Study of Additional Eye-Related Features for Future Eye-Tracking Techniques

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Abstract
We investigated additional eye-related features that can be tracked by modified Video-Oculography (VOG) and Photosensor Oculography (PSOG) systems in order to improve their data quality. Using a VOG technique in conjunction with the developed method of detection of actively moving eye-related features, we performed an experimental evaluation of movement characteristics of the observed features, such as eyelashes and eyebrows. Our results shown strong correlation between the lower eyelashes and limbus, which was taken as a control measure of eye movements. Our results can be implemented in applications that require high data quality of eye-tracking, such as in Virtual Reality (VR).

CHI'17 Extended Abstracts, May 06-11, 2017, Denver, CO, USA
ACM 978-1-4503-4656-6/17/05.
http://dx.doi.org/10.1145/3027063.3053095.

Author Keywords
Eye-tracking; photosensor oculography; video-based oculography.

ACM Classification Keywords
H.1.2. [User/Machine Systems] – Human factors,
H.5.2. [User Interfaces] – Input devices and strategies,
H.5.2. [User Interfaces] – Theory and methods.

Introduction
Virtual Reality (VR) is coming to be a part of humans' future. Today most of VR devices have a form-factor of head-mounted devices (HMD) with one or two screens in front of the eyes. To provide a smooth picture for the eye, these screens should have a resolution about 2160 x 1200 px at 90Hz [1]. It is challenging to maintain this resolution for the entire screen because it requires a fast graphics system and high power expenditures. One of the approaches to such issues is a human-computer interaction (HCI) technique known as *foveated*

rendering [4, 11]. It can substantially reduce the requirements for the graphics system without degrading the perceptual quality of the picture.

The procedure of recording individual's eye movements is named *oculography* (OG) or *eye-tracking* [2, 5]. It can be done using invasive approaches such as scleral coil and non-invasive approaches, that is preferable for VR, such as electrooculography (EOG), video-oculography (VOG), which is used now for VR HMD for its simple hardware setup, or Photosensor Oculography (PSOG) [15]. Whereas EOG is challenging to be employed to determine of individual's point of regard (POR), VOG and PSOG can provide such an output. VOG employs a camera that records images of the eye(s) to locate key features, like the pupil and the corneal reflection. PSOG [3] was designed as a part of HMD. Placed closely to the user's eyes, a PSOG device evaluates the rotation of the eyeballs by measuring the amount of reflected radiation from the eyes illuminated by infrared light using photocells. It aims to track a particular eye-related feature like eye limbus (boundary between cornea and sclera) [10], entire iris [12] or some parts of it [21].

However, both of these approaches have flaws in implementation for foveated rendering in VR HMD that affects data quality. VOG systems are prone to high-frequency noise and optical artifacts and cannot record POR if the eyes are closed, during blinks, for example [5]. PSOG requires very careful sensor placement; it limits the range of correctly recorded eye movements by ±15° to ±10° due to the ration between the recorded signal and eye position is not highly linear [12]; it has cross-coupling between horizontal and vertical signal components.

There are evidences that data quality can be improved by adding more eye-related features taken into account by eye-tracking systems based on VOG and PSOG. Adding tracking a corneal reflection to an original VOG design that tracked only a pupil made VOG more robust to slight head movements [5]. Adding more photocells covering limbus at different angles to original PSOG design that was able to track horizontal eye movements only provided capability to track also vertical eye movements [21]. Since a VOG system records the image of the eye and the area around it by default, tracking the additional features primarily means modifying of employed image processing algorithm and does not require modifications in hardware setup. Extra photocells for PSOG are inexpensive and consume low power, therefore it should not significantly raise the cost of such eye-tracking systems.

The goal of our study was to investigate what additional eye-related features that can provide data for accurate tracking eye movements and determination of POR. This is an initial step to the long-term goal: to improve VOG and PSOG data quality to be sufficient for VR HMDs. The summary of the contribution of this paper is the following:

1. We developed a method of extraction of information about how the eye works, specifically – what additional features like eyelashes, eyebrow are active in motion extent, during eye movements.
2. We measured their activity as numerical values during an experiment and found how it corresponds with the control measure of eye movements, the motion of limbus. We found that one of the features, lower eyelashes, could be a source of information about eye movements and POR if tracked by modified VOG

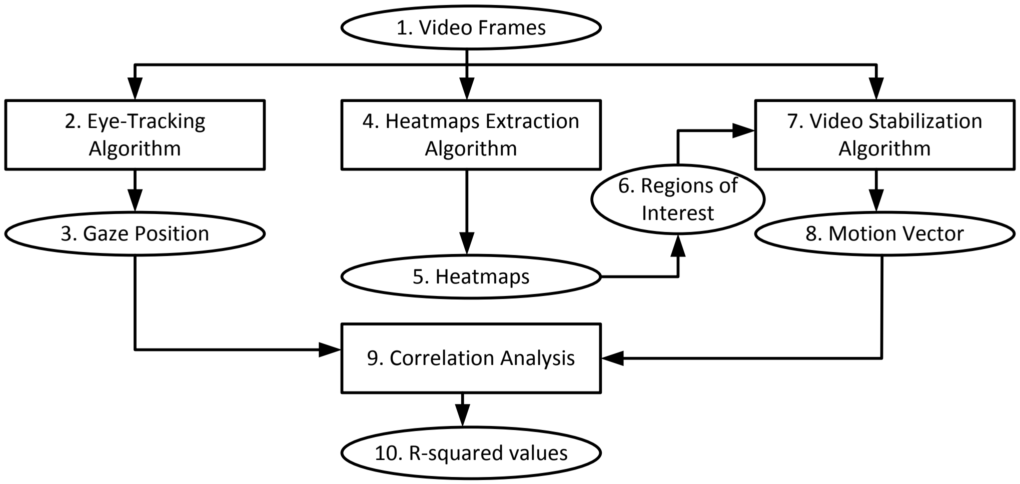

Figure 1. General workflow

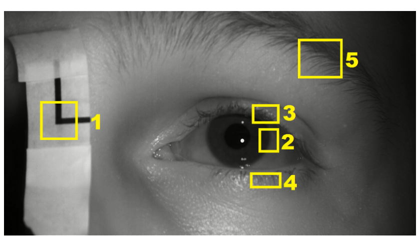

Figure 2. ROI pattern for tracking by motion measurement algorithm: 1 – head movements, high-contrast "L" shape pattern; 2 – limbus, control feature; 3 – upper eyelashes; 4 – lower eyelashes; 5 – eyebrow.

image processing algorithm or extra photocells of PSOG device.

Previous work

There are reported studies where tracking other or additional features in VOG systems was employed to attain different goals such as blink detection [16], dual-state eye-tracking [7, 17] and providing capabilities to track the eye under different light conditions [13]. But we are not aware of any prior studies aimed to analyze motion characteristics of different eye-related features to estimate its potential utilization for eye-tracking purposes.

PSOG was developed much earlier than VOG [6, 18, 21]. Later, with technological advances in electronics and optics VOG systems became dominant [5], that inhibited further development of PSOG devices. Before that, several patterns of photocells placement were investigated in different studies [21], including tracking upper eyelid [20] or lower eyelid [8] but also without evaluation of how a particular feature affects eye-tracking data quality.

Method

This study is targeted to attain following goals: a) Determine what eye-related features are active during eye movements – we will use a special notation for them – Active Eye Features, AEFs. b) Group AEFs into two subsets – Informative AEFs for ones that are correlated with eye movements, to use them to get an extra information for eye-tracking; Interfering AEFs, otherwise, to ignore them from further processing.

This can be done by recording a high-resolution video of the eye to be able to detect even slight movements and process the frames in different ways to get numerical values of eye rotation and AEFs movements, merging the outputs at the final stage (Figure 1).

Eye tracking

Pre-recorded video stream was fed to VOG software to obtain numerical estimation of eye rotation. Then, with the assumption that the head was stabilized and they looked at the screen during recording excludes blinks, the point of regard was converted to eye rotation measurements.

Heatmap extraction

In order to determine AEFs, we developed a new method of frames processing that gives an output as a heatmap image, where 'hot' colors indicate areas that had changes across analyzed range. The ground of this method is an assumption that for one saccade duration plus allowance, the head movement was relatively

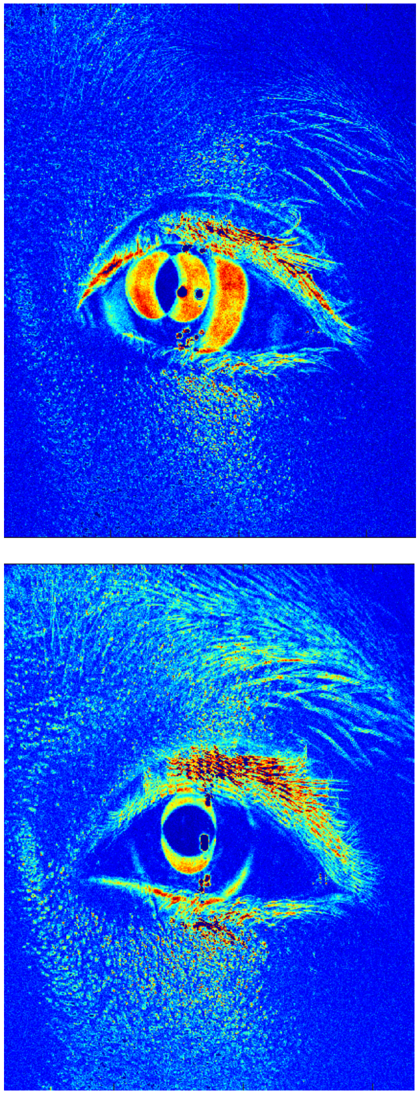

Figure 3. Heatmap examples for rightward horizontal (top) and upward vertical (bottom) saccades

small. With this assumption, it is possible to get all of the consequent frames with movement related to a particular saccade by examining the frames for evidence of motion and consider that there is no head movement in there. Then we calculated the absolute difference for each for each pair of frames next to each other, forming the difference image. The maximum absolute values among the difference images formed a result image. The next step was removing the bright spots like corneal reflections by thresholding to emphasize AEFs on the image. The brightness threshold was set at 50 by an empirical evaluation. All of the pixels with brightness above the threshold were set to zeros. Then the heatmap was drawn based on the resulting image. The examples of heatmaps are presented on Figure 3. For each individual, we obtained four heatmaps – for upward, downward, leftward and rightward saccades, one heatmap per saccade.

Measuring AEFs' movements

After analyzing heatmaps, three potential AEFs were determined for this study: upper eyelashes, lower eyelashes and eyebrow, due to their activity. Furthermore, they are dark and have lower reflectance than other features nearby so their impact to PSOG sensors should be substantial. To ensure that the movement measurements is done correctly, a control feature, limbus, was also included. It is anticipated to show a strong correlation with data from the VOG eye-tracker. All of the features are located on the first frame of the video and defined as Regions of Interest (ROI) – a rectangular part of the frame, which movements will be measured at the next stage. To be able to compensate head movements, they were measured as a movements of a high-contrast "L" shape control pattern fixed on the of individual's nasion before recording the video (Figure 2).

After defining a particular ROI, the video is fed to a video stabilization algorithm. To stabilize frames, this algorithm first measures motion of a ROI. The output contains motion vector as a relative shift between current and previous frame in horizontal and vertical axes and the total shift was obtained directly as Euclidean distance.

Participants

We analyzed data from 15 student subjects (11 males/4 females), ages 18-35 (M = 24.7 years, SD = 4.7), compensated by a course credit. Texas State University's institutional review board approved the study, and subjects provided informed consent.

Apparatus and software

In order to be able to record a video of eye movement, we built a non-commercial eye-tracker. Its hardware part includes ThorLabs DCC1545M camera set to resolution of 1280x696 pix to achieve the frame rate of 30 fps and to analyze AEFs in detail. The camera has Navitar MVL7000 tele-photo lens. The setup also included chin and front rest to stabilize a head. An eye-tracker algorithm based on software ITU GazeTracker [14] was modified to process all of the frames at full resolution without losses. It was run on Windows-based desktop with Intel Core i7-6700K CPU at 4GHz and 16GB RAM. To display a visual stimulus we used a computer monitor with screen dimensions of 374x300 mm and resolution at 1280x1024 pix, placed at the distance of 500mm from the participants' eyes, which were aligned to monitor's center.

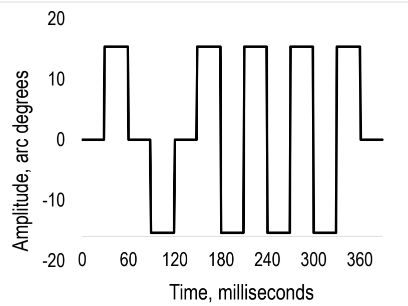

Figure 4. Horizontal position of the dot stimulus for horizontal saccades, vertical position was equal to 0°. For vertical saccades, vertical position amplitude was 6.6°, horizontal position was equal to 0°

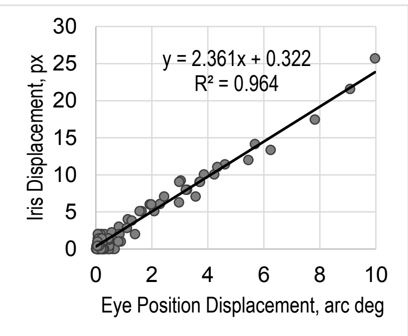

Figure 5. Linear regression for vertical saccades, subject 4

Procedure

The vast majority of eye movements can be roughly split into two subsets – *saccades* and *fixations*. While fixations are time intervals when the eye is relatively stable getting information about a visual target, saccades are rapid movements between fixations.

The visual stimulus was presented as a single white dot on black background d=0.67° with jumping movements either to the left or right, forming pure horizontal saccades at amplitude=15.4°, or up and down, forming pure vertical saccades at amplitude=6.6° from the screen center (Figure 4). Dwell time was 1 sec. for all dot positions. We tested a range of amplitudes from 2.2 to 17.6° for horizontal saccades and from 2.2 to 8.8° for vertical saccades with step of 2.2°, and the selected values were the largest ones provided stable tracking by both eye-tracking and computer vision video stabilization algorithm. We recorded left eye only, monocular mode, left eye. Average calibration accuracy was 0.46° (SD=0.21°), average validity of analyzed parts of records were 97.4% (SD=4.8%) for horizontal saccades and 96.8% (SD =3.9%) for vertical saccades, respectively. Blinks and noisy parts were filtered out by an amplitude-based algorithm and checked by visual inspection. We filtered out samples when no motion was detected for all AEFs from the motion data.

Results

Average R^2 values for all considered AEFs are presented in Table 1. Figures 5 and 6 contain examples of linear regression for one of the records for samples remain after outliers removal outside range of 3 standard deviations from the mean. Presented values of pixels less than 1 are the result of compensation of measured head movements by subtraction from AEFs movements. The compensation is partial because the method can take into account only horizontal and vertical movements and does not measure rotational ones. Nevertheless, this method compensates the head movement at a substantial part. Grouping of samples around zero values occurred to the rule of data filtration – the sample is taken into account if at least one AEF made a movement at more than one pixel, movement at one pixel is a threshold of equipment noise.

AEF	Limbus	Upper Eyelashes	Lower Eyelashes	Eyebrow
Pure Horizontal Saccades				
Mean (STD)	***0.982*** *(0.011)*	*0.723 (0.179)*	*0.739 (0.157)*	*0.076 (0.125)*
Pure Vertical Saccades				
Mean (STD)	***0.951*** *(0.033)*	*0.820 (0.105)*	***0.926*** *(0.051)*	*0.064 (0.050)*

Table 1. R^2 values between eye rotation evaluated by the eye-tracker and AEFs.

Discussion

Since VOG eye-tracker measures the position of pupil, we took limbus as a control measure due to its bigger size and higher contrast with sclera. Its motion shown high R^2 values close to 1 indicating that the method of AEFs motion works correctly. Differences from 1 can be explained by small internal movements of the pupil inside iris [9] and measurement error.

The main finding of our study is a strong correlation for lower eyelashes movements in PVS, which is close to R^2 between evaluated eye rotation and limbus position. In particular, information from lower eyelashes can be used to determine eye rotation in vertical saccades,

Figure 6. Linear regression for vertical saccades, subject 4

and potentially, oblique saccades. This result is helpful to improve one of the weaknesses of earlier implementations of PSOG, which characteristics for vertical saccades are significantly worse than for horizontal [19] turning 'lid artifacts' to useful feature to track. Whereas eyelashes caused distortions in the signal for those devices, measuring its movements can be an Informative AEF. Tracking vertical position of lower eyelashes as an extra feature can be done by directing a small array of IR photocells on that area. This technique should improve the linearity of the PSOG, reduce its cross-coupling and potentially provides a capability to get a valid and correct eye rotation even during blinks, that can be useful for precise and robust eye-tracking in VR.

Correlation of upper and lower eyelashes are mediocre for horizontal saccades for precise measurement of eye rotation, which requires high R^2 values. This result corresponds with the earlier studies that found cross-coupling artifacts in recorded signal from PSOG devices [12], because the movements of eyelashes being correlated in general with horizontal eye movements, has some uncorrelated component of such a movement that can disrupt the device and be recognized as cross-coupled vertical movements. Other mediocre R^2 values, between evaluated eye rotation and upper eyelashes for vertical saccades can be an evidence of another artifact that causes distortions of the amplitude of vertical saccades. This artifact is connected with neuronal pulse to the upper eyelid, it has been measured by PSOG and EOG and reported in the earlier studies [19]. The eyebrow seems to be uncorrelated with saccades. These features are considered as Interfering AEFs.

Future work

Our work has several limitations at this time that we target to address at the next stages of our research. The currently investigated features were eyelashes and eyebrow, which have low reflectance in IR light. We plan to add more features and record more different stimuli with wider ranges of amplitude and eye positions. This also includes more complex analysis of AEFs' movements, taking into account their direction. Potential impact of facial expression is also planned to be analyzed. Addressing technical limitations, we plan to perform binocular recordings, increase sampling rate, stabilize the images with advanced stabilization algorithm to take into account rotational movements and perform stabilization for all stages including heatmap extraction.

Conclusion

In this paper, we investigate what additional eye-related features can be used in VOG and PSOG eye-tracking devices by checking the correlation of their motion with limbus motion that was taken as a control measure. We found that the information from lower eyelashes could be used to improve eye-tracking data quality to allow its usage in VR applications such as foveal rendering in VR HMD. Such information can be captured by performing suitable modifications of VOG image processing algorithms and exploring new PSOG photocell placement patterns to track the new features that will be a goal of our further research.

Acknowledgements

This work is supported by NSF CAREER Grant #CNS-1250718. We express a special gratitude to D. Lohr, E. Hanson, R. Collins, and N. Calderon for proctoring eye movement recordings and data processing.

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