Design of a Low Cost Pupil Detector Using Asynchronous Differential Stroboscopic Lighting

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ABSTRACT

An eye tracker is a device that measures eye movements and estimates the point of gaze. Despite recent advancements in eye tracking technology, low cost high performance eye trackers are not yet available. In this paper we describe the design of a pupil detector using asynchronous differential stroboscopic lighting (ADSL). ADSL is an extension of the differential lighting (DL) technique developed in the 90’s for analog cameras. DL uses two sets of infrared light sources to alternately generate bright and dark pupil images. The pupils are then robustly detected from the difference of two consecutive video frames. Though DL is a simple and computationally efficient solution for robust pupil detection, its implementation using low cost digital cameras poses challenges due to the lack of external video synchronization and the use of rolling shutters that causes each scanline to be shifted in time. Our design will overcome these problems by synchronizing the stroboscopic lighting with the video frames using lightweight image processing algorithms.

Author Keywords

Eye tracker; pupil detector, low cost camera; stroboscopic lighting; differential lighting.

ACM Classification Keywords

C.3 Special-purpose and application-based systems: Real-time and embedded systems

INTRODUCTION

An eye tracker is a device that measures eye movements and estimates the point of gaze. Common techniques used for eye tracking in the 90’s include electrooculography, contact lenses, and video-based methods. Today, video-based eye trackers have become dominant [8, 5]. Eye trackers have been widely used in psychological and psychophysical studies, and helped people with motor disabilities [3, 6]. But despite recent advancements in eye tracking technology [2], improving overall performance and reducing size, low cost high performance eye trackers are not yet available.

In this paper we introduce the design of a novel pupil detector based on the Asynchronous Differential Stroboscopic Lighting (ADSL) technique that can be used to build low cost high performance eye trackers.

ADSL is an extension of the differential lighting (DL) technique developed in the 90’s for analog cameras [7]. DL uses two sets of infrared light sources to alternately generate bright and dark pupil images. The pupils are then robustly detected from the difference of two consecutive video frames. Though DL is a simple and computationally efficient solution for robust pupil detection, its implementation using low cost digital cameras poses challenges that are overcome by using stroboscopic lighting. When the stroboscopic lighting is not synchronized with the video, a moving banding artifact is created. In this paper, we focus on the design of a solution to minimize such artifacts.

Because ADSL demands a relatively low computational load, it is appropriate for high speed cameras and low end computers such as mobile phones and tablets. The use of stroboscopic lighting also enhances the image quality, significantly reducing motion blur and artifacts from the rolling shutter. As a result of better image quality, ADSL based eye trackers might achieve better accuracy and precision.

DIFFERENTIAL STROBOSCOPIC LIGHTING

In [1] Borsato and Morimoto describe the principle of stroboscopic differential lighting for robust pupil detection. Similar to the original Differential Lighting (DL) technique [4, 7], the solution described in [1] synchronizes light pulses from two light sources with the even and odd video frames of the eye camera. Figure 1 illustrates the DL principle. Using near infrared cameras and light sources, when the light source is place far from the optical axis of the camera, the pupil image appears dark, as seen in the left image of Figure 1. When the light source is placed on (or near) the optical axis of the camera, the pupil appears bright due to the light reflection from the back of the eye.

By synchronizing the on and off-axis light sources with the video frames, the pupil region will correspond to high contrast regions in the difference image computed using two consecutive frames. As reported in [7], this is a robust and computationally efficient solution to detect and track eye movements. Despite these advantages, the application of the DL technique to low cost digital cameras is not straightforward primarily due...
to the lack of external video synchronization and the use of rolling shutters that causes each scanline to be shifted in time.

To use cameras without external synchronization input, Borsato and Morimoto [1] proposed an external electronic circuit connected to a USB port to synchronize the light sources with the video frames. When the lights and video are out of sync, a black stripe artifact is seen in the dark and bright pupil images. The stripe in each frame is detected and tracked to control the firing of the light sources, keeping the stripe outside the pupil region. To improve image quality and remove artifacts introduced by the rolling shutter mechanism, Borsato and Morimoto use stroboscopic light (very short light pulses) synchronized with the video.

**ASYNCHRONOUS DIFFERENTIAL STROBOSCOPIC LIGHTING**

A key issue with the solution presented in [1] is the need to keep an open link with the stroboscopic light controller. Although many engineering solutions might be proposed and possibly switch to a wireless link, we present next a new system design that eliminates the requirement of explicit light and video synchronization, considerably simplifying the external circuitry to, basically, an oscillator at the same video frequency, to control the lights.

Allowing the lights to fire independently, possibly at a different frequency from the camera, may result in images with patterns that can range from partially lit frames, dark stripes, bright stripes, and multiple stripes in the same video frame. The stripes can take several minutes to cross the visible scanline range or just a couple of frames. Some examples of such artifacts are shown in Figure 2.

If only a small difference in frequency is allowed, the time the stripe takes to cross the frame is bounded. As the stripe will eventually cover part of the pupil region (otherwise we have the synchronous case), we propose to track the stripe movement and correct the area affected by the artifact.

**Design issues**

We will assume that the frequency of the low cost video camera is known, and the frequency of the stroboscopic lighting oscillator has approximately the same frequency but not exactly the same to guarantee a moving dark stripe. Assuming that the camera is pointed at an eye, computer vision algorithms can detect the stripe as a horizontal sequence of dark lines. Dark lines can be guaranteed when the lighting frequency is lower than the video frequency. When the lighting is faster than the video, the on and off axis light pulses will overlap during a video frame, creating a bright stripe instead.

We also assume that the light pulses have very short duration to make sure the stripes are as narrow as possible. In practice, the stripe will move at an approximately constant speed, so we can also measure its frequency. Because the stripe can be hidden at times, a Kalman filter can be used to keep track of its position.

When the stripe is not over the pupil region, the pupil can be easily detected from the difference of consecutive frames. Problem arises when the stripe falls over the dark or bright pupil region. Such cases can be predicted from the estimated stripe position and previous pupil position. Figure 3 shows an example of the pupil region show bright and dark regions due to the lack of synchronicity between lights and video.

Assuming that the stripe can be made narrow as in Figure 3, most of the pupil can be segmented as high contrast regions from the difference of consecutive frames. Another alternative would be to combine the area above the stripe in the current frame with the area below the stripe of the previous frame to compose the true dark or bright pupil image generated by one of the on or off light pulses. This alternative would generate a virtually synchronized video, with up to one frame behind the true video frame.

When the light pulses cannot be made very narrow due, for example, to circuit or camera limitations, wide stripes will be generated which might cover most of the pupil. In such cases, the light pulses could repeat two or three on-axis pulses followed by the same amount of off-axis pulses, to guarantee...
Figure 2. Possible artifacts created when the video and lighting are not synchronized.

Figure 3. Dark and bright pupil images captured using asynchronous lighting.
that the whole pupil is seen, allowing the pupil to be tracked but with a reduced frame rate.

CONCLUSION

In this paper we have designed a computationally efficient pupil detector using a low cost camera and very simple external hardware composed of an oscillator and two near infrared light sources. The use of active infrared illuminators makes the system more robust to illumination conditions, though restricted to indoor use. Future work includes the prototyping of this design and performance evaluation of an eye tracker based on the asynchronous differential lighting technique presented in this paper. Because the algorithm is computational efficient, we expect that the prototype will be able to process about 200 frames per second using a low cost camera (such as the Sony PS3-Eye camera) in a low end computer.

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REFERENCES


