

Development and Validation of a Low-Cost Eye Tracking System

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Abstract

Eye tracking systems are often used to monitor various health concerns, but their high cost and requirement for laboratory settings limit their accessibility. To enable more research into eye movement applications in various settings at a low cost, we created a comfortable, wearable device that detects the eye position and calculates the velocity of an eye movement. The device consists of glasses with an adjustable camera that provides an unobstructed view and software that returns a graph of the position and velocity of the eye movement. This device enhances accessibility, diverse non-laboratory use cases, and serves as the building block for future research on eye-tracking technology.

1.0 Introduction

According to the book *Stolen Focus: Why You Can't Pay Attention*, US college students now focus on one task for 65 seconds, and office workers average only three minutes. The inability to focus is also prevalent in high school, and troublesome, as lack of focus in the classroom leads students to spend excess time trying to re-learn lesson material and decreases classroom performance significantly. For 3.3 million students with diagnosed attention deficit hyperactivity disorder (ADHD), inattention is experienced on a much larger and constant scale, significantly contributing to a decline in academic performance (Langberg 2011). Flintridge Sacred Heart's Learning Specialist, Margo Paine, who has over 20 years of experience in special education, suggests that "the quicker the students are aware that they are losing focus, the better they can maintain their focus" She suggests that a tool that provides real-time detection of

inattention through eye tracking and immediate feedback to assist those who struggle to stay focused in the classroom would be beneficial.

1.1 Background

1.1.1 Inattention Causes and Effects

Mental and physical factors such as fatigue, lack of sleep, post-traumatic stress disorders, and lack of exercise contribute to one's attention deficit. In addition, excessive technology use can significantly contribute to attention deficits (Betteridge et al., 2023). Inattentive behaviors impact one's learning experience in the classroom and can result in students missing details and becoming distracted easily, having trouble focusing on the task at hand, becoming bored quickly, having difficulty in learning or organizing new information, having difficulty completing homework, losing items needed to stay on task, and becoming confused easily, all potentially leading to poor grades, low academic achievement (Loe and Feldman, 2007).

1.1.2 What are Microsaccades

Saccades are rapid, jerky movements of the eye that change the center of gaze from one point to another. Saccadic movements voluntarily happen when we shift our view to a new target of interest. Microsaccades resemble regular saccades, but as the name suggests, they are much smaller movements and happen involuntarily during fixations. Saccades and microsaccades can be differentiated by their amplitude and velocity. Amplitude, a measure of angular distance traveled by the eye between two fixation points, occurs in regular saccades of 15 or 20 degrees. Microsaccades, on the other hand, have very small amplitudes, usually less than 1 degree with many being under 0.5 degrees (Collewyn 2008). The angular velocity of the eye movement also distinguishes saccades and microsaccades. While regular saccadic velocity reaches 300-400 degrees per second, microsaccades have a peak velocity of 150 degrees per second.

1.1.3 Why Microsaccades?

Studies suggest microsaccades are an indicator of visual inattention. According to a study by Hafed in 2015, attention is altered before the onset of a microsaccade, as neuronal signatures in the brain that signify a mental shift of attention are present before a microsaccade. Research has also demonstrated that those with high-ADHD-like traits have a higher frequency of microsaccades per second than those with low-ADHD-like traits. Those with high-ADHD-like traits had a rate of 2-3 microsaccades per second when completing a fixational gaze experiment (Panagiotidi, 2017), while the typical frequency of microsaccades is 1-2 per second.

1.1.4 Detection Measurements and Methods

Researchers typically use a forced-fixation setup to induce the occurrence of microsaccades. For example, in research conducted by Engbert and Kligil in 2003, microsaccades were induced by way of fixation in a “Gaze Game”. The eye movements were observed with high frame rate cameras such as EyeLink 1000 Plus or biomicroscopes and analyzed using image processing libraries in MATLAB, Open CV, Sci-Kit Image, etc. An example of using amplitude to detect microsaccades is demonstrated by tracking the center of the pupil. The center position of the pupil is determined by using the general equation of a conic section. The velocity of microsaccades is calculated with an algorithm developed by Engbert and Kligil, where the algorithm first transforms the time series of eye positions to velocities, and then calculates the velocity threshold by taking the median of the velocity time series.

1.2 Literature Review

A study conducted by Maria Panagiotidi in 2017 examines microsaccade differences in 43 non-clinical participants with high and low levels of ADHD-like traits. ADHD-like traits were assessed with the Adult ADHD Self-Report Scale, and microsaccade measurements were taken

with an Eyelink 1000, a video-based eye tracker. Horizontal and vertical eye positions for both eyes were sampled at a rate of 500hz. The participants were instructed to fixate on a white cross appearing on a black background in the center of a 20-inch monitor screen for 20 seconds. The peak velocity, amplitude, and frequency of microsaccades were detected by an algorithm created by Engbert and Kligel, and a positive correlation was found between overall ASRS scores and the number of microsaccades per second. However, the correlation between ASRS scores and peak velocity as well as amplitude were not made, leaving room for further research. Eyelink 1000's high cost and obtrusive design also create space for enhancement in developing a more efficient and less intrusive detection method.

Another research study conducted in 2010 by Ana A. Roig presents a non-invasive optical method for detecting and measuring fixational micro-movements. Using a biomicroscope equipped with a video camera that operates at 63 frames per second at the spatial resolution of 800 x 560, high-quality footage of the eye's surface was captured. The eye was illuminated with a high-intensity light to ensure maximum clarity and detail, and test subjects were asked to stare at a red LED light as a fixation point for 10 seconds. After capturing the images of an eye sophisticated algorithms in MATLAB were utilized to accurately detect the pupil and fit it into an ellipse. The movement of the eye was tracked by analyzing the center position of the ellipse, and consequently, slow drifts and sudden eye microsaccades were detected in horizontal movement. Increasing portability and detecting the movement of the entire iris instead of just the pupil (since pupils may be challenging to distinguish for individuals with dark-colored eyes) are potential adjustments suggested by this study.

Finally, a paper published in *Frontiers in Systems Neuroscience* and cited over 100 times, discusses the various experiments and findings from the past few decades that explore the effects

and implications of microsaccades (Hafed et al., 2015). In gaze fixation experiments the eye movements observed were not random and depicted a link between microsaccades and covert visual attention, as described in Section 2.2.

1.2 Problem Statement

Eye tracking systems are utilized to identify various health issues as eye movements show a correlation with factors such as inattention, stress, and fatigue. However, these systems come with a high cost and bulky hardware, which limits their use to laboratory settings.

Researchers need an affordable eye-tracking system that works in non-laboratory settings. To make the identification of psychological or attention issues more accessible, we created a low-cost, unobtrusive device that tracks the pupil position and calculates the velocity of eye movements.

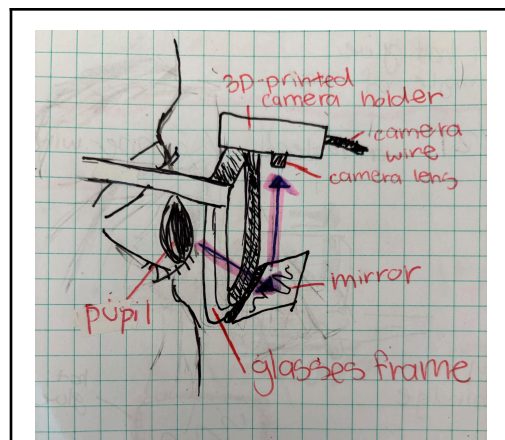


Figure 1: Theoretical Application of Hardware

2.0 Methods

2.1 Hardware Development

Hardware for this project was developed with 3 goals in mind: user comfort, consistent eye position detection, and durability. For durability, a plastic case for the Pi Camera was 3D printed. Durability was defined as consistent use without incurring performance issues or physical damage. Comfort was defined by having the user's view unobstructed and the glasses being able to be worn for at least an hour, while the user did stationary tasks that didn't require significant movement. Consistent eye detection requires a clear view of the eye (even when the face moved) and adaptability to different faces and eye colors. Several prototypes were developed to meet these 3 goals, with the final design based on the sketch of *Figure 1*.

2.2 Software Development

Since microsaccades have an average duration of 17 milliseconds, a frame rate of at least 60 Frames Per Second (FPS) is required. To ensure the camera can detect the microsaccades, we modified the original FPS of a Pi Camera (20-60 FPS) to 100 - 124 FPS using Python code (Suara, 2017).

Hough Circle Transform is an open-source method in the OpenCV library of image processing. To detect eye position, the transform identifies a circle centered on the iris. and returns the x and y coordinates of the circle center. To ensure a stable detection, both x and y coordinates were block averaged by two points.

The velocity of the eye movements was also calculated by dividing the displacement of two averaged points by the elapsed time.

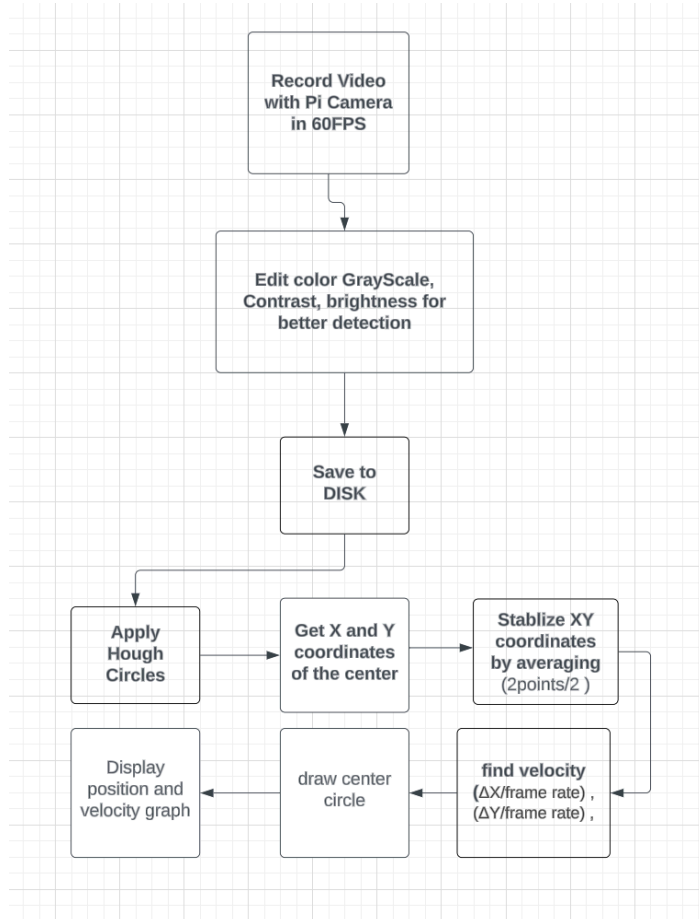
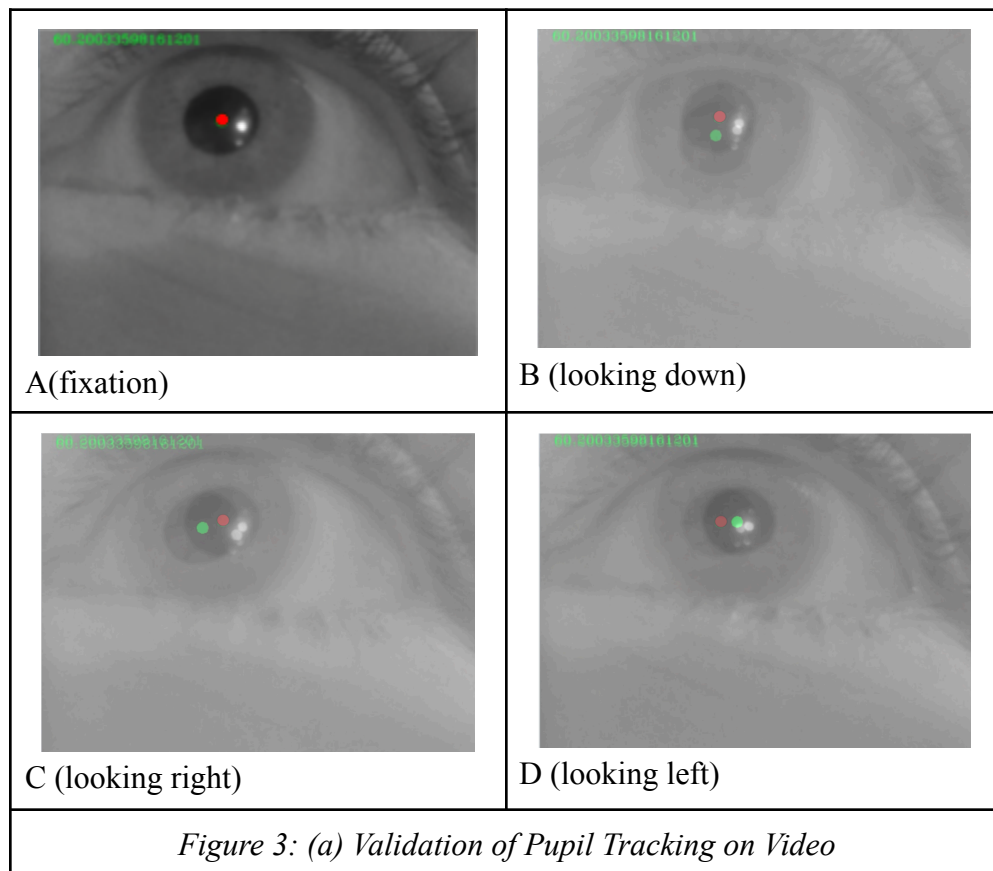


Figure 2: Software Flowchart

2.3 Validation Process

To validate the accuracy of coordinate detection, the video images were directly compared to an x-y plot of eye position coordinates. The change from origin to down/left/right are validated in the *Figure 3 (b)* images. These images are created by overlapping the image of an eye fixation (red dot) and eye movements (green dot). When the green dot is away from the red dot, an eye movement is indicated.



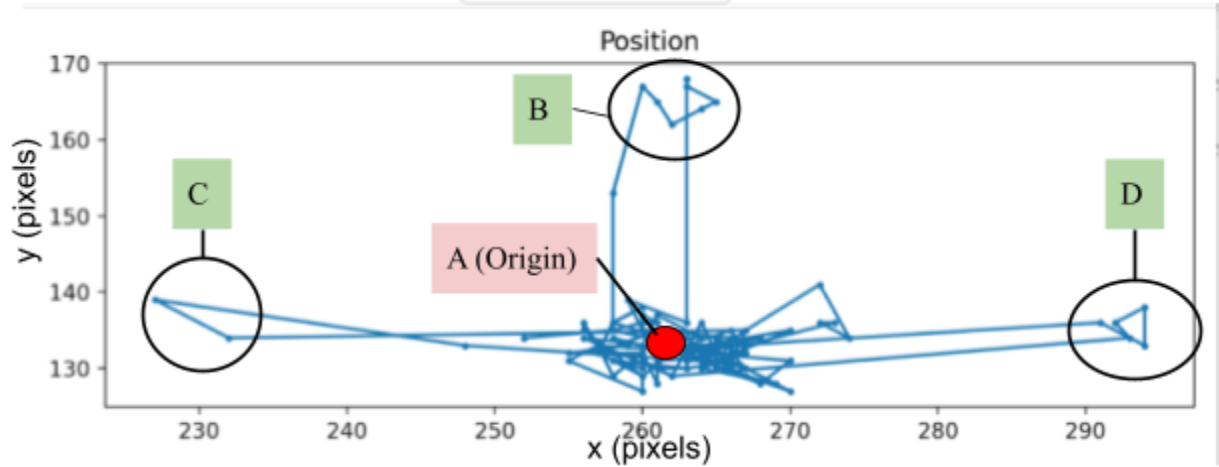


Figure 3: (b) Validation of pupil Tracking software result

When the eye position shifts downward, the position graph shows a significant increase in the vertical position. Left and right eye movements are evident as decreases and increases in the horizontal position.

3.0 Results

3.1 Hardware Results

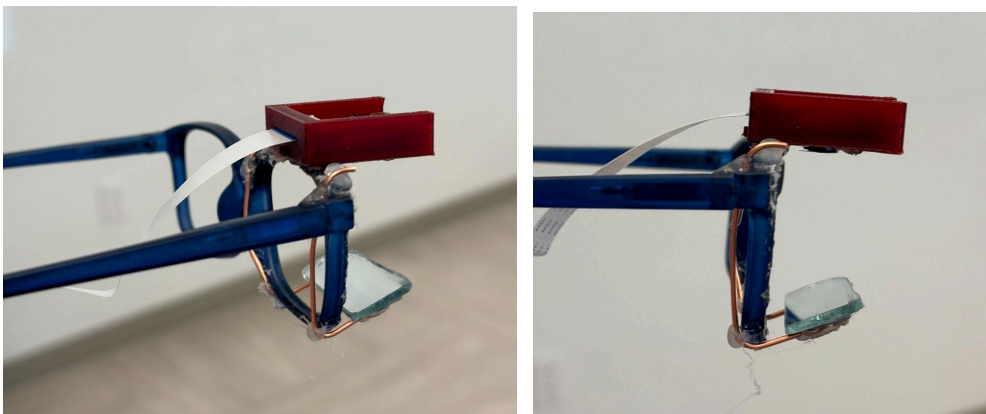


Figure 4: Hardware used in Final

The prototype shown in Figure 4 reflects an eye tracking device that meets all the design requirements: comfortable, consistent eye position detection, and durable eye camera. The mirror piece (approximately 1.4cm x 3.5cm) is attached to a copper wire which can be bent either upwards or downwards to reflect one's pupil into the camera. To ensure user safety, the edges of the cut glass are sanded down. The camera is attached to a meter-long cable, allowing decent user mobility when connected to the Raspberry Pi.

The camera used is a Raspberry Pi NoIR Module v2 Camera, sensitive to infrared light and the eye was illuminated with an IR flashlight during testing to enhance clarity.

One thing to be highlighted was the placement of the camera on the glasses frame, as it was placed on top of the frame. This allowed comfortability, stable image capturing, and unobstructed view for the user, all important factors. The use of a mirror piece allowed the pupil to be reflected into the camera lens, providing a clear view for the subject and eliminating problems caused by obtrusive camera settings. Follow the highlighted arrows in the diagram for reference.

3.2 Software Results

Using a scale conversion of actual eye length to eye image size, a microsaccade will show a 1.077-pixel movement on a 640x480 video and a 1.13-pixel movement on a 1624×1594 video. Even with a perfectly fixated eye position the movement of the hough circle coordinates in software varies from 1 to 10

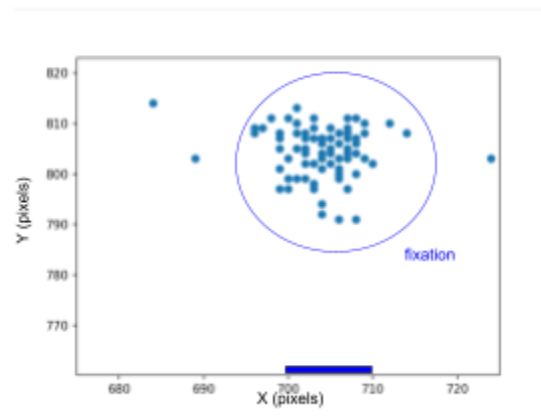
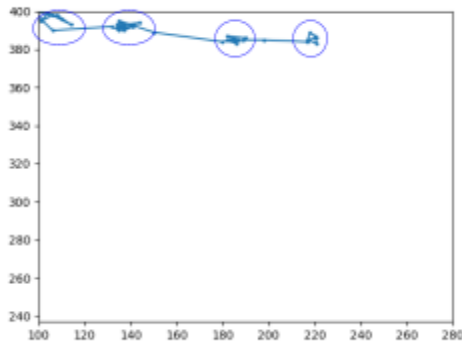
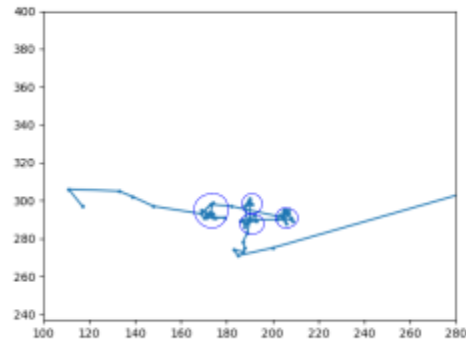


Figure 5: Position Graph of Fixation on 1624×1594 video

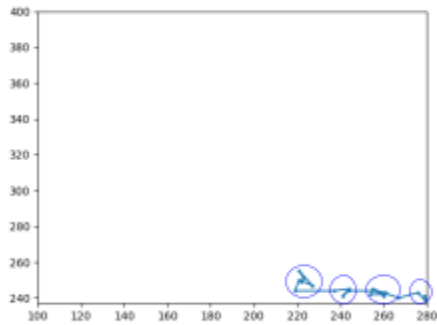
pixels. (Figure 5) Therefore, using positions as the determinant of a microsaccade is beyond the technical capabilities of this prototype. To determine the precision limit of a normal saccade (i.e. non-micro), a reading test was conducted. During the test, the subject read the following four words: “Micro Saccade Reading Test” with the space between words set at 6,4,2 and 1 cm and an eye-word reading distance of 115 cm.



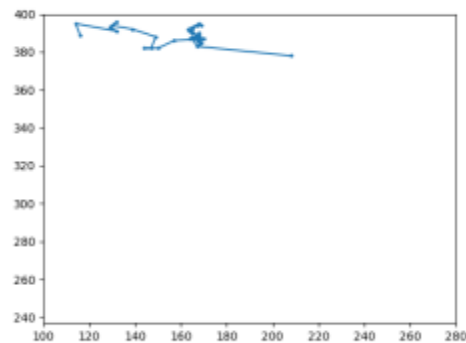
(a): 6cm / 2.987°



(b): 4cm / 1.992°



(c): 2cm / 0.9963°



(d): 1cm / 0.4982°

Figure 6: Position Results of Reading Test

While the 6cm, 4cm, and 2cm tests show distinct groups of points with at least five points in each fixation point, the test for 1cm gaps did not produce distinct groups of points. This result

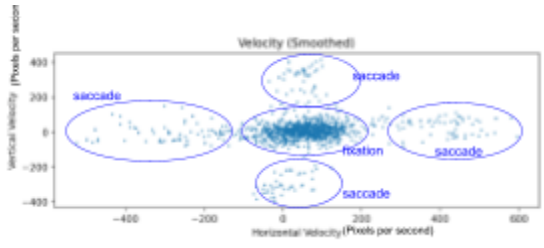


Figure 7: velocity graph of fixation test

sets the precision limit of the current prototype at $2\text{cm}/0.9963^\circ$, meaning a typical microsaccade of $<1^\circ$ is not resolvable, but a saccade of $>1^\circ$ is. The corresponding velocity graph shows a dense clutter around the origin, representing low or near-zero velocities during

fixation. There are also scattered points extending outward from the origin in both positive and negative directions, indicating higher velocities during saccadic movements.

4.0 Discussion

A low-cost and stable method to track eye movement and velocity was designed and fabricated. The prototype is easily replicated and wearable with a glasses frame, camera, mirror piece, and piece of copper wire.

Because of its portability, the prototype glasses can be used in non-laboratory settings, and studies related to eye movement could be conducted in daily life. The need for a face rest or physical restraint has been removed. For example, in a study published in 2019 meant to understand saccades, the face was stabilized by resting the person's face with foam pads on the temple and nose (Reeves & McLellan, 2020). The device presented here removes the stabilization requirements and allows the experiment to be reproduced in any setting.

Although the hardware was adjustable, users with prescription glasses would be unable to have corrected vision while wearing the eye camera. Future prototypes could implement a clip-on camera set-up for those who already wear glasses. Another possibility would be the

addition of horizontal adjustment for a camera. Shifting the camera to the left or right would allow a higher pupil-capturing precision, as the camera angle can be adjusted based on the subject's eye features.

Since saccade velocities can be differentiated from fixations (as shown in Figure 7) another future enhancement could be to differentiate microsaccades and saccades accurately. Investigating the limitations of the angular resolution of the velocity calculations could open the device to be used for microsaccade detection (e.g. attention and focus detection). Finally, researching an alternative to the Hough Circle Transform to increase the precision and stability of detection is worth exploring.

5.0 Conclusion

Eye movements indicate health concerns such as inattention, fatigue, schizophrenia, and stress. To assist the process of tracking eye movements, a pair of eyeglasses that capture high-quality video of the eye while providing an uninterrupted view for everyday use was developed. The software tracks the position and calculates the velocity of eye movements. This tool significantly enhances the accessibility of eye-tracking systems and widens spaces for developing its applications.

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