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Pupil Position Estimation Error in an Eye Tracking System Based on the MEMS Mirror Scanning Method

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Summary: The paper presents the research results on the impact of key parameters of the eye tracking system on the accuracy of pupil position estimation. The system was based on the method of scanning the eye surface with a laser beam through a 2D MEMS mirror. The research was conducted based on a virtual simulator. During the tests, the effects of the detector's field of view, signal sampling frequency and frequency ratio of the MEMS mirror axis was examined. With the expand of detector's field of view, errors increase – when reduced from 2° to 0.1°, the relative error decreased by 45,3 %. Increasing the sampling rate resulted in a 59 % decrease in error compared to the initial value and a stabilization at a 0.4° relative error rate. As the frequency ratio increased, the relative error decreased - increasing the ratio from 5 to 20, resulted in a 46.2 % error reduction.

Keywords: Eye tracking, MEMS mirror, Laser scanning, Head-mounted display.

1. Introduction

Eye tracking systems are used in various market areas – marketing analysis, psychology, neurology, medicine, automotive industry, and others. Depending on the accuracy of the device, saccades and eye fixation points can be detected. Eye tracking systems are nowadays largely based on image analysis [1]. In such systems, the IR camera captures the image of the eye, illuminated by a set of diodes. The software, on the other hand, analyzes the image and looks for a pupil in the frame. However, image processing is computationally very demanding. Especially in the case of systems with higher resolution - the analysis must pass through every pixel. Eye-tracking systems based on image analysis require a high-end PC for analytical work. To adapt such a system to the computing capabilities of a mobile system, it is necessary to use cameras with very low resolutions [2]. An alternative to vision tracking is systems based on laser scanning [3]. An example is a system using a 2D MEMS mirror. Such a system scans the eye area by changing the orientation of the MEMS mirror. The curve drawn by the laser beam depends on the type and frequency of the mirror vibrations in both axes. Bi-resonant mirrors are usually found. In this case, the beam path can be described by a Lissajous curve and its shape depends on the frequency ratio of both axes.

The quality of eye tracking is dependent on the accuracy of the eye's orientation determination. This in turn is based on matching the estimated pupil position with the eye model [4]. Then, the determination of the point observed by the user in space consists of finding the intersection point of normal vectors to both eyes' pupils.

This paper presents research on key parameters of the MEMS scanning eye tracking system and their impact on the accuracy of pupil estimation. The system is designed for use in HMD (head-mounted display).

2. Materials and Methods

To test the operation of an eye tracking based on the MEMS mirror scanning method, a virtual simulator of such a system was built (Unity3D v.2019.3.3f1). The simulator consisted of geometric models of individual elements of the system and the eye (together with the face of the virtual user). The algorithms responsible for movement and functions of individual elements were implemented. The output product of the simulator was data from the virtual detector saved to file. Estimation of the pupil position of the virtual eye based on the data from the detector was performed in MATLAB (v.2019b) software from MathWorks.

Based on the simulator, the effect of the spatial distribution of the elements on the pupil position estimation errors was examined. As the system was adapted to work in HMD, different variants of mounting positions of the MEMS mirror, laser and detector were tested inside such a device (in relation to the axis of the eye - HMD lens).

Moreover, the effect of main elements' parameters – the detector's field of view, signal sampling frequency, or the ratio of operating frequency of the MEMS mirror axes was also examined. For each of the examined parameters 10 independent series were carried out at different settings of the system. In each series 15 000 – 25 000 measurement samples were collected.

3. Results

The research on the detector's parameters has shown that with the increase of its field of view (FoV), errors in estimating pupil position also increase. The correlation coefficient was 0.96. When the FoV was reduced from 2° to 0.1°, the relative error decreased by 45.3 %.

Studies on the effect of sampling resolution showed a negative correlation (-0.88) between the number of samples per slow axis period of the MEMS mirror and the relative error of pupil position estimation. A diagram of this effect is shown in Fig. 1.

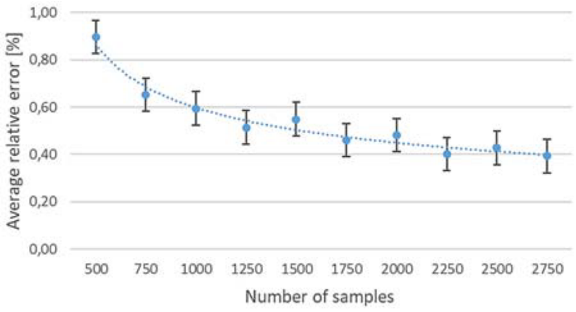

Fig. 1. Correlation between the number of samples and the pupil position estimation error.

Studies on the influence of frequency ratio on the error of pupil position estimation showed a negative correlation (-0.76). As the frequency ratio increased, the mean relative error decreased. The study showed that for low ratios (f/s<10) the relative error was about 0.6°, and for high ratios (f/s>15) 0.4°. As the ratio increased from 5 to 20, the errors decreased by 46.2 %. The graph of this relation is shown in Fig. 2.

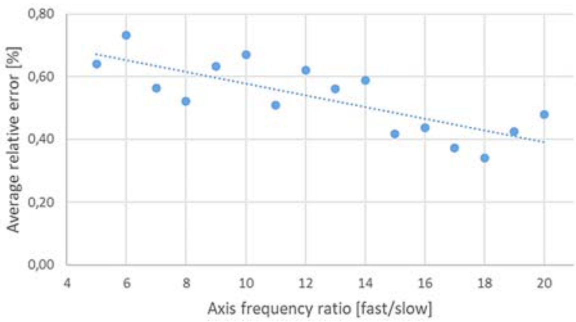

Fig. 2. A graph of the relation between the axis frequency ratio and the error of pupil position estimation.

Studies on the spatial distribution of the MEMS mirror, laser and detector showed a correlation between the distance from the eye/lens axis and an increase in the pupil position estimation error. When the MEMS mirror was mounted directly in the lens circumference area, the average relative error was 0.7° (standard deviation 0.32°). In the peripheral area it was 1.4°, with a standard deviation of 0.24°. The most accurate areas were perpendicular to the axis (vertical and horizontal), where the error averaged 0.35°.

4. Discussion

As the detector's field of view increases, the area it averages increases. This smoothes the signal slope. The pupil circumference points are determined less precisely on flatter slopes. This makes the error of estimating the pupil position larger for a higher detector's FoV. However, increasing the averaging area can have a positive effect in terms of eliminating random measurement errors.

The signal sampling rate determines how many measurement points were collected during one period of the slow axis. This parameter is similar to the resolution in video systems. A larger number of samples allows for more accurate determination of pupil circumference points. As the number of measuring points increases, the error value is aiming at a constant value of about 0.4 %.

The MEMS mirror's axis frequency ratio tests showed its effects on pupil position estimation error. With a low frequency ratio, the relative resolution of points on the vertical axis increased, which resulted in accurate measurements of pupil position in specific eye settings. However, when the eyeball took a different orientation, the error increased significantly. For large ratios, the standard deviation was much lower, and the average relative error was smaller.

Studies of the spatial distribution of the system elements showed its influence on the error of pupil position estimation. When increasing the distance of the MEMS mirror from the optical axis (eye - HMD lens), the error increased. Horizontal positions (relative to the eye) were the most accurate settings. For vertical, the scanning area was obscured by the user's eyelashes and caused more error.

5. Conclusions

The developed simulator made it possible to determine the correlation curves of the elements' parameters with the error of pupil position estimation. This allowed to find the optimal configuration of their values. The study of the spatial setting showed at which setting the errors will be the smallest. These studies will enable the construction of a stand consisting of real, physical elements with optimal configuration of the setting and parameters.

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References

[1]. C. H. Morimoto, M. R. M. Mimica, Eye gaze tracking techniques for interactive applications, *Computer Vision and Image Understanding*, Vol. 98, Issue 1, April 2005, pp. 4-24.

[2]. W. Fuhl, M. Tonsen, A. Bulling, E. Kasneci, Pupil detection for head-mounted eye tracking in the wild:

An evaluation of the state of the art, *Machine Vision and Applications*, Vol. 27, Issue 8, 2016, pp. 1275-1288.

[3]. S. T. S. Holmström, U. Baran, H. Urey, MEMS laser scanners: A review, *Journal of Microelectromechanical Systems*, Vol. 23, Issue 2, 2014, pp. 259-275.

[4]. Z. Wan, X. Wang, K. Zhou, X. Chen, X. Wang, A Novel method for estimating free space 3D point-of-regard using pupillary reflex and line-of-sight convergence points, *Sensors*, Vol. 18, Issue 7, July 2018, 2292.