Building a lightweight eyetracking headgear

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Abstract

Eyetracking systems that use video-based cameras to monitor the eye and scene can be made significantly smaller thanks to tiny micro-lens video cameras. Pupil detection algorithms are generally implemented in hardware, allowing for real-time eyetracking. However, it is likely that real-time eyetracking will soon be fully accomplished in software alone. This paper encourages an "open-source" approach to eyetracking by providing practical tips on building a lightweight eyetracker from commercially available micro-lens cameras and other parts. While the headgear described here can be used with any dark-pupil eyetracking controller, it also opens the door to open-source software solutions that could be developed by the eyetracking and image-processing communities. Such systems could be optimized without concern for real-time performance because the systems could be run offline.

Keywords: lightweight, eyetracking, wearable, headgear

1 Introduction

In the last five years the ability to do eyetracking outside of the laboratory has expanded the range of experiments that are possible. Experiments performed in artificial laboratory settings have shifted towards experiments performed under realistic conditions where observers can move their heads and walk freely. Only recently has the technology been available to study eye movements that occur under these more natural conditions. Land et al. (1992, 1997, 1999), Pelz et. al. (2000, 2001), Canosa (2000), and Babcock et. al. (2002), have used portable video-based eyetrackers to monitor subjects' eye movements as they perform over-learned tasks such as tea making, handwashing, and even how people compose photographs with digital cameras.

While this research has provided novel insight into observers' visual strategies and behavior, there is also great potential to use eyetracking as a means of interacting with computers and other devices. Unfortunately, commercially available eyetrackers can be expensive, platform specific, and difficult to use. An open-source system would virtually allow anyone to explore eyetracking in many new ways. Further, new avenues of interaction for electronic media will certainly develop as a result of an open-source system. For this to happen it is clear that the next generation of eyetrackers should be more robust, less obtrusive, lightweight, and, most importantly, accessible to a larger audience.

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Because of the need for mobility, the studies listed above have used custom eyetrackers, or modifications of commercially available systems, to make portable eyetracking practical. The aim of this paper is to provide enough background for the ambitious reader to build a simple, lightweight, dark-pupil eyetracking headgear. Figure 1 shows an example of a prototype built completely from off-the-shelf components. The following sections detail some of the design considerations in building such systems.

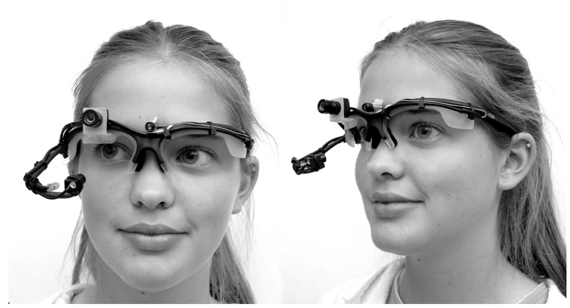

Figure 1- Lightweight, dark-pupil, eyetracking headgear

2 Where to Start: Choosing Frames

The first step in building a lightweight eyetracker is to choose something to mount the scene and eye cameras to. Figure 2 shows a low-cost pair of safety glasses used to make the headgear shown in Figure 1. It is important to choose frames with a joining nose bridge. This provides the best stability, preventing large movements of the headgear during use. The first step in making the headgear is to cut away most of the plastic lens. It is recommended that some plastic be left near the edges of the frame to maintain the frame's structure. Extra surface area can also be used for mounting the scene camera as shown in Figure 2. Once trimmed, the goggles should be sanded with emery paper to smooth any rough edges.

Figure 2- Safety glasses used to make the lightweight headgear.

3 Infrared LED, Eye, and Scene Cameras

3.1 Infrared LED

Video-based eyetracking systems use an infrared (IR) source to illuminate the eye, usually with one or more IR LEDs (IRED). In this design, a small IRED is positioned next to the eye camera as shown in Figure 5. The resulting configuration is called dark-pupil illumination since the IR source is off-axis with respect to the camera's focal axis. In this configuration the narrow retroreflected beam from the eye is not seen by the camera (unlike the bright-pupil technique). Figure 3 shows an example of a dark-pupil image. While this paper does not discuss a particular method to determine gaze (for the purpose of encouraging an open-source solution), a common approach is to measure the vector distance between the center of the pupil and the center of the corneal reflection resulting from the IRED. The prototype in Figure 1 uses a 5mm, 940nm, Radio Shack IRED (part number 276-143).

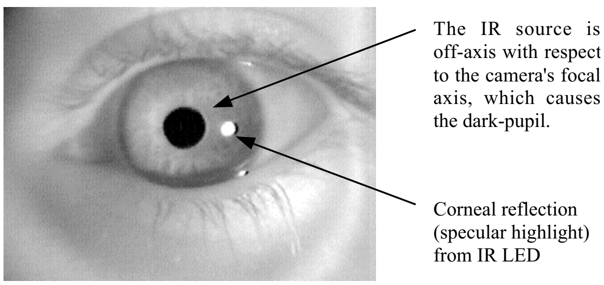

Figure 3 – Brightpupil illumination

3.2 Voltage Regulator

It is important to drive the IR LED at the proper forward voltage. This can be accomplished with an adjustable voltage regulator (LM317T) also purchased from Radio Shack. Assuming a 12 volt DC input, the circuit in Figure 4 can be used to drive the LED. These specifications may vary with different voltage regulators and LEDs. The 5k potentiometer can be used to adjust the circuit to the desired voltage level. For this particular LED and voltage regulator circuit, R2 was adjusted so that V_{out} was 1.2 volts. It is also recommended that the circuit include a resistor in series with V_{out} to limit current to the IRED. In our prototype we use a resistor in the range from 120 to 220 Ohms, preferably rated at two watts.

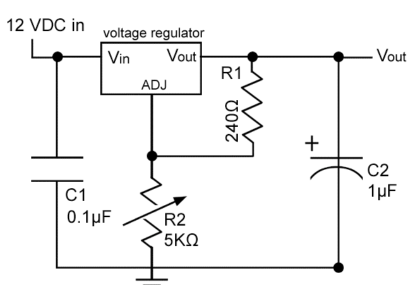

Figure 4 – Typical voltage regulator circuit

3.3 Safe Infrared Exposure

A critical design parameter of any video-based eyetracker is the level of infrared power incident on the eye. The retina is insensitive to energy in the near-infrared, so one cannot rely on subjective reports of brightness. The irradiance (mW/cm^2) at the eye is a function of the power emitted by the IRED, the area over which that energy is spread, and the uniformity of the illumination pattern. An irradiance level less than 10 mW/cm^2 is considered safe for chronic IR exposure in the 720-1400 nm range (Sliney & Myron, 1980, ICNIRP, 1997, 2000). The IR illuminator in our system provides adequate illumination for the eye camera with an irradiance of only 0.8 mW/cm^2, well below the recommended safety level.

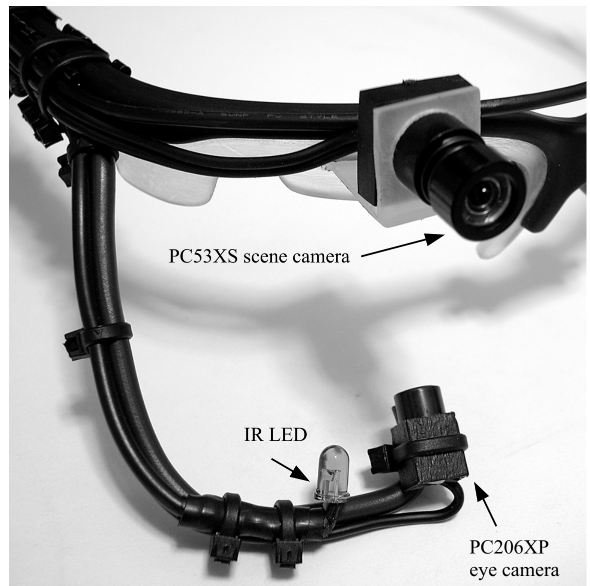

Figure 5a – Closeup of the IRED, eye, and scene cameras.

3.4 Eye Camera

Thanks to micro-lens video cameras, the size of eyetrackers will get significantly smaller. Companies like Supercircuits (http://www.supercircuits.com) sell a variety of micro-lens cameras. Although these cameras provide less resolution than many larger NTSC video cameras, they have been essential in making the lightweight system shown in Figure 1.

The Supercircuits PC206XP camera is mounted to the headgear frame via a flexible 10-gauge wire. The camera lens is pointed at the eye, resulting in a dark-pupil image as shown in Figure 3. Designing the headgear for dark-pupil instead of bright-pupil illumination greatly simplifies the headgear because beam-splitters and folding mirrors are not necessary. Occlusion of the subject’s field of view is minimal because the camera measures only 0.95cm square by 1.6cm. The PC206XP houses a 0.36cm black and white CMOS imager with 380 lines of resolution. Despite its size, this camera provides adequate image-quality for threshold and edge detection algorithms employed by most commercially based eyetrackers. The focusable lens provides an 80 degree field of view, and the camera is powered with 12 volts DC at 20 milliamps. This camera is ideal for monitoring the eye because of its small size, low power consumption, and low cost.

3.5 Infrared pass filter

With the infrared illumination, the PC206XP camera captures an adequate image of the eye. However, any visible light source, such as overhead fluorescent lamps, can produce unwanted corneal reflections on the surface of the eye. Kodak's 87c Wratten filter can be used to block visible light so that only infrared illumination will pass. Installation requires unscrewing the eye-camera lens and placing a small piece of the Wratten filter flush with the camera's sensor.

3.6 Scene Camera

The color PC53XS CMOS scene camera was selected because it is one of the smallest commercially available color cameras. This camera provides a frame of reference by capturing the scene from the observer's point of view. It weights 1/3 of an ounce and consumes 50 milliamps at 12 volts DC. The base of the camera is 1.62cm square, with a lens extending to 2.67cm. The scene camera is tension-mounted by sliding the lens barrel through a hole (11.95mm) just above the left eye as shown in Figures 5a and 5b. The final position is secured using epoxy.

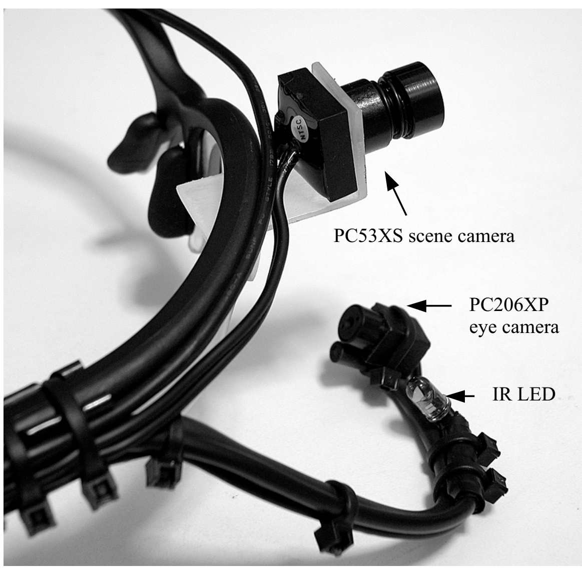

Figure 5b – Closeup of the IR LED, eye, and scene cameras.

4 Calibrator: LASER and 2-D Diffraction Grating

Video-based eyetracking systems, such as Applied Science Laboratories and ISCAN, use a regular grid of calibration points for calibration. Typically, these grids are presented on a monitor or stationary plane, such as a wall or table. Because the observer's head moves independently of the calibration grid, some error can result without using a chinrest for stabilization.

In this system, a laser diode and 2D diffraction grating are used to split the laser beam into a grid of 9-points that can be projected onto a wall or flat surface in front of the person wearing the headgear. The 9-point grid is imaged by the scene camera and thus provides a reference for calibrating the eye position with respect to the scene image. The system shown in this paper uses an adjustable focus laser diode (17.25 x 6.4 mm, Digikey part# 3B-102-ND) coupled with a 13,500 lines per inch double-axis diffraction grating (http://www.rainbowsymphony.com). The diffraction grating is sandwiched against the lens of the laser diode after the desired beam size is adjusted. Like the LED, it is important to drive the laser diode at the proper forward voltage. Assuming 12 VDC, a duplicate of the circuit in Figure 4 can be used to provide 3 volts to the laser. It is important to note that these specifications may vary with different voltage regulators and lasers.

Figures 6a and 6b show a close-up of the laser module mounted on the frame, and a conceptual projection of the 9-point target. This feature is important because the calibration target always moves with respect to the scene image and can be used to quickly check the accuracy of the track.

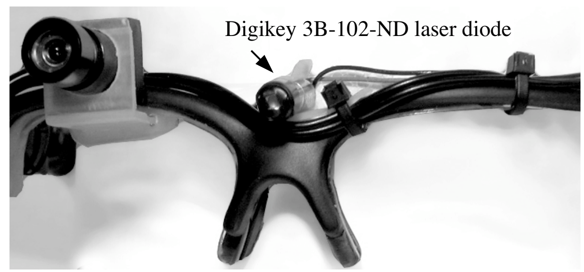

Figure 6a – Close up of the laser diode.

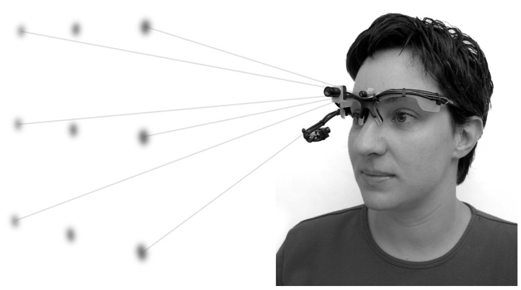

Figure 6b – Illustration of laser projection system (note that the points must be projected onto a flat surface, i.e. a wall, table, etc.).

5 Other Hardware

The components needed during an eyetracking experiment depend on whether eyetracking has to be done in real-time. Real-time eyetracking may be required in cases where eye position is used for control, such as moving a mouse or entering text, or when the display is to be updated based on eye position. In other cases the raw video eye image and scene image can be captured during the experiment and processed through the eyetracking algorithm later. We refer to this as the offline approach and will discuss different methods of offline eyetracking and their advantages.

5.1 Offline Eye/Scene Capture

Early, film-based eyetrackers were inherently "offline" systems in that eye position was determined only after developing the photographic film used to record the eye position. Some systems captured the two-dimensional movements on a single, stationary sheet of film (e.g., Yarbus, 1967). Others recorded eye movements by capturing the horizontal and vertical components

independently on moving strips of film (e.g., Buswell, 1935, Brandt, 1945). Modern systems, from Dual-Purkinje eyetrackers through lightweight video-based systems are typically designed to operate in real-time. In these systems, images of the eye or landmarks on the eye are tracked. While some experiments, such as saccade-contingent updating tasks, require real-time feedback of eye position, many do not. In experiments where eye movement data is analyzed only after a trial is completed, there can be advantages to returning to systems that capture raw information during a trial, but delay processing until later.
Offline analysis requires that both eye and scene camera images be stored, then synchronized on playback. Synchronization can be accomplished in a number of ways. Professional video editing systems can play back multiple video streams while ensuring frame-accurate synchronization between the time codes. Accuracy of a few frames can be achieved by including a visual or auditory cue at the beginning of each tape to allow them to be "aligned" on playback. If the eye and scene tapes are played back on camcorders, they can be paused at a specific event (e.g., a light flash), then using a single remote control to start them in tandem.

Another alternative is to record the eye and scene images onto a single videotape. While this could be accomplished in a number of ways, such as recording eye and scene on alternating video fields or digitizing the images and storing the resultant sequence, we are now using a system that combines the two images as an anamorphic pair so that they may be recorded to a single video frame. Figures 7a and 7b show custom off-line systems used in our laboratory for single video capture.

Figure 7a – Custom off-line eye and scene recording box

Figure 7b – Off-line eye and scene capture housed in a backpack

In cases where mobile eyetracking is needed, a small backpack can be used to carry the components. Figure 7b shows a person wearing a Camelbak hydration backpack, which holds components similar to those shown in Figure 7a.

The box and backpack systems include a small LCD display, an external laptop battery, a Sony DCR-TRV19 Digital Video Camera, and a video splitter that combines the eye and scene images into a single video image. We have used two methods for combining the eye and scene video streams; video editing decks such as a Videonics MX-1 digital video editor allow a "sweep" transition where two video images can be displayed and recorded side-by-side, and a video multiplexer from ISCAN inc, provides the same anamorphic split-screen image seen in Figure 8.

Figure 8 – Anamorphic split-screen image from ISCAN

In systems that allow the user to specify a window in which the pupil and corneal reflection must be found, the raw tape can be used for the eye image. Alternatively, the anamorphic image pairs can be split back into separate eye and scene images. If analysis is to be accomplished off-line, there is no need to operate in real-time, so each frame can be digitized and analyzed individually. This option is at the heart of our long-term plan to work toward an open-source eyetracking structure based on offline analysis (although we are also pursuing real-time solutions as well). The combination of relatively inexpensive headgear, recording the eye and head video together using a standard video mixer, and offline analysis of individual video frames offers a unique opportunity to develop license-free eyetrackers.

5.2 Advantages to offline systems

When eye position is calculated in real-time, there is only one opportunity to capture eye movements. Momentary track losses, illumination variation, pupil diameter variation, and other problems all lead to permanent loss of eye position data. Offline processing allows the experimenter the flexibility to explore tradeoffs in parameter settings such as field-averaging, and region-of-interest windowing. When running video-based eyetrackers in online mode, the experimenter has to select the number of 1msec video fields that are averaged together when eye position is calculated. Averaging over a small number of fields (or not averaging at all) improves the temporal resolution at the expense of increased noise; averaging over a larger number of fields can significantly reduce noise, but fine-grain temporal information about rapid eye movements is lost. The choice is dependent on individual subjects and experimental conditions.

If the raw video image is captured for off-line analysis, the decision about field averaging, threshold values, etc. can be postponed until after the video is collected, when there is more information on which to base the decision. It is also possible to run the video through the eyetracker device several times so one can test various parameter values.

Off-line analysis can also simplify calibration. Calibrating real-time video eyetrackers typically requires a two-step process in which a number of calibration points are first located in the scene image, then the subject is instructed to look at the same points. This is often a challenging process that limits calibration accuracy because any head motion during the entire process will limit accuracy. The experimenter must also time the instant at which to capture the image of the eye at each point. A blink or a drift in the subject's line of gaze will cause errors in the calibration. By performing calibration offline, it is possible to "freeze-frame" the eye and scene video to ensure a stable eye and scene image. Perhaps more importantly, it is possible to locate the calibration points in the scene image and capture raw eye position images on the same video frame rather than later in the sequence. This can completely eliminate errors normally induced by movement of a subject's head in the time between locating the calibration points and the subject fixating on the same points. While the laser calibrator described in the previous section addresses the problem of maintaining head position during the entire calibration process, offline processing also allows the experimenter to eliminate the possibility of a blink interfering with the calibration.

6 Conclusion

Researchers doing eyetracking in natural environments have expressed the need for custom, easy-to-use eyetrackers. Tiny micro-lens cameras have made it possible to build inexpensive, lightweight headgear that can be used with today's commercial eyetrackers. This paper has provided some practical tips on putting together a lightweight portable eyetracking headgear mainly to encourage an open-source approach to eyetracking. We discuss benefits of utilizing an offline system, which further advocates the license-free idea. As a future step, we also encourage the development of open-source eyetracking software that will complement the hardware discussed in this paper.

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