Eye Tracking as a Method of Controlling Applications on Mobile Devices

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Abstract: The possibility of using eye tracking in multimodal interaction is discussed. Nowadays, communication by eye movements can be both natural and intuitive. The main goal of the present work was to develop a method which allows for controlling a smartphone application by using eye movements. The designed software was based on the Open Source Computer Vision Library (OpenCV) and dedicated for Android system. We conducted two sets of tests: usability tests of the new solution, and tests on how the methods of template matching affect the operation of the device. The results, obtained by testing a small group of people, showed that the application meets all stated expectations.

1 INTRODUCTION

1.1 Motivation

The use of eye tracking in multimedia includes many different applications (Duchowski, 2007), among which the psychology (psychophysiology) of classical studies of the Human Visual System or the visual control for the disabled can be enumerated. It is true to say that recently multimodal interaction has become one of the most important fields of multimedia. The dynamic development of natural methods supporting the communication with various intelligent devices is recognized and appreciated by professionals from practically all fields of science and technology. Not so long ago no one imagined that it would be possible to enter information using other devices than a keyboard and a computer mouse. Currently most of us exchanged mobile phones for smartphones – devices, which have unnoticeably 'lost' the classic keyboard, replaced by multi-point touch control. With such a rapid development of multimodal interaction; in a dozen or so (or maybe in a few) years, the brain computer interface could be the most important and common form of interaction with electronic devices. Nevertheless, before this happens, it is worth considering whether today we can communicate in a more natural and intuitive way. On the other hand, it also results from our expectations. Who has not dreamt about more comfortable and simpler way to operate the smartphone when traveling by metro in the morning rush hour and having only one free hand? Moreover, it should be emphasized that the described problem is socially significant, especially in the field of communication with disabled for whom eye movements provide the only possibility to transmit information.

If we can recognize the sight direction using eye tracking, it is worth to applying the eye to control the device. Unfortunately, the effective use of eye tracking in mobile devices becomes a problem. The question arises whether we can correctly and effectively recognize the direction of sight based on an image from a smartphone camera. Especially, when the image is capture by the only one camera and also not a professional one.

1.2 The Aim of the Article

The aim of this paper is to develop a method of control in multimodal interaction by using eye tracking based on the recognition of the eye image from one camera of the mobile device. The key method for recognizing the direction of looking in our solution is an appropriate template matching method. An additional goal of the work was therefore to check which method of template matching is best suited to our solution.

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2 EYE TRACKING AND ITS APPLICATIONS IN MULTIMODAL INTERACTION

In recent years, many methods have been developed to track the movements of the eyeballs. Two approaches for recording eye movements are worth mentioning: techniques for monitoring eye position in relation to the head and methods for determining the orientation of the eye in space (or in relation to the selected reference point). The latter is commonly used to identify elements of the visual scene, such as graphic objects in interactive applications (Young and Sheena, 1975).

There are many methods of measuring eye movement. Among the most commonly used the following can be mentioned: Electro-OculoGraphy (EOG), Photo-OculoGraphy (POG) and Video-OculoGraphy (VOG), Purkinje imaging, video-based reflection systems based on pupil and corneal. The book (Duchowski, 2007) and document (Patel and Panchal, 2014) are the interesting reviews of the methods and techniques used in eye tracking.

Oculography is used in many areas of human activity - from medicine and psychology, through marketing, education and sports to entertainment. In recent years, eye tracking technology has also become popular among engineers working on human-computer interaction (HCI), particularly in multimodal HCI. A survey of different methods of communications can be found in (Jaimes and Sebe, 2007). In the multimodal HCI, oculography is often used in equipment dedicated to people with disabilities, who, thanks to that, can communicate using the eyesight (Strumiłło and Pajor, 2012).

In the case of nonmedical applications of multimodal interaction, there are many attempts of replacing the pointing device by eye tracking. In (Al-Rahayfeh and Faezipour, 2013) Authors presented a survey of methods used in eye tracking and head position detections. A survey of eye tracking methods in relation to multimodal interaction was also presented in (Singh and Singh, 2012). There are known studies of using single calibrated camera for head (face and eyes) position analysis in HCI. In (Rougier et al., 2013) the Authors calculated in real-time a 3D trajectory, using proposed algorithm to analyze the image from one camera.

There are few publications about controlling a mobile device using eye tracking with a built-in camera of this mobile device. In (Drewes et al., 2007) the Authors discussed possibility of using eye-gaze tracking for mobile phones and showed that it could be alternative and attractive method for interaction. The main idea of using eye gestures to control a mobile device with an additional light source (e.g. IR LED) has been patented (Sztuk et al., 2017). The most advanced project of oculography for a mobile device has been described in 2016 (Krafka et al., 2016). However, in that article the Authors used large-scale dataset for eye image analyzing (almost 2.5M frames – over 1450 people) and a convolutional neural network for eye tracking. In our project we focused on geometrical methods and tried to select method of template matching.

3 DESIGN ASSUMPTIONS

The aim of the work was to design and implement an application that allows the user to focus on the screen of a mobile device and enable control by eye movements. The following design assumptions were adopted:

- The front camera of the mobile device will be used. A camera that allows for capturing low resolution images, but at least 640x480 pixels;
- The expected accuracy: the ability to identify several regions of user's interest in the device screen. Regions that are associated primarily with eye movements of left-right and up-down;
- Recognition will work in real time – the purpose of the application is to control the device;
- Recognizing the viewing direction (recognizing the selected region on the screen) should be insensitive to changes in lighting conditions;
- Modularity of the application will allow for the integration with the operating system of the mobile device.

The majority of commercially available, mid-range devices of this type are characterized by poor quality of installed front camera. Therefore it is very important to design a graphical user interface (GUI) that will help to reduce any possible hardware limitations. On the other hand, the GUI must be intuitive and unambiguous. This will be important if the application is used by the disabled. Therefore we have adopted the following assumptions regarding GUI preparation:

- The graphical user interface should be as simple as possible and unambiguous;
- We should use simple unambiguous geometric forms instead of complicated graphics;
- The individual components of the GUI should be arranged in such a way as to make navigation easier by using eye movement;

- Colors should be selected in such a way as to facilitate the navigation. If possible, the colors should match the generally accepted convention (e.g. green is usually associated with acceptance). They will be used up to 4 different colors.

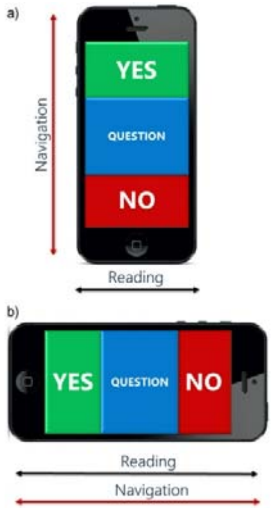

Figure 1: GUI and layout: a) vertical, b) horizontal.

Initially, two GUI prototypes were considered: vertical (Fig.1.a) and horizontal (Fig.1.b) layout of the components. In the case of the horizontal layout (Fig.1.b) there are concerns that the participant will move the eyes along the text while reading it. This situation, in turn, can interfere with the navigation of the application. The application of control in a direction perpendicular to the reading direction (Fig.1.a) could prevent such situation. Additionally, very short sentences are used in the proposed application, so this problem should not matter. At the same time the movement of the eyes in one plane (left-right) may be more convenient for the user. On the other hand, recognizing the vertical changes in the eye's position is much more difficult. The eyelids partially cover the iris, which leads to additional errors when the camera is of low resolution. We have conducted preliminary tests, how these errors affect getting the correct eye image The tests have shown that the effective operation of our solution can be achieved practically only in horizontal layout.

It should be noted here, that in case of real applications of such GUI, it is necessary to prepare a series of test screens. This would allow the user to become familiar with the operation of the application and to practice how to use it. The user should also be able to choose one of the considered systems according to his habits and personal preferences.

4 IMPLEMENTATION. ALGORITHM OF THE EYE TRACKING

Android smartphone was chosen as a mobile device because of its prevalence. The developed application was prepared in Android Studio environment, using Open Source Computer Vision Library (OpenCV, 2014). This solution will ensure modularity of the application and easy integration into the operating system.

The image retrieved from the mobile device's camera is processed and analyzed to determine the direction of the sight. The designated direction of sight allows for determining the area of the screen that the user is looking at. On this basis, the appropriate procedure of control is started. The application for image processing and analysis performs consecutively the following functions:

1. **Face Detection in the Image.** We have used the Viola-Jones method (Viola and Jones, 2001), which is a cascade classifier based on Haar features. This analysis allows for focusing on the selected features of the image, abandoning the processing of some information (such as pixel brightness) in later stages of the algorithm. Moreover, the use of cascade classifiers allows for eliminating areas where there is no face, effectively and quickly. The result of the detection is a rectangle covering the face.
2. **Determination of the Proper ROI (Region of Interest).** We are looking for a rectangular area in which the eyes are located. Based on the known geometrical features of the face (size of elements and proportions), areas of the face where there are no eyes, are eliminated. Then, the rectangle containing the eyes is divided into two parts, so that the image can be processed independently for the left and right eye.
3. **Determination of the Pupil in the Eye ROI.** The eye image is extracted from the ROI using Haar's classifier. Then the darkest point and its dark surrounding forming the pupil is sought in the image of the eye.
4. **Analysis of the Pupil Position.** The position of the pupil is monitored. Changes in position mean that the eyes are turned towards another direction. We have experimentally determined the dependencies between recorded changes in pupil position and screen areas, which are related to the corresponding viewing directions. An identified visual stop on a specific screen area triggers the appropriate control procedure.

Analysis of change in the position of the pupil is carried out using the method of template matching.

The analysis of the relationship between the position of the pupil (recognized) and the direction of looking is very important. It is independent of the individual human characteristics – each of us moves the eyeball in the same way to direct the eyesight in the proper direction. This relationship allows for performing a simple calibration of the device by each user, taking into account the individual way of holding the device.

5 THE PROTOTYPE AND USABILITY TESTS

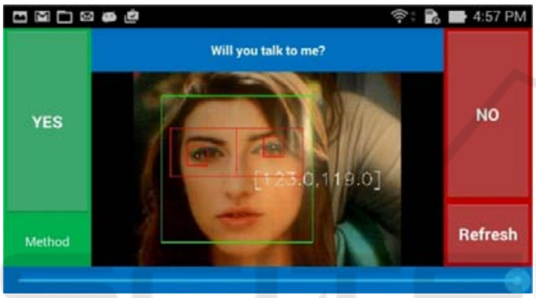

Figure 2: The screen of application. The rectangle of face and ROI of the eyes are marked. The current coordinates of the identified left eye pupil are also marked.

After initial testing in the environment of Android Studio and Android Device Monitor, the developed software was implemented in the tested smartphone. The final version of the screen is shown in Figure 2. The question for the user is placed above the camera image; the answers are situated to its left (the positive answer) and right (negative answer) side. We decided that the user have to be gazing at the button for a certain duration of time in order to activate/confirm that button. At the bottom of the screen there is a bar that allows for changing the geometric method of shape matching. This feature was used at the optimization step of the application. Applying the proposed scheme for control / selection in the operating system means implementing the binary decision tree. Such a control is not always the most effective one, but makes it possible to implement any solution.

5.1 Tests of the Main Function in the Proposed Solution

The main function of the developed application (i.e., control by eye movement) was tested on a group of several users. The experiment was conducted in a small group of 6 participants. The experiment was developed on the basis of standard tests (Fawcett, 2006, Powers, 2011), giving an objective assessment of the interface quality, using standard evaluation criteria. The purpose of the experiment was to answer a series of questions using a new eye tracking solution. Each participant had to answer 40 questions: 10 answers given correctly using left field, 10 answers given intentionally incorrectly using left field, 10 correct answers using right field, 10 intentionally incorrect answers using right field. The order of the questions was random and the program counted the results as: True Positive, False Negative, True Negative, False Positive respectively. Before performing the experiment, we explained how the device works and each participant had the opportunity to work for a few minutes. Then we explained the rules of the experiment. The results of all participants are presented in Table 1. After the experiment we discussed the new solution with test participants. There were, of course, subjective assessments, however this discussion was very important for our conclusions. Everyone emphasized that the solution is convenient, easy to use and user-friendly.

The experiments have shown that the introduced solution allows for visual control, therefore the aim has been achieved. However, the designed mechanism is not devoid of faults. Basic one is low resistance to head movements recorded by the camera. It is worth noting that this is a relative head movement. The problem occurs in both situation: when the device is stably held in hands but the user moves his head during the operation and also when the head is motionless but the user moves the device. Moreover, in practice both cases can occur simultaneously. In principle, such a problem was expected in our solution.

On the other hand, the problem of stability has not hindered the work. The way for avoiding this problem is to pay special attention to maintaining stable position. All the persons who used the application after a few attempts have mastered the basics of control and have learned how to work properly and avoid interfering movements.

5.2 The Impact of the Face Lighting

We have tested several different lighting options. The application was launched during the day - in daylight, at twilight - with two types of lighting (both natural and artificial) and in the evening - with full artificial lighting.

Table 1: Results of tests True Positive Rate (TPR), True Negative Rate (TBR), Accuracy (ACC), Standard Deviation (SD).

Parti cipant	For the left field				For the right field				TPR	TNR	ACC
	TP	FN	TN	FP	TP	FN	TN	FP			
1.	20	0	13	7	14	6	20	0	0.85	0.83	0.84
2.	20	0	14	6	11	9	18	2	0.78	0.8	0.79
3.	20	0	11	9	12	8	20	0	0.8	0.78	0.79
4.	19	1	14	6	14	6	20	0	0.83	0.85	0.84
5.	20	0	13	7	12	8	20	0	0.8	0.83	0.81
6.	20	0	12	8	13	7	19	1	0.83	0.78	0.8
Mean	19.83	0.17	12.83	7.17	12.67	7.33	19.50	0.50	0.81	0.81	0.81
SD	0.37	0.37	1.07	1.07	1.11	1.11	0.76	0.76			

Experiments have shown that the application worked correctly in practically all tested conditions and had a high resistance to changes of lighting. The problem can only be caused by reflections of the light sources, visible on the iris. Such elements could be wrongly interpreted by the detection algorithm, which can lead to a reduction in precision. However, this did not cause the program to work incorrectly. On the other hand, users can influence the head position with respect to external lighting and easily avoid such errors.

5.3 The Impact of the Background in the Field of View

The tests performed has not showed problems with proper face recognition. We have also made a test when oval-shaped elements appeared close to the human face in the camera's field of view. Using background with geometric figures that are close to the face shape results in the worse performance of the recognition algorithm. Background objects are treated as another face, causing the application to malfunction. Selection of the wrong background can be a factor strongly influencing the proper functioning of our program. However, such a problem does not occur in a typical environment (without oval-shaped elements and images of face close to the user's face in the camera's field of view).

5.4 Usage of the Developed Application in Classical Oculography

Although the use of traditional oculography was not an assumption of this work, a basic analysis has also been made in this field. An appropriate research stand was prepared to test the eye tracking device. A rectangular image was placed on the wall in front of the user's seat. In this image four extreme areas (rectangles in the corners of the image) and one central area were marked. Smartphone with built-in front camera was placed on a special stand and set at eye level of the user. Thanks to this solution, interference of the user's hand shaking has been eliminated. The mobile device was connected to the notebook, allowing for real time data collection.

In the first stage of the experiment, the participant was asked to concentrate on the central point, to relax and prepare for a change of focus. Then, the participant had to move his gaze along consecutive points, with at least ten seconds stop on the indicated place (for device calibration). Finally, the participant was asked to look at a randomly selected characteristic point within the test plane. Participants of the experiment were informed that they should not move their head during the test.

Unfortunately, the repeatability of the results was very low. It was not possible to completely eliminate the head movements, which resulted in significant deviations during subsequent attempts to complete the task. The difficulty of the task was to define an universal reference point for head positioning. Probably this problem could be eliminated by using an additional camera or by using a phone with a higher quality camera. Methods of geometric stability could also be added in order to reduce the impact of dynamic disturbances.

On the other hand, it has been proved in our experiments, that it is possible to use the proposed system for classical oculography. However, the obtained results are not accurate enough to allow the designed system to compete in this area with solutions available on the market.

6 TESTS OF THE METHOD OF TEMPLATE MATCHING AND ITS IMPACT ON THE OPERATION OF THE DEVICE

Analysis of the pupil position has been carried out using the method of template matching. This is a key method for determining the viewing direction in our solution.

There are many methods of template matching, based on different similarity measures of images (Brunelli, 2011). In our tests we used 3 different methods with proper measures, each in normalized and not normalized version. In this way, we carried out tests with 6 similarity measures of images – formulas (1) – (6). In all formulas $T(x,y)$ means the intensity/luminance of (x,y) point in the template and $I(x,y)$ means the intensity/luminance of (x,y) point in the image. The size of template is defined by w and h.

Normalization in the template matching helps to reduce the impact of disturbing factors such as non-uniform illumination or changes in the saturation of the image. We decided to use also the normalized versions, although we tried to provide the right conditions - using the conclusions from the first part of the tests.

Sum of Squared Differences (SSD):

$$SSD(x,y) = \\ = \sum_{x',y'} (T(x',y') - I(x+x',y+y'))^2 \quad (1)$$

Normalized Sum of Squared Differences (SSDN):

$$SSDN(x,y) = \\ = \frac{\sum_{x',y'}(T(x',y') - I(x+x',y+y'))^2}{\sqrt{\sum_{x',y'}(T(x',y')^2 \cdot \sum_{x',y'} I(x+x',y+y')^2}} \quad (2)$$

Cross Correlation (CC):

$$CC(x,y) = \\ = \sum_{x',y'} \left(T(x',y') \cdot I(x+x',y+y')\right) \quad (3)$$

Normalized Cross Correlation (CCN):

$$CCN(x,y) = \\ = \frac{\sum_{x',y'}(T(x',y') \cdot I(x+x',y+y'))}{\sqrt{\sum_{x',y'}(T(x',y')^2 \cdot \sum_{x',y'} I(x+x',y+y')^2}} \quad (4)$$

Coefficient Correlation (CoC):

$$CoC(x,y) = \\ = \sum_{x',y'} (T'(x',y') \cdot I(x+x',y+y')) \quad (5)$$

where:

$$T'(x',y') = \\ = T(x',y') - 1(w \cdot h) \cdot \sum_{x'',y''} T(x'',y'')$$

$$I'(x+x',y+y') = I(x+x',y+y') + \\ -1(w \cdot h) \cdot \sum_{x'',y''} I\left(x+x'',y+y''\right)$$

Normalized Coefficient Correlation (CoCN):

$$CoCN(x,y) = \\ = \frac{\sum_{x',y'}(T(x',y') \cdot I(x+x',y+y'))}{\sqrt{\sum_{x',y'}(T(x',y')^2 \cdot \sum_{x',y'} I(x+x',y+y')^2}} \quad (6)$$

At first the test of device usability was performed. The results and interviews with participants allowed for determining the impact of various factors on the operation of the device. In the test of template matching techniques, we tried to create such conditions (background, uniform lighting) so that only the method of matching influenced the final result.

The test was analogous to the previous one (described in section 5.1), but 6 other participants took part in it. As previously the order of the questions was random and the program counted the results as: True Positive, False Negative, True Negative, and False Positive. Before performing the experiment, we explained how the device works and each participant had the opportunity to work for a few minutes. Then we explained the rules of the experiment. As we tested 6 different methods of template matching, so each participant repeated the tests 6 times. The results for 6 different methods and for all participants are presented in Table 2.

The analysis of the results allows for the formulation of several observations. All tested methods give the possibility of correct operation (i.e. TPR, TNT and ACC at the level of 80% or higher).

It is generally assumed that SSD and SSDN are the most commonly used methods (due to computational simplicity), although they are also the least sensitive. The one advantage of the SSD/SSDN measure is correct operation with Gaussian noise (but only Gaussian). The other advantage is that the signal energy (the sum of squares in a specific area) is taken into account. Correlation measures may be

Table 2: Results of tests True Positive Rate (TPR), True Negative Rate (TBR), Accuracy (ACC), Standard Deviation (SD).

			SSD	SSDN	CC	CCN	CoC	CoCN
Left Field	TP	Mean	19.17	19.00	19.17	19.00	19.17	19.83
		SD	0.69	0.82	0.69	0.82	0.37	0.37
	FN	Mean	0.83	1.00	0.83	1.00	0.83	0.17
		SD	0.69	0.82	0.69	0.82	0.37	0.37
	TN	Mean	13.33	12.50	14.33	13.50	14.17	16.67
		SD	1.11	1.50	1.80	1.71	1.86	0.94
	FP	Mean	7.00	7.50	5.67	6.50	5.83	3.33
		SD	1.00	1.50	1.80	1.71	1.86	0.94
Right Field	TP	Mean	13.50	12.83	13.83	14.00	13.50	13.83
		SD	1.12	1.34	1.57	1.29	1.71	1.34
	FN	Mean	6.50	7.17	6.17	6.00	6.50	6.17
		SD	1.12	1.34	1.57	1.29	1.71	1.34
	TN	Mean	19.00	19.00	19.00	18.83	18.67	19.33
		SD	0.82	0.82	0.82	0.90	0.75	0.75
	FP	Mean	1.00	1.00	1.00	1.17	1.33	0.83
		SD	0.82	0.82	0.82	0.90	0.75	0.69
TPR			82%	80%	83%	83%	82%	84%
TNR			80%	79%	83%	81%	82%	90%
ACC			80.9%	79.2%	82.9%	81.7%	81.9%	86.9%

too sensitive to local areas of very low or very high intensity. In the case of our solution, both advantages are unusable. The image of the eye is only slightly noisy, similar images are compared, taken with the same camera in short intervals of time.

Normalization helped only in one case (CoC/CoCN). This means that the final result could have been influenced by additional factors that are difficult to eliminate, e.g. reflection of light from the surface of the eye. However if so, simpler methods (e.g. SSD/SSDN) should give slightly worse effects and indeed, this is confirmed in the results.

The best effect was obtained when using CoCN measure. It is normalized and the most advanced measure among the tested ones. The computational complexity of this method did not affect the work comfort of our solution.

The group of participants was small. However, it was enough to check the acceptance of the solution, and confirm the method of template matching.

7 SUMMARY

The aim of this study was to develop the control method by eye movements for the application running on the mobile device.

A method has been developed for determining the point of the screen of the mobile device, in which the user's eyes are focused. The graphical user interface (GUI), which is controlled using only eye movements and has been specially designed for this purpose, has been proposed. The designed application has been dedicated for mobile devices with Android operating system. We have conducted a series of tests that have confirmed the assumptions and correct operation of the developed program. We have also analyzed the impact of external factors that could affect the effectiveness of the solution. We have investigated, among others, the impact of lighting and background on work of the camera and the influence of the head position on the work of the eyes detection algorithm. We have also tested the use of the proposed solution in classic oculography.

Additionally, we have tested 6 methods of template matching. Such method is required in our solution to analyze the pupil position, and in consequence, to determine the viewing direction. All tested methods give the possibility of correct operation. However, the most popular and simplest methods (SSD/SSDN) have given the worst results. The tests showed that the CoCN method turned out to be the best in our solution.

Based on the conducted research it can be demonstrated that it is possible to implement the algorithm of eye tracking in a mobile device. It has been proven that it is possible to control the functions of a mobile phone using only eye movement. On the other hand, the tests have shown, however, that the low precision of eye tracking does not allow for using the proposed solution to the classic oculography. It is worth emphasizing that this problem has a great application potential.

Considering the rapid development of digital technology, it can be expected that similar solutions will become a standard in the near future.

We plan to improve the efficiency of eye tracking by adding image stabilization algorithms. However, the operation of such algorithm in real time requires more computing power. The use of binary decision tree in our solution is not the most convenient way of controlling. However, preliminary tests have shown that we can correctly identify more areas by eye tracking. We are considering future trials with a quadtree, octree or sufficiently large icons.

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