the pupil size is also analyzed as pupil dilations are results of strong emotion stimuli or working memory load, this allows researchers to deduce the thought process of the user.

2.3.4 Head Mounting Setups

The design of the head mounting setups for the eye tracker is crucial for user experience and is required to fulfill several criteria to become a viable product for the users. There are several approaches to choose a head mounting system such as a mask, customized frames, modified safety googles and so on, but the basic idea is to select a head mounting system that provides the best stability, preventing movements of the gears while in use, this is important to reduce the occurrence of gaze error due to slippage of the eye tracking device. A good head mounting system should be able to integrate and to hold the position of the electronic components of the eye tracking system (Makeroni, 2015).

With the bulk of the weight in modified cameras for the pupil image processing, a head mounting setup without proper counterweights is prone to rotation in the Z-axis and putting weight on the wearer’s nose (Kim et al, 2014), thus it is important that the chosen head mounting setup is compact, lightweight and sturdy without sacrificing the functionality of the eye tracker.

After comparing several approaches to the head mounting setup, it is decided that we would opt for the customized glasses frame setup that will be printed out using PLA filament. 3-D printing is a technology that can physically replicate concepts represented as digital data, it is proposed that the mechanical properties of 3-D printed frames are more favorable having comparatively high strength, customizable and is lighter in weight (Ayyildiz, 2018)

2.4 Autonomous Wheelchair Control Mechanism

Several studies have discussed the various methods and interfaces used as the control mechanism for a HCI controlled wheelchair. There are various existing devices and data acquisition methods for a HCI controlled wheelchair which includes bio-potential based methods which utilizes special instruments such as the Electrooculography, Voice based, motion based and Image analysis-based methods (Cerejo et al, 2015)

For this study, the image analysis method will be discussed as the eye tracker system utilizes the camera to analyze the user’s intentions and converts them into digital data. In general, the general process from data acquisition up to the movement command control is shown in Figure 2.5. The microcontroller is the heart of the system that controls the entire work of the system (Gupta et al, n.d) by analyzing and transforming the output signal from the image processing mechanism into control signals on the motor drive circuit of the wheelchair.

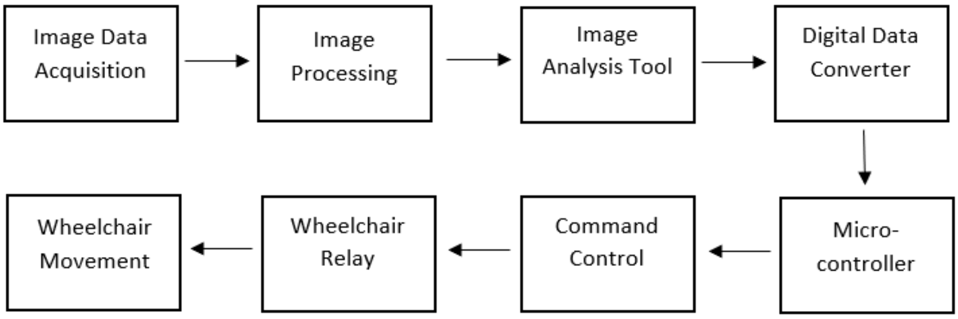

Figure 2-5: Flow of working system (Gupta et al, n.d).

Besides the integration of the microcontroller into the HCI system, it is also important that we select a proper command selection process and interface to ensure that the user will be able to control the wheelchair effectively using the eye tracker. The most basic command selection process is to have the users gaze to the corresponding command box for a certain timeframe (Meena et al, 2017). In fact, majority of research involving eye-controlled power wheelchairs implement gaze-based interfaces that uses gaze dwell time interactions to decide the Wheelchair motor controls (Singer,2018). For instance, in the command selection method proposed by Lin et al, 2006 known as the nine-zone selection method, the user is required to gaze at a command selection interface and by continuously gazing at the same area of interest for a prolonged period, the user will be able to increase the speed of the wheelchair by using a simple incremental programming sequence for counting and judgement of the user’s intention based on gaze time. The authors approach to control the wheelchair is rather simple yet effective.

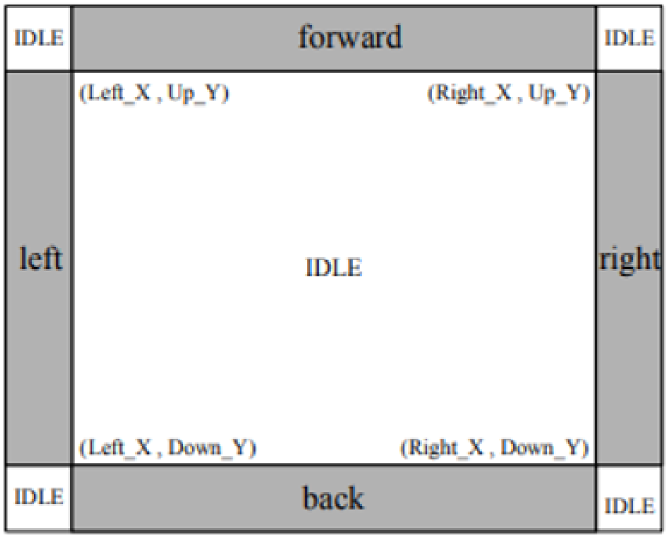

Figure 2-6: Nine command zones of eye control wheelchair (Source: Lin et al, 2006).

2.5 Related Work

Many papers discussed the concepts of Human-Computer interaction for various reasons from communication, evaluation, and medical purposes. Many Authors of several studies recognizes that eye movements are a significant gesture and have been used as a basis for their designs in various Human-computer interfaces.

The World Health Organization reports that approximately 2.4% of the entire population live with significant disabilities and requires a wheelchair to carry out daily activities, among them are individuals suffering from severe motor disabilities such as Amyotrophic lateral sclerosis (ALS) or tetraplegia that are unable to control their wheelchair using interfaces such as the joystick. As the need for wheelchair increases, extensive studies and efforts have been made throughout the years to develop suitable human computer interfaces and control mechanisms to help these individuals regain their autonomy.

Izzuddin et al (2015) proposed a system to detect movement intentions of the user using a Brain-computer interface whereby signals from the brain are extracted using Electroencephalography (EEG). A Brain-computer Interface mechanism for extracting the signals from the brain was proposed by Williams et al (2014) for non-vocal quadriplegics, through the use of software and an Emotive EEG headset, patients were able to utilize their system to control and click the mouse on the computer.

Vazquez et al (2011) developed a low-cost, high-performance eye-tracker as a communication system for people with motor disabilities based on voluntary ocular movements, their study also involved utilizing accelerometers to compensate for the low tolerance for head movements of eye trackers during that period. A study done by Lin et al (2006) similarly developed an eye-tracking system to control a powered wheelchair, the authors looked to control the wheelchair using the nine-zone method whereby when the user gazes at a specific distributed zone of the interface, the input command to control the wheelchair increases continuously and the control command is sent out. The direction and speed of the powered wheelchair will depend on the times of gazing at the command zone. In Mahmoud et al (2015) the authors proposed using an Arduino microcontroller and Bluetooth technology to facilitate the control of an eye-tracker controlled wheelchair.

Alshaer et al (2016) evaluates the effects of visual representation of input devices in a virtual power wheelchair simulator. Their study proposed that by providing suitable visual properties of a virtual input device based on real-world input devices such as a gaming joystick, it guides the user to control the wheelchair more efficiently. Next, Gupta et al, 2020 opted for the Raspberry pi as their microprocessor to control the entire system of the eye-controlled wheelchair. A noteworthy point is that in this study the authors utilized the Python ‘dlib’ library to process the image and detect the facial features and expressions of the user from the input image, which allows them to determine when the user is blinking. This is interesting as accurate detection of user’s blinking can be used as a control command input in future developments of an eye tracking HCI system. The authors also connected ultrasonic sensors to the Raspberry Pi to measure distances between the wheelchair and obstacles as a safety feature.

2.6 Summary

In summary, eye-tracking technology has been given increasing attention as an input method for HCI systems. Many previous studies have also used open-sourced eye-tracking software such as the Pupil Capture, as it is inefficient and difficult to develop similar software from scratch. Most researchers consider the IR illumination eye-tracking technique the most reliable method, which is compatible with the Pupil Capture software. However, researchers have not paid attention to design customized frames for their wearable eye trackers. Many studies have modified eyewear such as safety glasses and sunglasses into the eye-tracking frames; the modification approach would, in most cases, produce a prototype that is uncomfortable to wear and is prone to slippage effects.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The current price for commercial wearable eye-tracker available in the market is relatively expensive. For instance, pupil labs have a wearable eye-tracker priced at MYR 12000 while Tobii eye-trackers are priced between MYR 32000 to MYR 48000 (Farnsworth, 2019; Colaner, 2018). Furthermore, based on the data from the 1995 Current Population Survey, 38.3% of adults with severe work disabilities live in poverty (Batavia and Beaulaurier, 2001) while 42.2% of people with severe disabilities have incomes below the median income, it would be natural to assume that the commercially ready wearable eye-trackers mentioned above would be financially burdening. Thus, we must consider the cost of the product for the best interest of the user. This project would continue to improvise on a previously built low-cost wearable eye-tracker prototype, which cost MYR 328.48 to build and weighed 138.42g. In the following sections of this chapter, two main parts will be discussed, including the hardware and software used to construct the wearable eye-tracker and the components required to integrate the eye-tracker to control the autonomous wheelchair.

3.2 System Overview for Wearable Eye-Tracker

The main objective of the current project is to develop an eye tracker that seeks to compensate for shortcomings of the previous prototype that will be discussed in the following sections. As a general overview, the eye tracker would be a monocular eye tracker, which takes information from one eye of the user. An infrared light source will illuminate the user's eye, and the reflection of this light passing through the eyeball would be captured using a visible light filtered webcam camera. The gaze information acquired from the user would then be projected onto a computer screen for data processing and calibration purposes.

3.3 Hardware For Wearable Eye-Tracker

Hardware components that will be used to develop the wearable eye-tracker are listed below and will be discussed in detail following the sequence.

1. Webcam Camera
2. Head mounting structure
3. Camera Filter
4. Infrared LEDs

3.3.1 Camera Module

The cameras of the eye-tracker system are considered the most crucial piece of hardware in the system; a good camera is required to accurately and efficiently receive gaze information of the user to process these data to avoid severe lagging responses while controlling the wheelchair. It is notable that in this project, the monocular eye-tracking design would be used instead of the binocular method – as proposed by Hooge et al. (2018), it is sometimes better to use a single signal in eye-tracking systems based on the requirements and applications of the user, in this project, user experience of the end product is essential. Furthermore, a binocular eye-tracking system would mean additional weight for the eye-tracker and discomfort to the user due to the rotation of the product in the Z-axis caused by the additional weights of the camera.

Compared to the previous prototype that opted for the Sony IMX291 USD Camera Module, this study looks to reduce the weight and size of the overall device by utilizing customized camera modules. Two different camera modules were used as the eye camera and the world camera. The camera module used as the eye camera had a rated resolution of 2 Megapixels (MP), whereas the camera module used for the world camera had a rated resolution of 5 MP. While costing only approximately RM40 for the eye camera and RM80 for the world camera, both camera modules were technically capable enough to determine the user's gaze accurately. In addition, the camera modules were lighter, weighing only approximately 3g each and measured 60mm x 8mm x 1mm in dimension, whereas the Sony IMX291 in the previous prototype weighed 50g each. However, the downside of opting for the customized camera is that it is very challenging to modify the components of the camera module and usually requires specialized tools due to the size of the camera module.

Figure 3-1: Customized Camera Module

3.3.2 Customized Frame

While the eye tracker's head mounting device could be constructed in several ways, for instance, the do-it-yourself approach whereby researchers and hobbyists have tried modifying common safety googles to hold the eye-tracking components while using a strap or band to keep the google in place. However, the resulting mounting devices usually sacrifice certain design aspects to work, and some would be uncomfortable to wear daily. Therefore, the design aspects of the frame should include aspects of functionality, comfort and aesthetics. In addition, the frame should fulfil the following criteria (1) lightweight yet sturdy enough to withstand the weight of other components, (2) Resistant to slippage of components when in use, (3) comfortable to wear for long periods without causing any visual obstruction or discomfort to the user and finally (4) aesthetically user-friendly and straightforward.

The mainframe of the head mount is shown in Figure 3.2. The frame is designed to fit the user without causing any discomfort ergonomically. The nose bridge support is also for added comfort and stability. The frame's dimensions can be customized based on each user with just simple changes on the dimensions through Solidworks. The extruded compartment on the top of the frame is for placing the world camera, while the extended piece on the left side of the eye tracker would be the connecting arm for the eye camera. A ball joint is created at the end of the arm to assemble the mainframe and the eye camera holder.

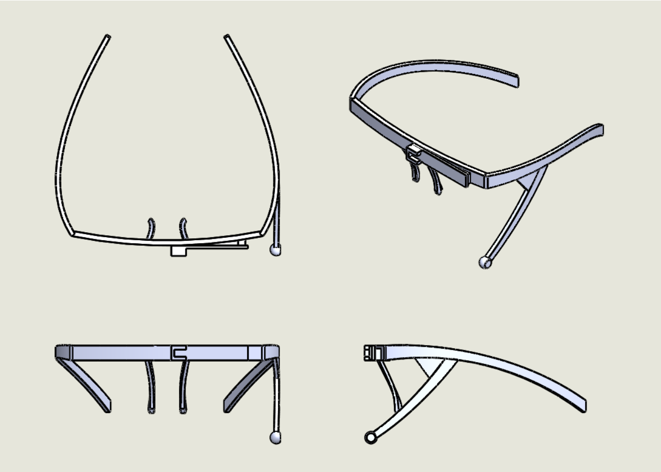

Figure 3-2: Orthogonal and isometric view of the main frame.

After the mainframe, the next step of the design would be to design the joint and the eye camera holder. Figure 3.3 shows the orthogonal and isometric view of the eye camera holder designed to hold the eye camera in place. Figure 3.4 shows the orthogonal and isometric view of the eye camera holder joint to connect the eye camera holder and the ball joint of the mainframe. Finally, figure 3.5 shows the Orthogonal and isometric view of the nut. It is important to note that the eye camera holder joint in Figure 3.4 was 3D printed using Thermoplastic Polyurethane (TPU) while the nuts were printed using Polylactic Acid (PLA) filaments. The TPU filament produces flexible prints, while the PLA filament produces rigid models. The reason for this design is to tighten the grip of the eye camera holder joint onto the ball joint of the mainframe as the nut is threaded further. This method allows the user to adjust manually and lock the eye camera once it has achieved the desired orientation.

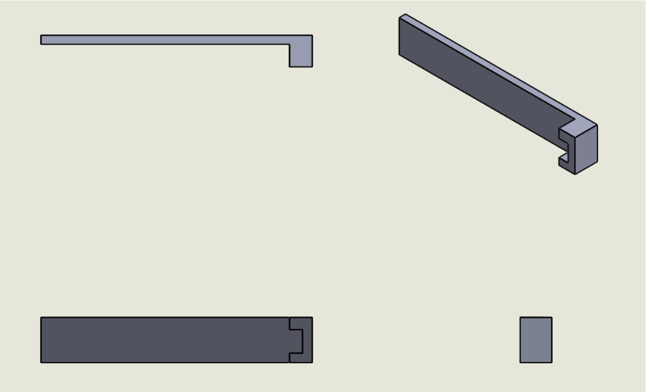

Figure 3-3: Orthogonal and isometric view of the eye camera holder

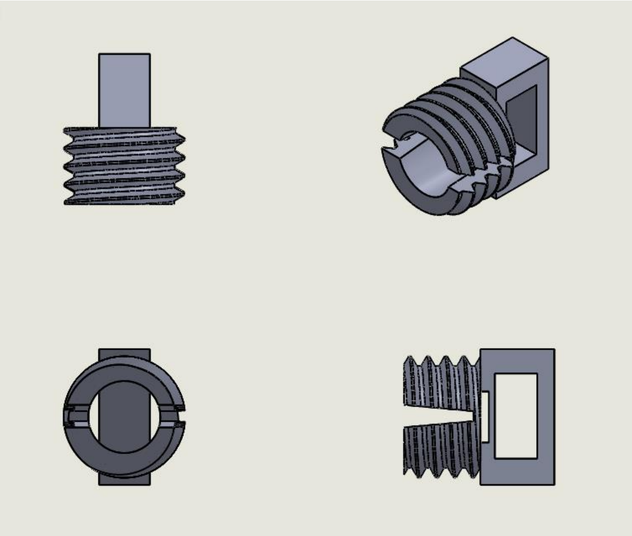

Figure 3-4: Orthogonal and isometric view of the eye camera holder joint

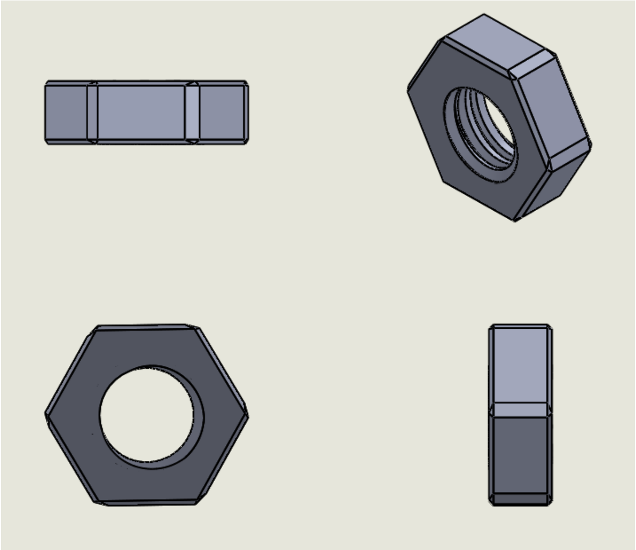

Figure 3-5: Orthogonal and isometric view of the camera holder joint nut

The final step of the frame would be to design the eye camera casing. Finally, the design frame and parts have been printed using Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU) filaments according to the functionalities and mechanical requirements of the respective parts. All the printed parts were printed with 100% infill to ensure maximum mechanical strength since most parts in the design are long and thin. The final 3D printed frame and parts weighed 63g and cost RM18.50. The final design for the customized frame is shown in Figure 3.6.

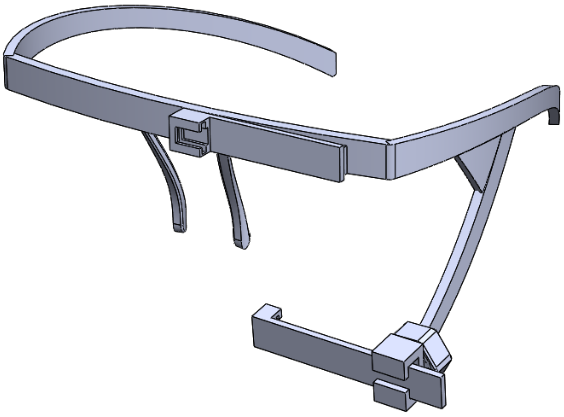

Figure 3-6: Assembly of customized frame and parts

3.3.3 Camera Filter

The camera modules come with an IR light filter that is attached initially to the camera. The manufacturer removed the IR light filter upon request. It would have been not easy to perform the modification without specialized tools. In addition, a filament of visible light filter will be added to the camera to reduce the interference of surrounding visible light during the eye-tracking process. Due to the size and complexity of the camera module, it is advised that this step is performed with caution to avoid any damage to the camera lens or electrical components.

3.3.4 Infrared LED

An infrared LED module will be positioned next to the eye camera. The IR light would illuminate the eye resulting in the configuration known as the Bright/dark-pupil illumination and corneal reflection in the eyes. The Visible light LED that comes initially with the camera module will be disabled not to cause interference during gaze detection. A voltage regulator will be used to drive the IR LED at the proper forward voltage.

On the other hand, it is of utmost importance that infrared light exposure on the user is within the safe range. Therefore, it is a critical design parameter for any video-based eye-tracker to monitor the level of infrared irradiance introduced to the eye. As the retina is insensitive to the energy in the near infrared, the users cannot rely on subjective reports of brightness to determine whether or not the IR irradiance is within the safe range. For chronic IR exposure in the 720 to 1400 nm range, irradiance levels less $10mW/cm^2$ than is considered safe (Sliney and Myron, 1980, ICNIRP, 2000), however an irradiance of below is well sufficient for the camera to detect gaze information, which is well below the recommended irradiance safety level of $10mW/cm^2$.

3.4 Software Gaze Detection

As the hardware components obtain raw gaze information from the user, a data processing algorithm or software is needed to use the raw image data captured by the eye cameras. Due to the low-cost nature of this project, the study would be using open-source software that is already available in the current eye-tracking community.

Among the vast choices of open-sourced eye-tracking software in the community, this project has shortlisted *Pupil Capture* as the software of choice. Pupil Capture is open-source software developed by Pupil Labs, a market leader in wearable eye-tracking technology. Pupil labs claimed that the open-sourced software Pupil Capture could compensate for hardware slippage and achieve accuracy and precision of up to 0.6 ° and 0.08 °. However, the results vary slightly as the Pupil capture was initially developed for Pupil Labs’ wearable eye tracker frame with much higher customizability and customized camera modules for eye tracking.

3.4.1 Gaze Detection Procedure

After launching the Pupil Capture software is a common problem for non-Pupil Lab hardware to have incompatible USB drivers. Hence the Pupil Capture software would not be able to detect the camera connected to the device initially. So first, download the compatible driver – libusbk 3.0.7.0, then download and install Zadig. Zadig is a software that allows the modification of USB drivers for hardware. After changing the device driver from WinUSB to libusbk v3.0.7.0, the Pupil Capture software should locate the webcam camera.

After successfully detecting both the eye and world camera, the calibration process is ready to go. The first step to the calibration process would be to check the pupil detection aspect. The eye camera should be in the correct orientation whereby it can capture good raw videos of the eyes, the design of the frame allows the user to adjust the eye cameras and tighten the ball joint physically to hold the eye camera in place. The pupil detection step is important moving down the calibration process, there would be a 'pupil confidence graph' at the top of the main window of Pupil Capture where 1.0 suggests high confidence pupil detection, and 0.0 = no confidence. The user should move their gaze around to ensure that the eye camera can detect the pupil's extreme movements. It is recommended that the setup achieve at least a 0.80 confidence value on average to ensure that the data collected is high quality.

Next, after the pupil is successfully detected, click the 'C' alphabet on the left side of the screen to enter calibration mode. The calibration process establishes a mapping from pupil to gaze coordinates. Ensure that the world camera has the whole screen in view. When the calibration process starts, screen markers appear, and the user shall follow the market on the screen with their eyes while trying to keep their head stationary. The calibration step can be done several times before moving on to the validation interface on the software, where markers would randomly appear on the screen, and the user would have to repeat the process of following the markers with their eyes. The accuracy and precision deviation of the eye-tracking setup will be displayed on the software log, whereby PupilLab claims that their eye trackers can achieve a deviation of less than one degree.

3.5 Experimental Method

3.5.1 Participants And Stimuli

Three volunteers between the age of 24 and 63 participated in the experiment. All participants had corrected-to-normal vision and none wore glasses. The experiment was conducted in a home environment due to restrictions during the MCO (Movement Control Order).

In a fluorescent tube lit room, participants will stand 0.6m away from a display screen. However, participants were positioned whereby the visible light from the fluorescent tubes would not cause directly visible light interference to the eye and world camera during the experiment. Participants were seated approximately 0.6m away from the display screen to ensure that the world camera captures clear images of the entire display screen. Only the left pupil of the participants was involved throughout the experiment due to the monocular design of the eye tracker.

For the data analysis method of the eye-tracking experiments, this project would be mainly focused on following the procedures as proposed in (Nierhoster et al., 2020). The participants were first required to calibrate the eye-tracker using the Pupil Labs' calibration interface in the Pupil Capture software by fixating on the center of the animated Calibration Markers. The participants will then be asked to use the validation process in the Pupil Capture software to get a second reading for the eye tracker. The calibration process consists of animated markers as seen in Figure 3.5 appearing on fixed positions on the screen, while the validation process consists of animated markers appearing on randomized positions on the screen.

Figure 3-7: Pupil Capture's calibration and validation markers

3.5.2 Procedure

Participants were then required to follow specific instructions to model facial and head movements during the eye-tracking process, each task would be repeated three times to increase the accuracy of the experiment, and the average of all participants in each repetition would form the value for each sample. Thus, for example, the data of Sample 1 would be the average value obtained by averaging the gaze information of all participants obtained during the first repetition of a task. The value of a sample is obtained from the following equation:

$$Sample\ x\ =\ \frac{a_x + b_x + c_x}{Number\ of\ participants} \tag{3.1}$$

Where,

x = Repetition count

a_x = Data obtained from participant 1

b_x = Data obtained from participant 2

c_x = Data obtained from participant 3

Task (1) to (8) is repeated three times each. Task (1) to (2) evaluates performance of the eye tracker without facial or head movement. Task (3) to (4) evaluates the eye tracker when experiencing facial movements. Task (5) and (6) evaluates the eye tracker when experiencing head movements.

1. **Calibration**

   Participants will be required to fixate at the center of each of all appearing calibration markers on the display screen until the end of the calibration process
2. **No movement**

   Participants will be required to fixate on the center of the calibration and validation markers without head movements.
3. **Vowels**

   In order to model hardware movement and slippage due to speech, participants will be instructed to recite the Vowels from A-Z while maintaining fixation at the central marker. The process is repeated twice.

4. **Facial expression**

   In order to model hardware movement and slippage due to facial expressions, participants will be required to raise their eyebrows repeatedly for approximately 10s at a frequency of approximately 2Hz while retaining gaze fixation at the marker.
5. **Horizontal eye-tracker movement**

   In order to imitate hardware movement and slippage due to horizontal head movement, the participants will be instructed to move their head in a nodding motion horizontally while performing the calibration for 10s at a rate of about 1 Hz.
6. **Vertical eye-tracker movement**

   Similar to the Horizontal eye-tracker movement experiment, however, participants are required to move their heads from left and right repetitively to mimic regular head movement.

Data samples with more than 10° angular deviation were considered outliers and discarded as it is most likely due to human error during the calibration process such as looking away from the calibration marker. Data acquired from the tracking interface will be analyzed and assessed in terms of accuracy, precision and data loss using the following mathematical functions:

(a) **Deviation** is used as an operationalization parameter to quantitatively evaluate accuracy. It is the median distance to the fixation target that was assigned the participant.

(b) **RMS-S2S** is used as an operationalization parameter to quantitatively evaluate precision. It is the root mean square of the sample-to sample displacement between successive fixation targets.

(c) **Data Loss** was operationalized as the number of missing samples expressed as a percentage of the number expected samples during a recording interval. The number of samples lost can be obtained from the PupilCapture world log whereby it states how many percentages of pupil data is being dismissed based on the confidence value.

The mathematical values above will indicate whether the wearable eye-tracker developed can be used for its intended application to accurately and precisely provide input signals to control the autonomous wheelchair

3.6 Summary

In summary, the monocular eye-tracking approach was chosen whereby the eye camera would be placed near the left pupil for pupil detection. The camera module chosen for the current prototype was much more compact than the Sony IMX291 used in prototype v1. However, modifications on the camera modules were much more challenging due to the size of the components.

The eyewear components for the eye tracker were also redesigned to fit the design criteria better. Most components of the eye tracker frame were 3-D printed with 100% infill PLA to ensure maximum strength due to the long and thin structure, while the eye camera holder joint that connects the mainframe and the eye camera holder was printed in TPU to allow selective tightening of the joint.

The performance of the eye tracker was then tested using the Pupil Capture software, which was an open-source eye-tracking software developed by Pupil Labs. A series of tasks were assigned to the participants in this experiment, according to Nierhoster et al. (2020), to evaluate the performance of the eye tracker. The performance data of the current prototype is then compared to the prototype v1 from Ong (2020).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Performance Of Prototype

The performance of the fabricated prototype is evaluated from the Pupil Capture calibration log. First, the results of calibration data without hardware slippage due to movements will be tabulated. Next, participants were instructed to perform a set of facial and head movements while undergoing the same calibration process. The results of the calibration were also tabulated. Finally, a discussion is done towards the end of subsection 4.1.

4.1.1 Calibration Results Without Slippage

After each calibration process, the deviation of angular accuracy and angular precision can be obtained from the Pupil Capture world log. Each participant had repeated the calibration process without slippage six times. Each Sample is the average value of data collected from all participants during the calibration process. For example, Sample 1 records the average value of gaze data collected from all participants during the first calibration process.

A baseline performance evaluation of the current prototype is shown in Table 4-1. It is seen that under calibration conditions without head or facial movements to create hardware slippage, the mean deviation of angular accuracy and angular precision for the current prototype is 1.6840° and 0.2159°, while the mean data loss during the calibration process is at 12.22%. The results obtained from this experiment will be used as reference values for upcoming experiments.

Table 4-1: Calibration Results for Samples Without Slippage.

Calibration Sample	**Deviation of Angular Accuracy (°)**	**Deviation of Angular Precision (°)**	**Data Loss (%)**
Sample 1	2.0578	0.2181	0
Sample 2	1.3856	0.1856	20.47
Sample 3	1.2784	0.2587	18.65
Sample 4	1.3582	0.2357	5.43
Sample 5	1.8963	0.2215	13.25
Sample 6	2.1275	0.1756	15.57
Mean value	**1.6840**	**0.2159**	**12.22**

4.1.2 Calibration Results with Movement Tasks

As discussed in Chapter 3 under experimental methods, the calibration results shown in Table 4.1.2 are when the participant was instructed to perform a set of facial movements, and Table 4.1.3 are when participants were instructed to perform tasks involving head movements.

Each participant was instructed to repeat each task 3 times. The experimental values before and after each task were recorded. The value of each Sample represents the average value of all participants during the corresponding repetition. For example, Sample 2 represents the average value of all participants during the second repetition of a task.

Table 4-2: Calibration Results with Facial Movements.

	Deviation of angular accuracy (°)	**Deviation of angular precision (°)**	**Data loss (%)**
Vowels: Before			
Sample 1	1.4329	0.1974	8.24
Sample 2	1.8538	0.2032	7.25
Sample 3	1.9033	0.2134	0
Mean	**1.7300**	**0.2057**	**5.16**
Vowels: After			
Sample 1	1.5356	0.2230	11.34
Sample 2	1.9451	0.2155	9.34
Sample 3	2.2564	0.2455	5.34
Mean	**1.9124**	**0.2280**	**8.67**
Facial Expressions: Before			
Sample 1	1.5070	0.2045	14.35
Sample 2	2.0156	0.1745	0
Sample 3	1.8793	0.2110	13.37
Mean	**1.8006**	**0.1967**	**9.24**
Facial Expressions: After			
Sample 1	1.5476	0.2087	14.91
Sample 2	2.1045	0.1884	4.31
Sample 3	2.0351	0.2039	15.76
Mean	**1.8957**	**0.2003**	**11.66**

Table 4-3: Calibration Results with Head Movements.

	Deviation of angular accuracy (°)	**Deviation of angular precision (°)**	**Data loss (%)**
Horizontal movements: Before			
Sample 1	2.0256	0.1987	13.56
Sample 2	1.5512	0.2014	5.33
Sample 3	1.4572	0.1894	5.76
Mean	**1.678**	**0.1965**	**8.22**
Horizontal movements: After			
Sample 1	2.4578	0.2351	22.47
Sample 2	2.3145	0.2455	17.98
Sample 3	1.9987	0.1956	13.44
Mean	**2.257**	**0.2254**	**17.96**
Vertical movements: Before			
Sample 1	2.1298	0.2242	11.39
Sample 2	1.9087	0.2091	8.56
Sample 3	1.9951	0.1567	0
Mean	**2.0112**	**0.1967**	**6.65**
Vertical movements: After			
Sample 1	2.6654	0.2569	27.65
Sample 2	2.4535	0.2776	24.51
Sample 3	2.8765	0.2897	19.34
Mean	**2.6651**	**0.2747**	**23.83**

4.1.3 Discussion On Eye Tracking Performance

As shown in Table 4.1.4, the eye-tracker prototype is quite resistant to slippages caused by facial movements. The deviation of angular accuracy and precision is within 0.3°, while the difference for the mean value of data loss percentage before and after the tasks were less than 5%.

However, the eye tracker is more sensitive to horizontal and vertical head movements. While the difference in deviation of accuracy and precision is more significant than those caused by facial expressions, the data loss due to head movements has primarily increased. The data loss due to horizontal head movements increased to 17.96% from 8.22%, whereas data loss due to vertical head movement has the most significant difference as it increased to 23.83% from 6.65%.

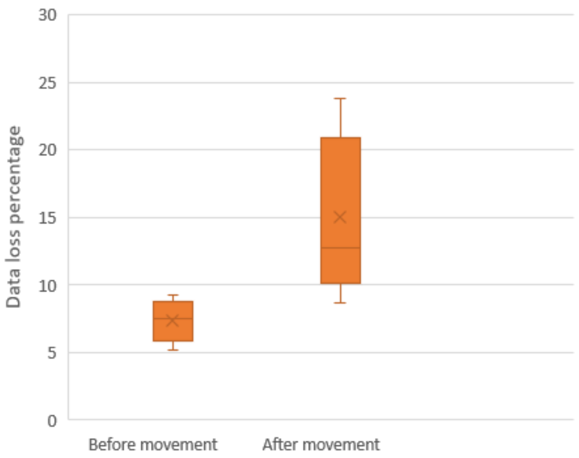

Figure 4-1: Data Loss Percentage of Calibration Before And After Movement.

From the feedback of participants and the video recordings of the experiment, it is believed that the increase in data loss was not due to hardware slippage. Although the design of the head mounting frame was quite resistant to slippage from both facial and head movements, the components of the eye-trackers were also tightly fit in place. Therefore, it is deduced that the loss of data is due to:

1. the movement of the world camera away from the calibration markers,
2. the world camera comes with a built-in auto-focus function, and breaking its focus due to head movements might cause the image to

blur for a short instance, creating a disturbance when calibrating the eye camera and the world camera,

3. In vertical movements, the pupil moves in the left and right direction to focus on the marker.

Moreover, it was seen in the recording that at specific positions of the pupil, the confidence value of pupil detection drops below 0.80, causing a loss of data. Likely, the orientation of the eye camera is not in the optimized state during the experiment.

Table 4-4: Results of Prototype for Movement Tasks.

	Deviation of angular accuracy (°)		Deviation of angular precision (°)		Data loss (%)	
Facial movements						
	Before	After	Before	After	Before	After
Vowels	1.7300	1.9124	0.2057	0.2280	5.16	8.67
Facial Expressions	1.8006	1.8957	0.1967	0.2003	9.24	11.66
Head movements						
	Before	After	Before	After	Before	After
Horizontal	1.678	2.257	0.1965	0.2254	8.22	17.96
Vertical	2.0112	2.6651	0.1967	0.2747	6.65	23.83
Averaged deviation due to slippage						
	Before	After	Before	After	Before	After
Mean	1.7362	2.0217	0.1996	0.2179	7.54	12.76

4.2 Performance Comparison

The data collected from the experiments using the current prototype, labelled prototype v2, is compared to a previous prototype of the low-cost eye tracker developed in the study of Ong (2020), which would be labelled prototype v1. It is seen that the current prototype has achieved constantly lower degrees of deviation in both accuracy and precision. However, after the movement tasks, both prototypes have shown higher deviation values of accuracy and precision.

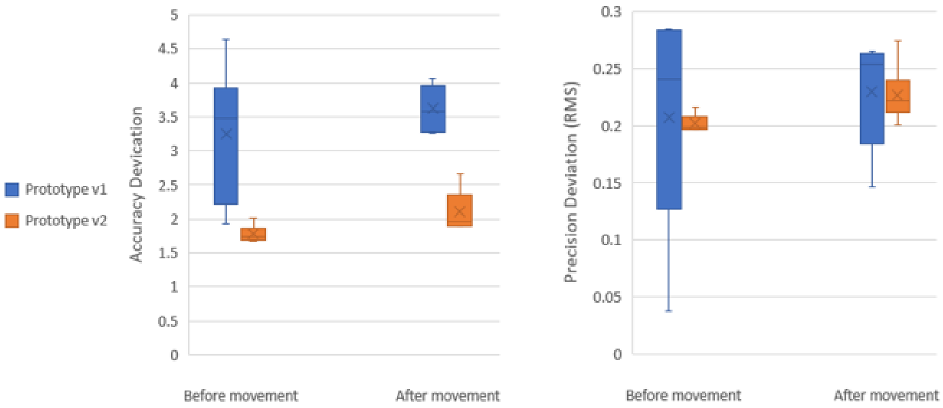

Figure 4-2: Accuracy and Precision Deviation Graph Between Prototype V1 And V1.

4.3 Weight and Cost Comparison

The components used to assemble the final design of the low-cost eye tracker is listed in Table 4-3 with the weight and costs of respective materials. In addition, a comparison is made between the current eye tracker prototype, Prototype v2, with the previous prototype, prototype v1 and a few well-known commercial eye trackers.

Table 4-5: Component List of Low-Cost Eye Tracker.

Components	**Weight (g)**	**Cost (RM)**
3D Printed components	59.50	18.50
World Camera (5MP camera module)	5.00	80.00
Eye Camera (2MP camera module)	3.00	32.50
IR Led Module	2.00	1.00
Total	**69.5**	**132**

Table 4-6: Comparison Table with Various Eye Trackers.

Product	**Weight (g)**	**Price (RM)**
Tobii Pro Glasses 2	45	41645
SMI Eye tracking Glasses 2.0	47	49557
Pupil Labs headset	22.75 (only frame)	12150
Prototype v1	138.42	330

As compared to prototype v1 (previous prototype), the current prototype v2 (prototype fabricated in this study) has reduced in weight by approximately 50% Moreover, cost approximately 60% lesser. The cost reduction is due to the choice of the camera module. The Sony IMX298 camera module used in the prototype v1 weighed approximately 50g each. On the other hand, most of the weight on prototype v2 comes from the 3D printed frame and parts, which contributes 59.5g or about 85% of the total weight. The parts were printed with 100% infill for maximum mechanical strength to ensure long and thin parts would not break when stressed. However, it is possible to print only certain parts with 100% infill and the majority of the parts with 40-50% infill, which would reduce the weight by approximately 40%. Therefore, the current prototype is technically able to achieve commercial eye tracker class weight within the 40-50g range but is recommended to stick to the current 100% infill as 30g is negligible in practice as the force is evenly distributed on the nose and ears.

4.4 Design Changes Since Prototype V1

Several design changes were made since prototype v1. The design of the eye tracker’s frame for prototype v1 is shown in Figure 4.3 while the side. The current prototype designed has an added nose bridge support for extra comfort and to prevent hardware slippage in the Z-axis direction that was prevalent in prototype v1. The reduction of slippage has contributed to lower deviation on accuracy and precision.

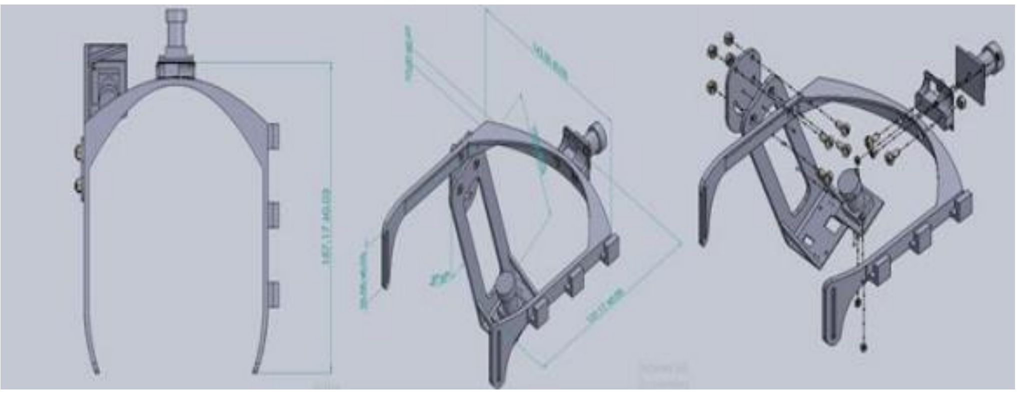

Figure 4-3: Different Views of the Frame Design of Prototype V1.

(Source: Ong, 2020)

The frame in prototype v1 required a strap or band to keep the eye-tracker in place, while the frame in prototype v2 was measured meticulously to ensure that the curvatures of the frame would ‘hug’ well around the head and comfortably sit on the ears. As a result, the slight pressure on the left and right sides of the head due to the frame’s ‘hugging’ is very minimal and negligible.

The last significant change to the design would be the standard method to hold the eye camera away from the eye. The side view of Prototype v1 is shown in Figure 4-4. Prototype v1 incorporates an extended arm with limited customizability to find the desired eye camera angle for pupil detection. The extended arm was only limited to adjustment in a predefined setting as shown in Figure 4.4. Furthermore, the angle of the eye camera was limited to a fixed setting. This problem was addressed using the ball joint method with the female joint printed in TPU filament. The joint printed in TPU would be tightened with a tightening nut when the eye camera is set to the desired angle. The only setback is that the arm extension that holds the eye camera cannot be further extended. However, this could be solved by personalized customization of the 3-D printed frame for each user. Furthermore, the current prototype does not require additional metal nuts and bolts for the assembly process. Figure 4.5 is an isometric view of the 3-D printed product. For a detailed picture of the design changes, refer to Figures 3.2, 3.3, 3.4 and the appendix for the images of the current design for prototype v2.

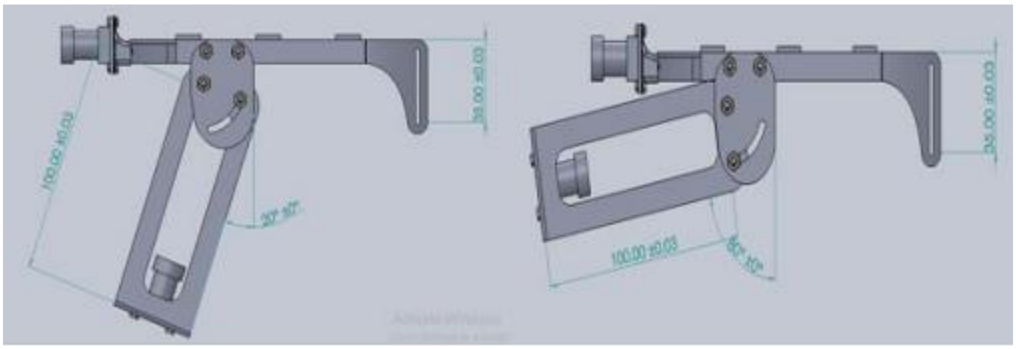

Figure 4-4: Side View of the Frame Design of Prototype V1.

(Source: Ong, 2020)

Figure 4-5: Isometric View of 3-D Printed Frame of Prototype V2

4.5 Limitations And Implications of The Developed Prototype To The Intended Application

The prototype was intended to be a control device for an autonomous wheelchair. While the prototype has achieved several improvements in various aspects since the previous research, the current prototype is not sufficiently reliable as a control device for the wheelchair. This design has several limitations that need to be addressed before it becomes a viable product for commercial use. While the average deviation in angular accuracy and angular precision is lower than the previous prototype, it is still not within the range of a commercial eye tracker.

There are instances where the confidence level of pupil detection falls below 0.80 during certain gaze positions. This design challenge must first be diffused to ensure that the gaze information is accurate at all pupil positions. Incorrect gaze data would be troublesome for users with severe motor disabilities as unwanted wheelchair movements can potentially lead to injury.

4.6 Summary

In summary, the current prototype was not able to achieve deviation of angular accuracy within 1°. However, the mean deviation angular accuracy and angular precision was decreased by about 30% since prototype v1 and is currently much more resistant to hardware slippage due to movement. The deviation and data loss during the calibration process is most likely due to the lack of confidence value during pupil detection at some point during gaze movement. For example, as the pupil moves towards a certain angle and position, the eye camera might have difficulties getting a clear image of the pupil, which affects the software algorithm's ability to detect the pupil. The root cause of this phenomenon is most likely the orientation of the eye camera.

The more glaring advantage of the current prototype would be the design changes and cost efficiency of components. The design has addressed the previous design flaws as mentioned in the problem statement and in elaborated in Section 4.4 regarding the design changes since prototype v1. The weight and cost of the prototype were reduced to 69.5gms and RM132.00 as compared to the previous prototype that weighed 138.4gms and RM330.00, while maintaining consistent deviations in accuracy and precision. The outcomes of the prototype were also comparable to several commercial eye trackers; however, further improvements are needed for the prototype to be used as a control device for an autonomous wheelchair. For instance, commercial eye trackers are equipped with accelerometers to compensate for head movements. Lastly, further development is needed to improvise the design for more customizability of the position of the eye camera to ensure that the pupil is constantly detected with high confidence.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the research objective has been fulfilled as the accuracy and the overall user experience for the low-cost eye-tracker has successfully been improvised. The eye-tracker has achieved lower deviations of accuracy and precision since the previous prototype, whereby the current average deviation of accuracy is within 1.5° to 2.5° range as compared to the average deviation of accuracy within the 3° to 5° range in prototype v1. While the deviation in angular accuracy and angular precision were slightly off compared to commercial eye trackers such as the ones from Pupil Labs that we can achieve deviation within 1°, it is reasonable considering that commercial eye trackers start from RM10,000 and beyond. Therefore, the current prototype is still well within an affordable price range while showing promising capabilities of achieving an average deviation within 1° with further development.

We have also successfully achieved greater cost efficiency whereby the total cost of the current prototype is RM132, a reduction of 60% is achieved compared to prototype v1, which costed RM330. The reduction of cost on the camera modules would make room for further development of the prototype, for example, installing Gyro and accelerometers to compensate for slippage effects due to head movements.

Furthermore, the frame of the eye tracker was redesigned to improve aspects of comfort and robustness to address the problem statement of this research. The current prototype weighs 69.5g as compared to prototype v1, which weighed 138.42g. The current prototype was quite resistant to hardware slippage due to movement, as seen from the experimental results, the deviation in angular accuracy and angular precision does not deviate far from its recorded values before the facial and head movement task, which proves that the current design is resistance to hardware slippage due to head movements. However, during the vertical head movement task, the data loss obtained from the PupilCapture log was significantly higher, this is most likely due to the drop of confidence level of pupil detection throughout at some points of the eye tracking process. Further development and improvements must be made to ensure that the eye camera is able to consistently detect the pupil with high confidence throughout the eye-tracking process.

The improvements made through this study were quite promising in terms whereby it is possible to develop a commercial level eye tracker while keeping the cost accessible to the general public. However, while the current prototype has made noticeable improvements since the prototype v1, it is evident that the research requires further improvisions to be considered a feasible device to control an autonomous wheelchair. This is because users with severe motor disabilities are at risk of involuntary head movements. In addition, due to the monocular approach of the current prototype, the confidence level of pupil detection at some head positions is not within the recommended range of more than 0.80, which causes an error in gaze detection.

5.2 Recommendations

There are two possible ways to reduce the effect of bad eye camera angle:

(1) Improvise the design of the frame's arm extension. First, it is advisable to re-design the arm to modify the arm's length manually. Next, the joint connecting the frame and the eye camera holder also has room for improvement. While the current prototype uses a ball joint method and gives the eye camera holder much more freedom for angle customization, it is still considerably limited. If the design successfully implements more degrees of freedom, the eye tracker becomes much more versatile, and it would be easier to find the proper orientation for the eye camera to capture high-quality pupil images.

(2) Since the cost and weight of the prototype have been largely reduced, it is possible to use a binocular eye tracker setup based on the current design. A binocular setup would vastly increase the eye tracker’s accuracy and precision. In addition, in a binocular setup, the user should run the software to detect pupil images for both eyes,

which would compensate for the lack of confidence value in pupil detection.

For instance, in the current prototype whereby the eye camera is position on the left side of the left eye, the confidence value drops when the pupil moves towards the right. A second camera module on the right side of the right eye would compensate for this pupil movement and keep the confidence value of pupil detection at a healthy level.

Lastly, it is recommended that the 3-D printed frame are properly printed without significant differences in dimensions. It is important to seek for professional 3-D printing services capable to printing products with low deviation of dimensions. Significant deviation of dimensions of the printed product from the CAD drawing might cause difficulties in fitting the camera modules, joints and nuts. It is also recommended that the 3-D printed parts are smoothened out before use, ensuring that there are no sharp edges. Depending on the work done, low-quality surface finishes by 3D printing might cause injury to the user.

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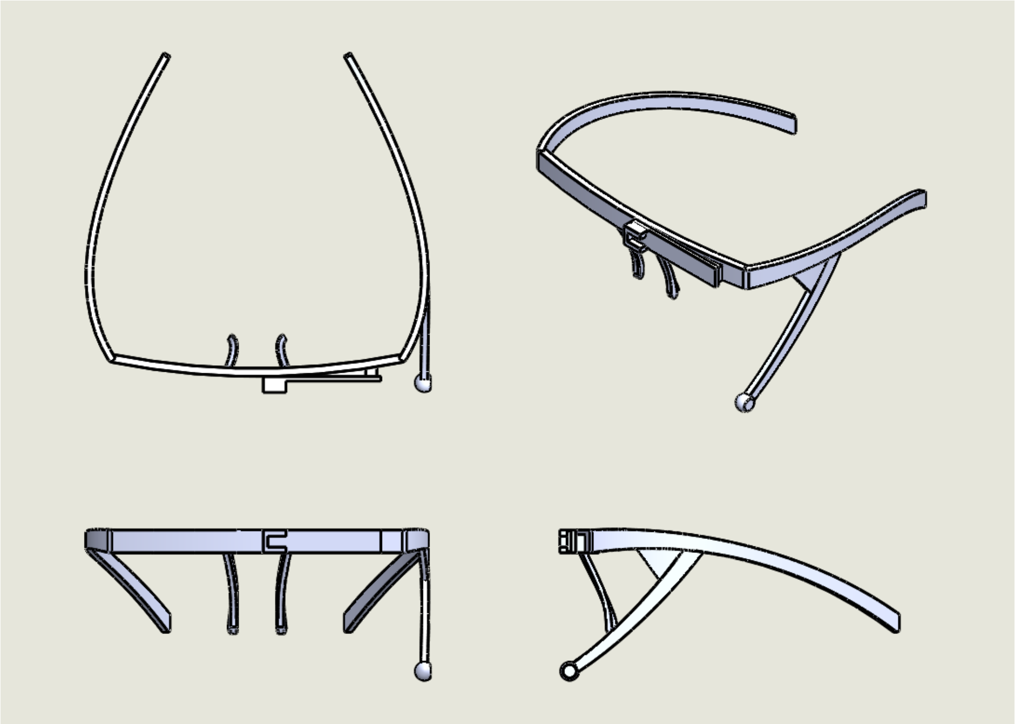
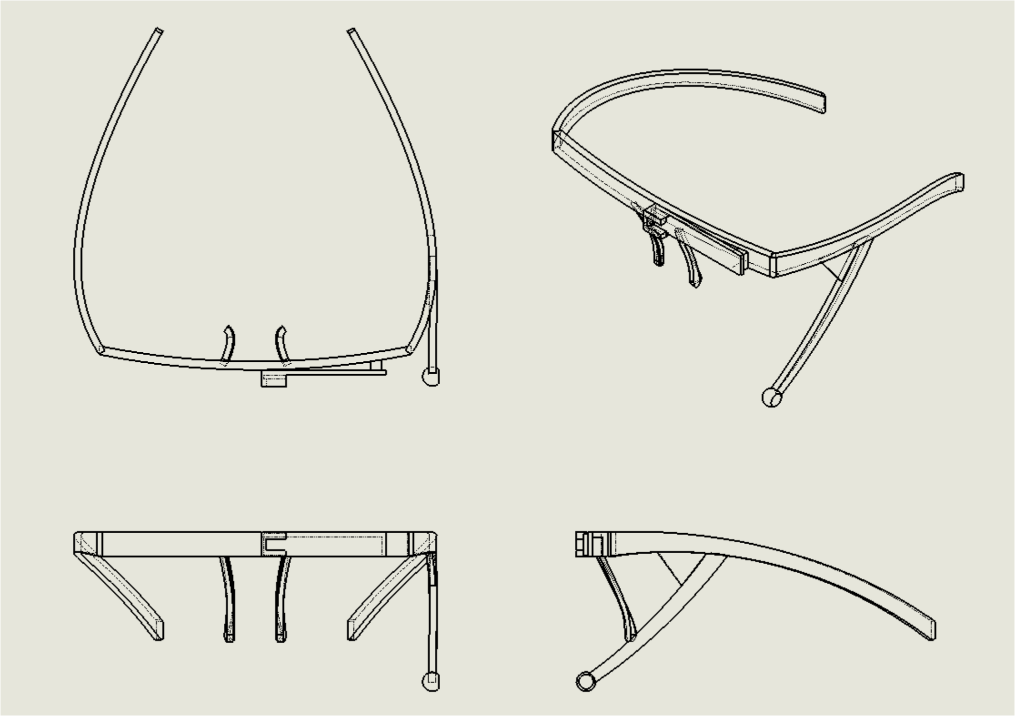
APPENDIX

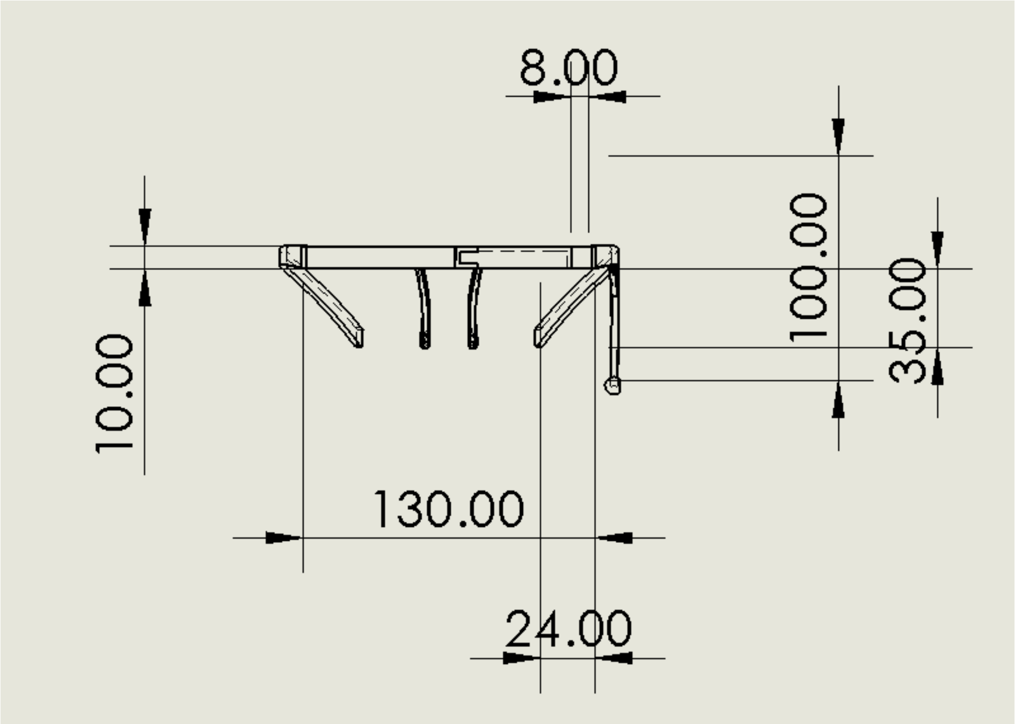
Drawing of Eye tracker Main frame with shaded edges



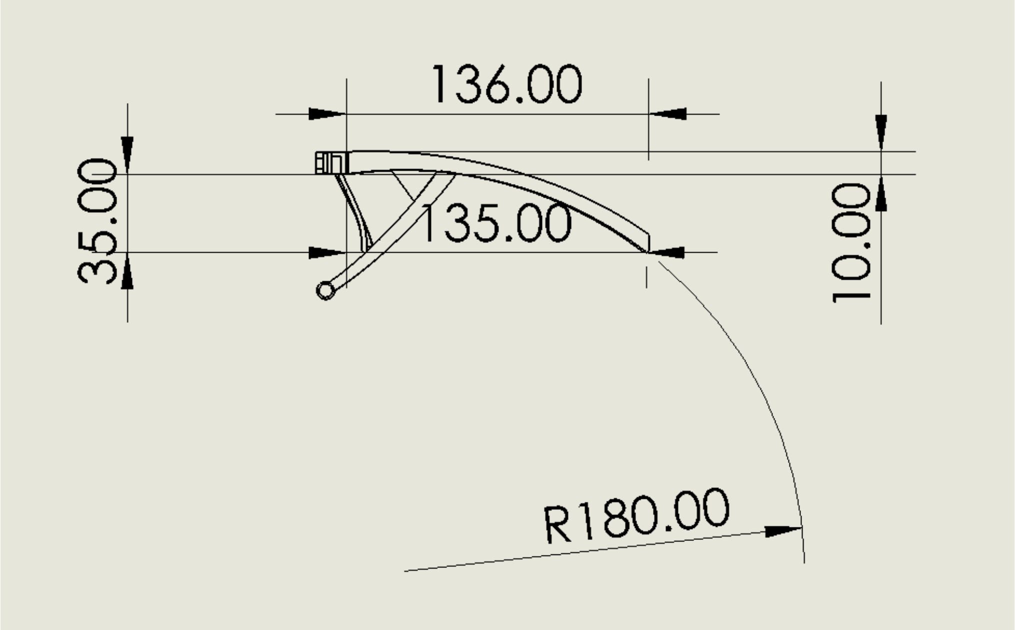
Drawing of Eye Tracker Main frame with visible hidden lines



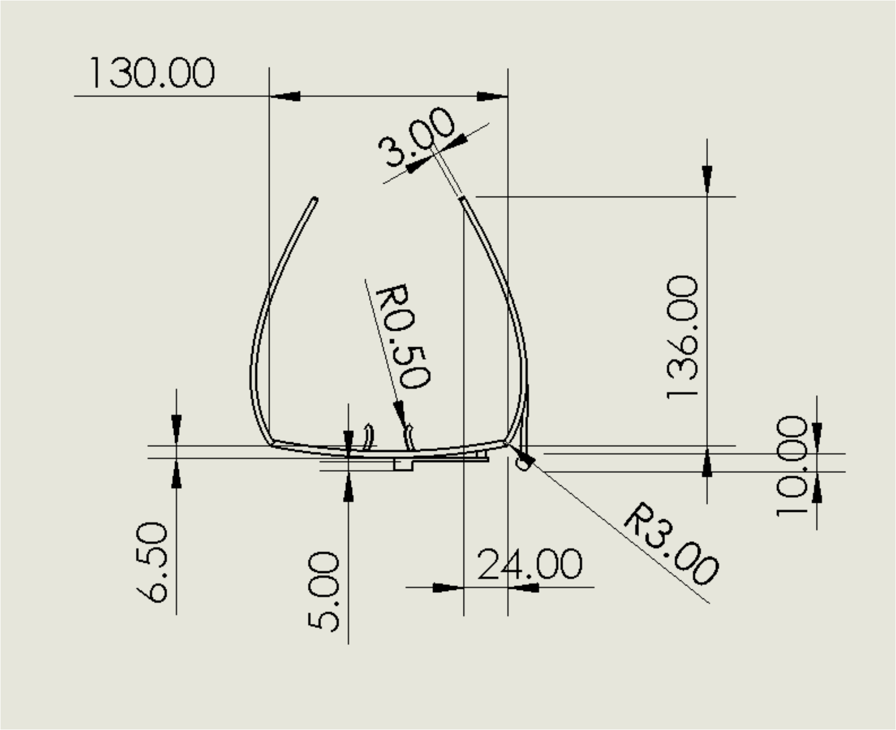
Front view of Eye Tracker Main Frame with dimensions



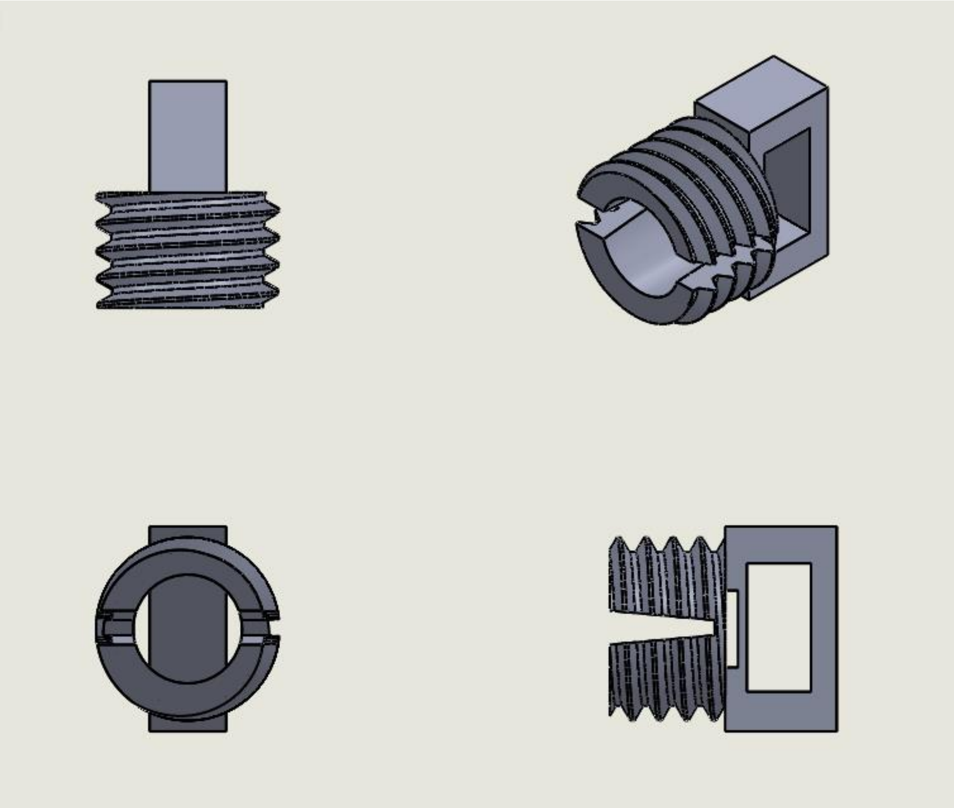
Right View of Eye tracker Main Frame with dimensions



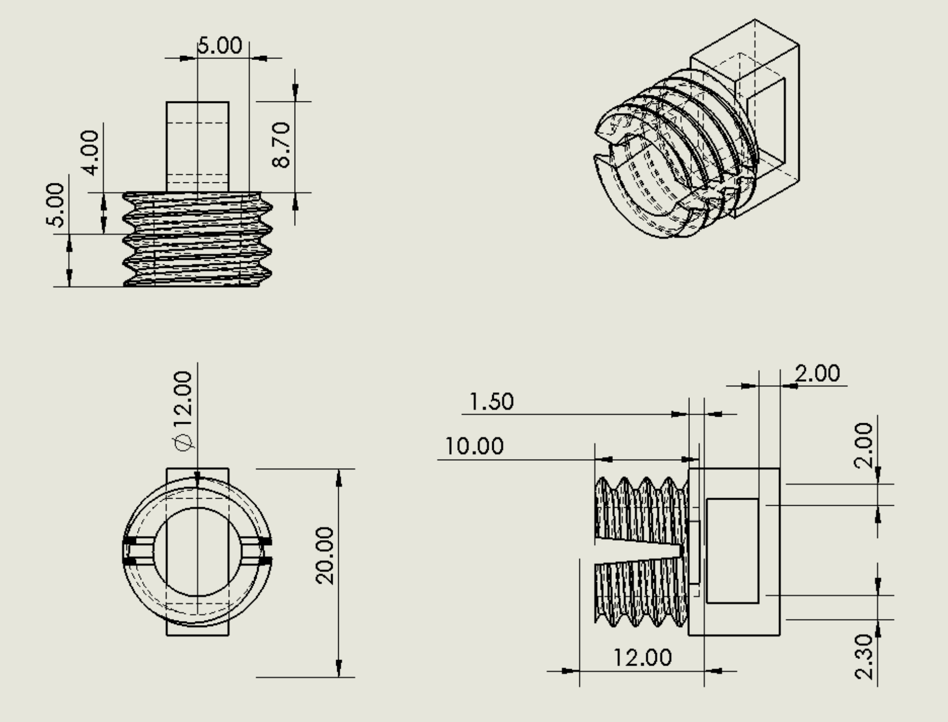
Top View of Eye Tracker main Frame with dimensions



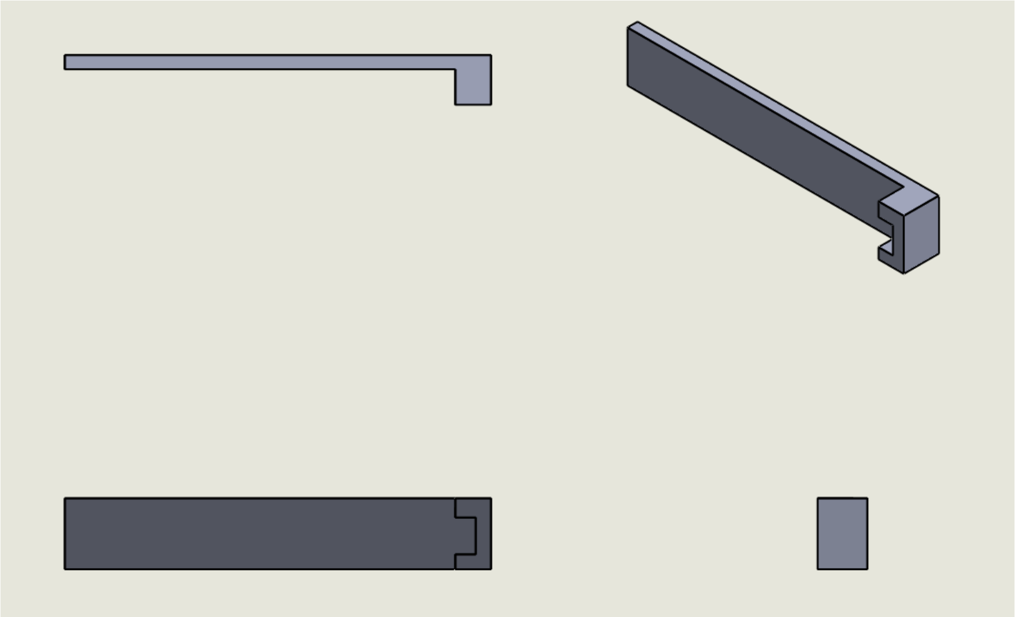
Drawing of Eye camera holder joint with shaded edges



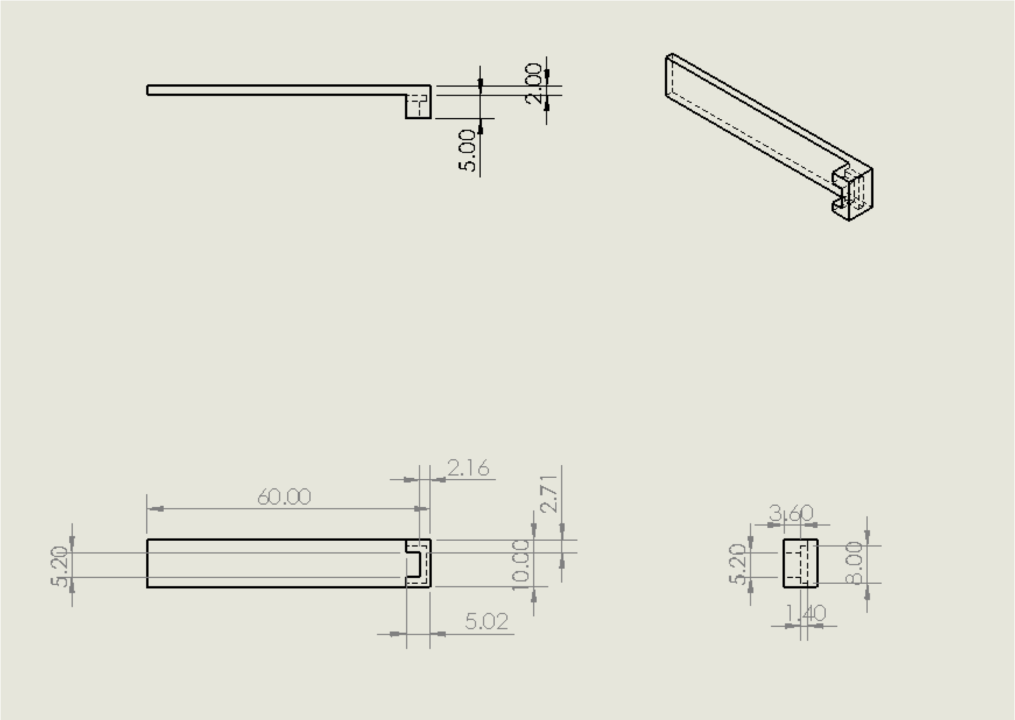
Engineering Drawing of Eye camera holder joint



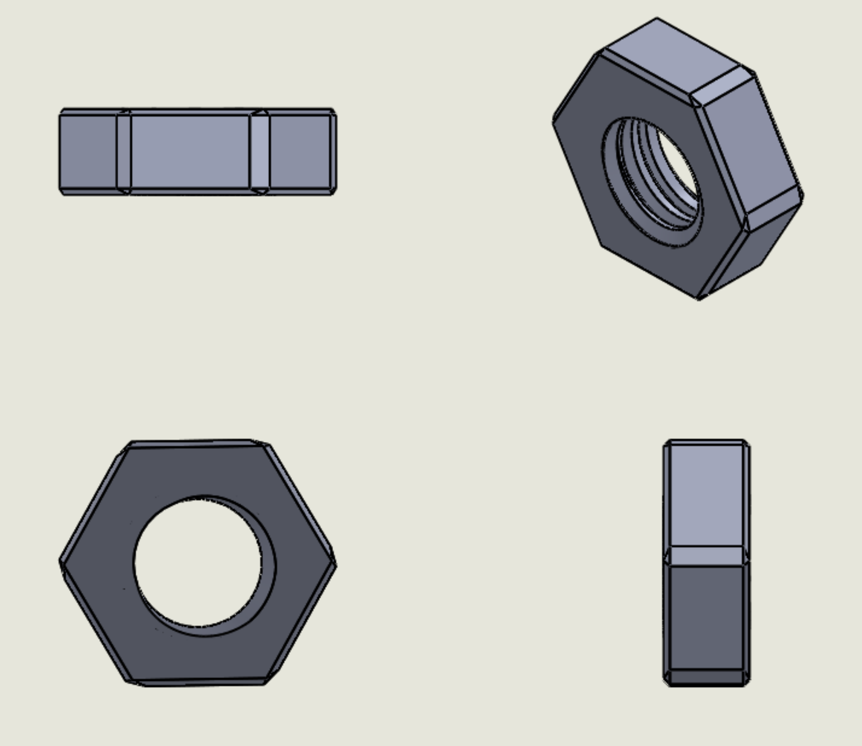
Drawing of Eye camera holder with shaded edges



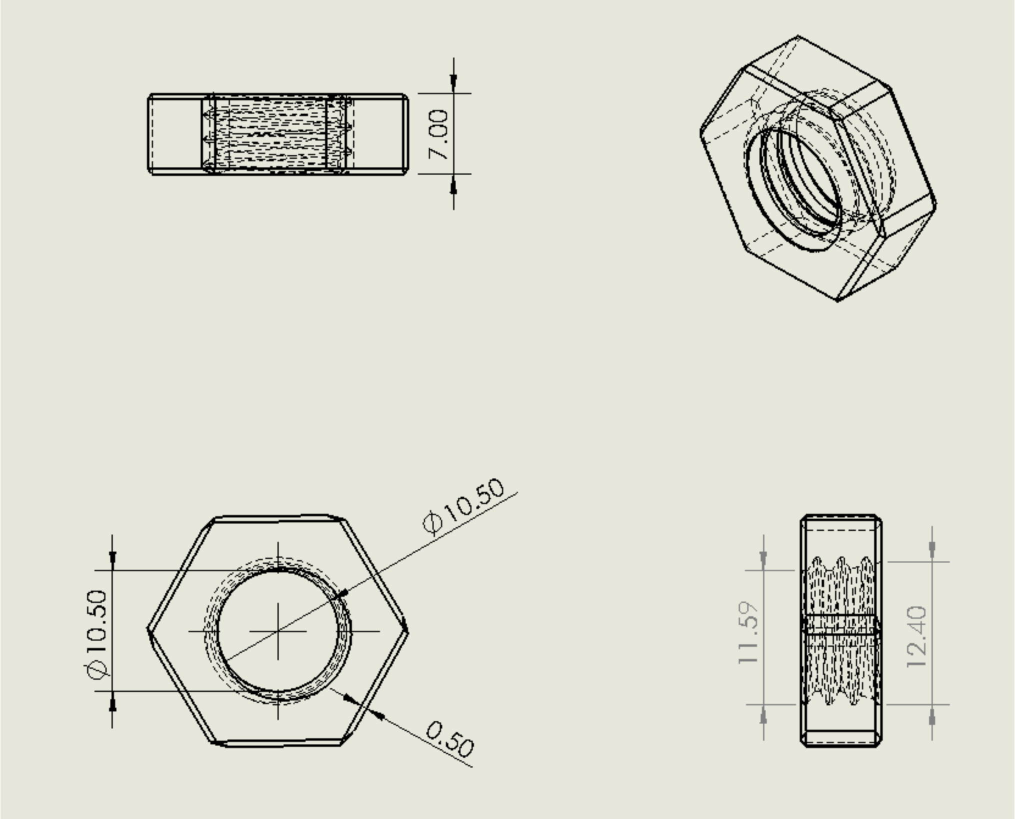
Engineering Drawing of Eye camera holder joint



Drawing of nut for camera holder joint with shaded edges

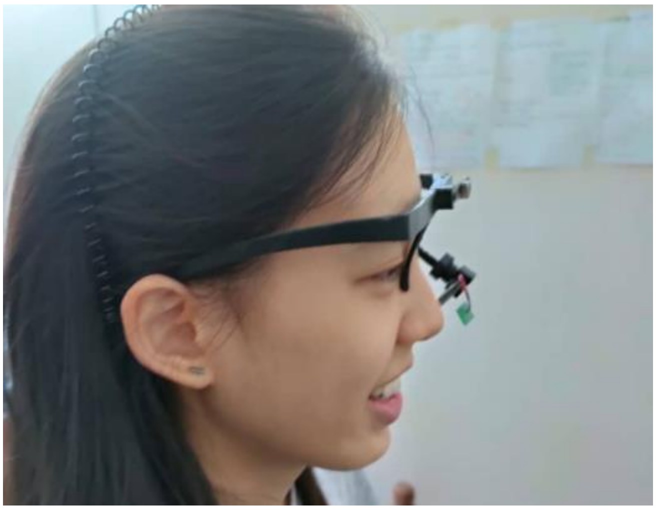


Engineering Drawing of nut for camera holder joint

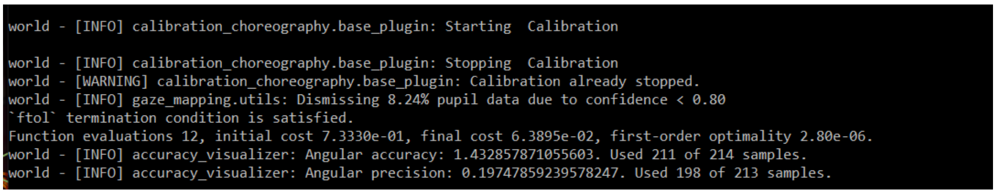


3-D Printed Eye tracking Frame

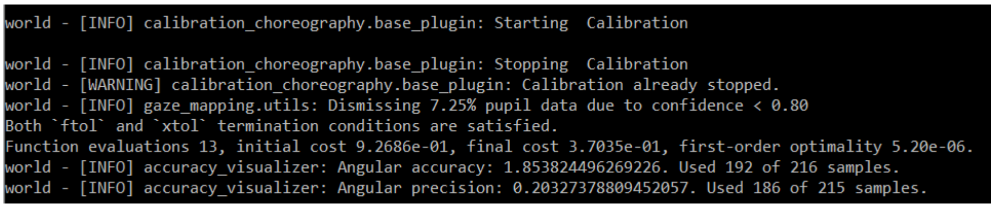
Participant wearing the eye tracker prototype



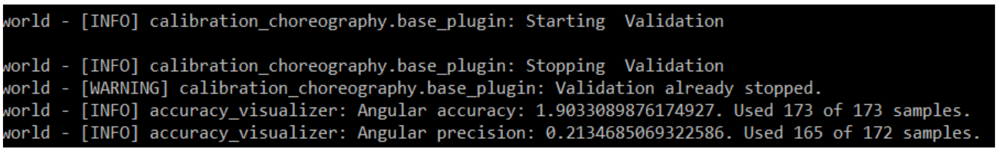
Calibration data from World Log



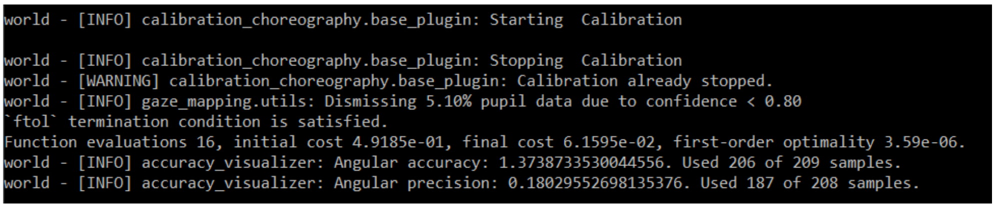
```
world - [INFO] calibration_choreography.base_plugin: Starting  Calibration

world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 8.24% pupil data due to confidence < 0.80
`ftol` termination condition is satisfied.
Function evaluations 12, initial cost 7.3330e-01, final cost 6.3895e-02, first-order optimality 2.80e-06.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.432857871055603. Used 211 of 214 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.19747859239578247. Used 198 of 213 samples.
```



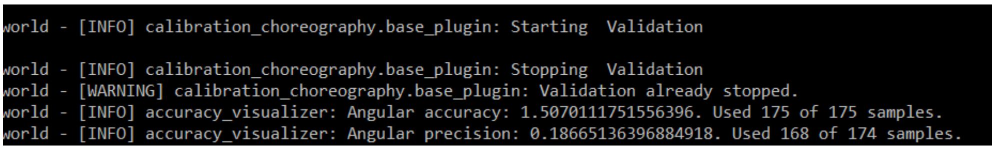
```
world - [INFO] calibration_choreography.base_plugin: Starting  Calibration

world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 7.25% pupil data due to confidence < 0.80
Both `ftol` and `xtol` termination conditions are satisfied.
Function evaluations 13, initial cost 9.2686e-01, final cost 3.7035e-01, first-order optimality 5.20e-06.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.853824496269226. Used 192 of 216 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.20327378809452057. Used 186 of 215 samples.
```



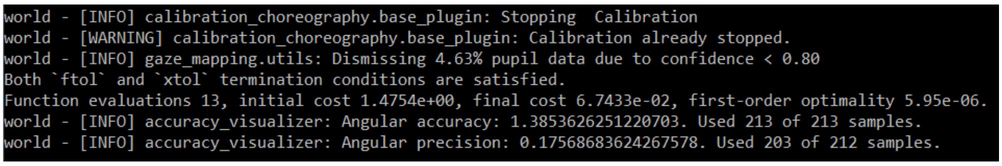
```
world - [INFO] calibration_choreography.base_plugin: Starting  Validation

world - [INFO] calibration_choreography.base_plugin: Stopping  Validation
world - [WARNING] calibration_choreography.base_plugin: Validation already stopped.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.9033089876174927. Used 173 of 173 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.2134685069322586. Used 165 of 172 samples.
```



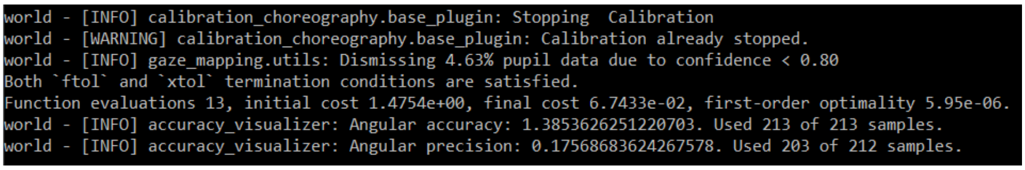
```
world - [INFO] calibration_choreography.base_plugin: Starting  Calibration

world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 5.10% pupil data due to confidence < 0.80
`ftol` termination condition is satisfied.
Function evaluations 16, initial cost 4.9185e-01, final cost 6.1595e-02, first-order optimality 3.59e-06.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.3738733530044556. Used 206 of 209 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.18029552698135376. Used 187 of 208 samples.
```



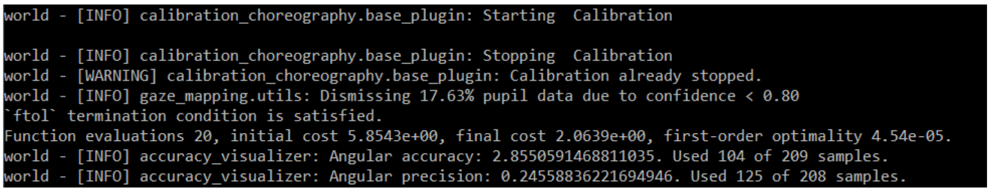
```
world - [INFO] calibration_choreography.base_plugin: Starting  Validation

world - [INFO] calibration_choreography.base_plugin: Stopping  Validation
world - [WARNING] calibration_choreography.base_plugin: Validation already stopped.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.5070111751556396. Used 175 of 175 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.18665136396884918. Used 168 of 174 samples.
```



```
world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 4.63% pupil data due to confidence < 0.80
Both `ftol` and `xtol` termination conditions are satisfied.
Function evaluations 13, initial cost 1.4754e+00, final cost 6.7433e-02, first-order optimality 5.95e-06.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.3853626251220703. Used 213 of 213 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.17568683624267578. Used 203 of 212 samples.
```

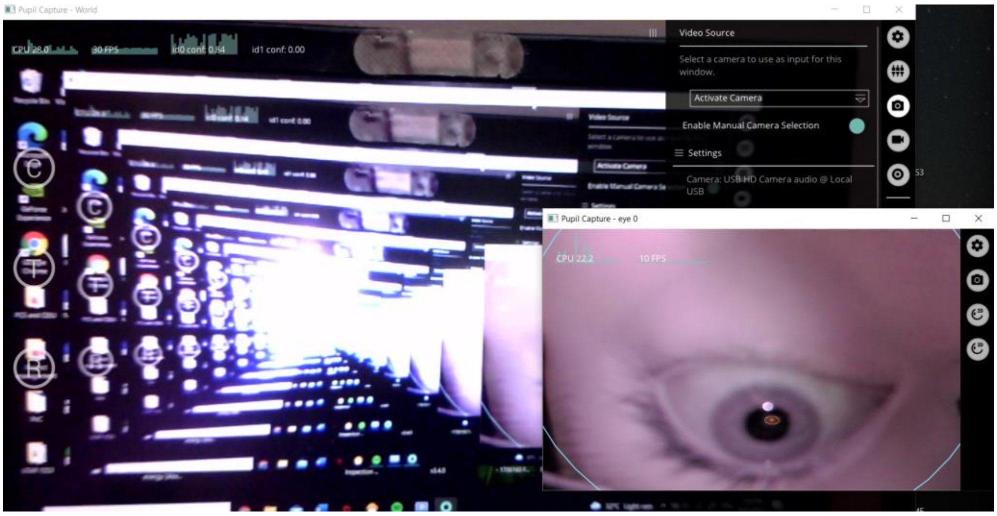


```
world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 4.63% pupil data due to confidence < 0.80
Both `ftol` and `xtol` termination conditions are satisfied.
Function evaluations 13, initial cost 1.4754e+00, final cost 6.7433e-02, first-order optimality 5.95e-06.
world - [INFO] accuracy_visualizer: Angular accuracy: 1.3853626251220703. Used 213 of 213 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.17568683624267578. Used 203 of 212 samples.
```



```
world - [INFO] calibration_choreography.base_plugin: Starting  Calibration

world - [INFO] calibration_choreography.base_plugin: Stopping  Calibration
world - [WARNING] calibration_choreography.base_plugin: Calibration already stopped.
world - [INFO] gaze_mapping.utils: Dismissing 17.63% pupil data due to confidence < 0.80
`ftol` termination condition is satisfied.
Function evaluations 20, initial cost 5.8543e+00, final cost 2.0639e+00, first-order optimality 4.54e-05.
world - [INFO] accuracy_visualizer: Angular accuracy: 2.8550591468811035. Used 104 of 209 samples.
world - [INFO] accuracy_visualizer: Angular precision: 0.24558836221694946. Used 125 of 208 samples.
```

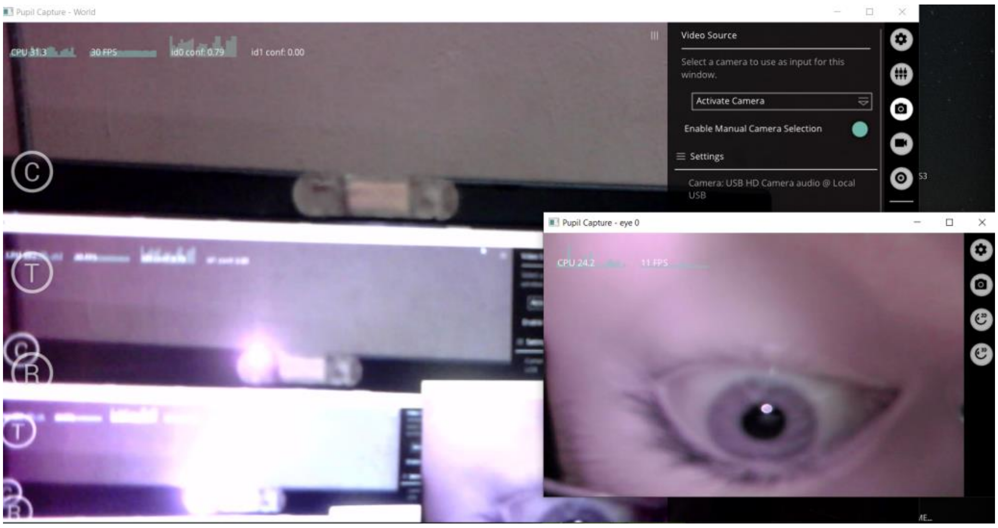
Eye camera and World camera window with confidence value



Select a camera to use as input for this window.

Enable Manual Camera Selection ●

Camera: USB HD Camera audio @ Local USB



Select a camera to use as input for this window.

Enable Manual Camera Selection ●

Camera: USB HD Camera audio @ Local USB