TESTS FOR EYE TRACKING ALGORITHMS

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Abstract: The paper describes the tests developed to evaluate the performance of eye tracking algorithms to quantify vertical and horizontal eye movements in real time. To perform the tests, we used a set of synthetic images built into a video, in order to simulate real eye movements.

Keywords: image processing, eye movement quantification, eye tracking.

Introduction

Several diseases and conditions affect the human balance [1]. There is a need for instruments that can objectively, non-invasively and precisely access and quantify human balance. Such an instrument was developed in LABIMA (Image Processing Laboratory) at PUCRS University in Porto Alegre, Brazil, under the leadership of Dr. Dario Azevedo [3, 4, 5].

The Vestibular System (VS) is located in the inner ear, and it is responsible for maintaining balance [1] [2]. This paper describes some techniques used in the development of a new improved instrument for human balance analysis for physiology studies of the vestibular system, for support to diagnostics, for patient evolution in treatment and for the adaptation process of physiotherapy and vestibular disorders.

These techniques include digital image processing for signal acquisition and enhancement, pupil detection and segmentation, pupil center calculation, and eye movement quantification. The new instrument has reduced production costs, and is portable.

The Vestibular System includes a network of tubes called semicircular canals located in three planes. Each plane can be individually stimulated by selective head movements that produce corresponding eye movements due to the vestibular-motor reflexes [2].

During a real exam, the images of the eye movements are captured by video cameras, under infrared illumination. The synthetic images simulate this part of the exam and were generated for testing purpose only, simulating the most critical situations, measuring performance, and checking consistency. Either from the camera (real exam) or from the simulated video, the images are digitized by a frame grabber, and processed in real time to locate the center of the pupil in each video frame. The vertical and horizontal coordinates of the pupil center are plot into graphs. Parameters are extracted from these curves and can be then be interpreted by a medical specialist.

Materials

The algorithm was implemented with C# and was compiled with Visual Studio 2010 in a windows project.

Two different low cost USB frame grabber cards (EasyCap usb and generic DC90) were used to digitize the video images from the cameras in real time and to digitize the synthetic eye movement video. These USB frame grabbers make it possible to use laptop computers, therefore making the instrument portable.

Algorithm

The algorithm developed to calculate the center of the pupil was designed in blocks for sequential execution, as seen in Fig.1.

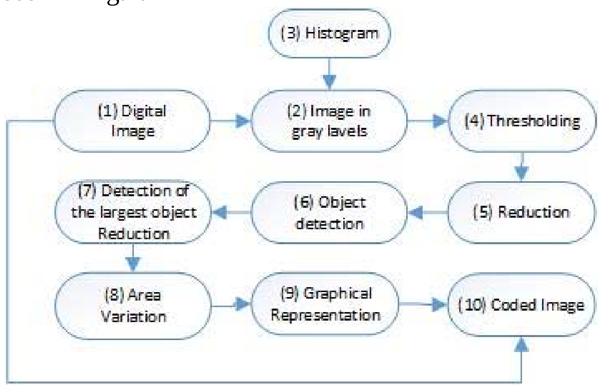

Fig. 1 Basic Block Diagram of the Algorithm.

Following is a description of the main functional blocks for the developed algorithm (Fig. 1):

1) *Digital Image (In color):* this block searches for all available imaging devices such as capture cards and USB cameras.

2 Image in gray levels: this block converts the original 24bpp color image into an 8bpp gray level image.

3) Histogram: this block generates an histogram of each image.

4)Thresholding: this block thresholds the image to obtain a binary pixel values, according to the range provided by the user, aiming to segment the pupil.

5) Reduction: this block reduces the size of the image into a smaller region of interest (ROI), starting from the four edges towards the center, using an interactive process, therefore reducing the amount of computation by segmentation of the pupil from background.

6) Object detection (Edges): The program searches for all objects or entities available in the image. The program analyzes the objects according to its closed edges, using 8-neighborhood-pixel criteria.

7) Detection of the largest object (area calculation): The program calculates the area of all of the segmented objects in the image and selects the object with the largest area (object of interest – OBI). The objective of this filter is to isolate the pupil from occasional spots with the same gray levels as the pupil.

The OBI area is calculated according to its perimeter. Any grey-level variations located inside of the perimeter of the OBI will not lead to variations in the calculation of its area, since the object will be filled-in starting from its perimeter.

8) Area variation: The program is previously configured by the user, regarding the maximum percentage of area variation accepted in the test. It compares the largest area of the object found in the image with the variation rate initially selected by the user. If the largest area found has a higher variation than the percentage selected by the user, the frame will be ignored by the program. This block reduces the main cause of errors: reflection of light sources, eyelashes, shadows, blinking, among other artifacts.

9)Graphical Representation (center of the pupil): The program calculates the center of the pupil based on averaging the pixel coordinates of the isolated area. The graph of the pupil center position for each movement direction is updated in each new frame. The Y axis of each graph represents the Xc and Yc positions of the center of the pupil, plotted against time (frame number in X-axis). Each curve is identified with a different color. The following equation is used to calculate the center of the pupil:

10) Coded Image: The calculated center of the pupil is marked with a cross in each frame of the original image.

Synthetic Video Information

The first frame of the video has the largest possible projected area of the pupil, corresponding to the minimum projection distortion of the pupil because it is located at the center of the eye, (equivalent to a subject who is instructed to aim straight, facing the camera in its optical center). When the subject is looking far up or far down (also far left or far right), occurs the maximum distortion of the projected pupil – from a circle to an elypsis.

The program calculates at each frame the percentual variation of the projected pupil area relative to the maximum projected area. Below is an example of an area variation description:

- Largest area without light source reflection (frame number 1): 1501 Pixels.
- Largest area with light source reflection (frame number 1): 1451 Pixels.
- Smaller area without light source reflection (frame number 489): 951 Pixels.
- Smaller area with light source reflection (frame number 489):891Pixels.

The percentage values of area variation for the synthetic pupil with the largest differences caused by eye movements are described below:

- The variation of the largest projected area: , relative to the corresponding largest area with light source reflection: 3.33% (without light source reflection), and 6.31% (with light source reflection).
- The maximum variation of the worst case projection distortion (looking far up/down or far left/right): : 36.67% (with no light source reflection), and 40.66% (with light source reflection).

Synthetic Eye Tests - The synthesized eye images in this paper have known pupil centers which were caculated to produce the desired synthetic movements in the tests described below:

1) Eye movements to the upper and lower orbital borders, without light source reflection.

2) Eye movements to the upper and lower orbital borders, with light source reflection.

3) Eye movements to the left and right orbital border, without light source reflection, compared to the same movement, with light source reflection.

4) Sinusoidal eye movement, with the pupil in the shape of an ellipse at the eye extremities, without light source reflection, compared to the same movement with light source reflection.

5) Movement including combinations of tests 1 to 4 in a single video sequence without light source reflection, compared to the same video with light source reflection, repeated 100 times.

Tests and Results

Description of the performed tests and their results:

1) Eye movements centered at the upper and lower orbital border, without a light source reflection.

The test aims to determine if the proposed algorithm has the ability to detect the pupil in upper and lower orbital boundary and calculate its center effectively, without reflection caused by the light source.

The test was performed with two initial movements of eye center toward the upper orbital limit. The test is repeated for the lower orbital limit.

Figure 2 shows the graph corresponding to the movement as well as the key frames with maximum upper and lower distortion of the pupil.

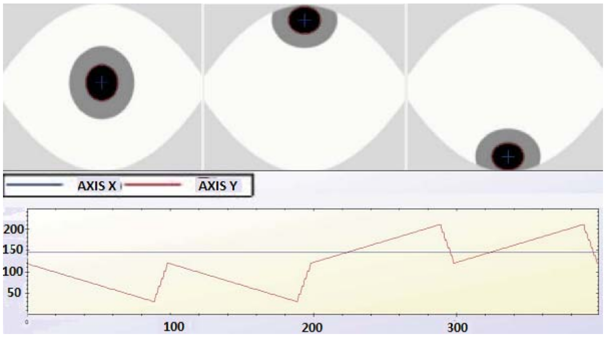

Fig. 2. Images of the synthetic eye on their orbital limits, upper and lower, and the graph corresponding to the video. The blue line represents the X-coordinate for pupil center and the red line represents the Y-coordinate for pupil center.

The test was performed 20 times, resulting in the same graph. The calculated pupil centers were compared to the expected location (as designed in the synthesized images), and obtained the maximum error of 1 pixel away from its expected location in the Xcenter and Ycenter axis.

2) Eye movements to the upper and lower orbital border, with a light source reflection.

The test was performed with the same movements and settings of Test *1*, with the addition of two light source reflections in the pupil image. Figure 3 illustrates the situations of greater difficulty of the pupil center detection such as:

- Two reflections caused by two light sources (Fig. 3A).
- Two reflections located simultaneously on both internal and external edges (Fig. 3B).
- One reflection located internally in the pupil (Fig. 3C).

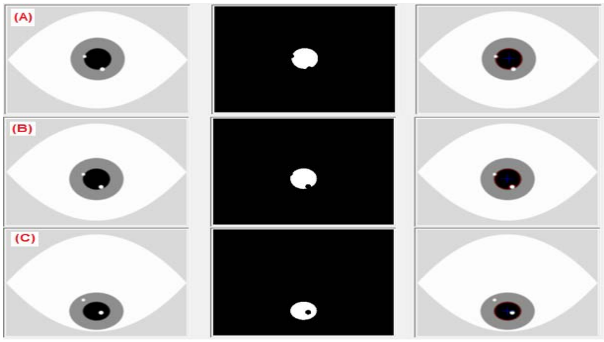

Fig. 3. Images of the synthetic eye with light source reflections on internal and external pupil edges. (A) Two light source reflections, (B) located on the edge both internal and external to pupil; (C) One reflection located internally in the pupil.

The measured pupil centers were compared to the expected locations (Test 1) and obtained the maximum error of 1 pixel in the Xcenter and Ycenter axis, despite various interferences caused by light source reflection and projection distortion of the pupil (ellipse-shaped).

3) Eye movements to the left and right orbital border, without a light source reflection compared to the same movement with a light source reflection.

The pupil shows its maximum projection distortion at the orbital limits left and right. The test was performed with two movements of the eye from the center toward the left edge of the orbit with immediate return to the center. Following, the test was repeated for the right limit of the orbit. Both tests were performed with and without light source reflections

The calculated pupil center without light source reflection during movement was compared with the same measured movement with light source reflection and it has produced the maximum error of 1 pixel in its location, both at the Xcenter and Ycenter axis. This error was considered negligible. Figure 4 shows the most critical situations for the calculation of the pupil center, including several artifacts at the most critical locations.

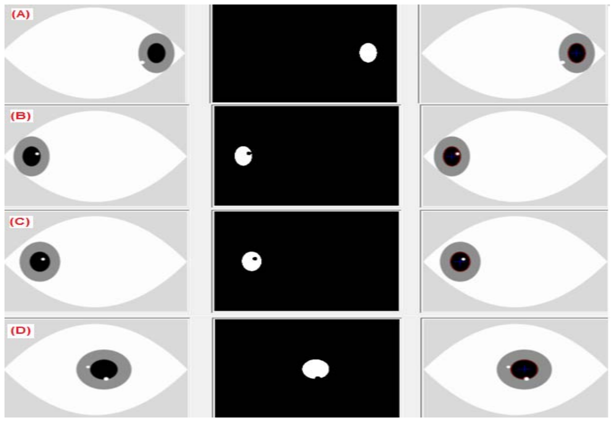

Figure 4: Images of critical “frames” with the location of the pupil center in blue and the pupil perimeter in red. (A) Center of the pupil (located at the extreme right of the orbit) without light source reflection. (B) Center of the pupil at the same location, with light source reflection at the edge, with maximum ellipse-shaped distortion (C) Center of the pupil with internal light source reflection and ellipse-shaped distortion. (D) Center of the pupil with light source reflection on the internal edge.

4) Sinusoidal eye movements, with the pupil in the shape of an ellipse at the eye extremities without light source reflection, compared to the same movement with light source reflection.

This test aimed to determine whether the proposed algorithm has the ability to detect the pupil in oscillatory motion in the X and Y axis, and calculate their center effectively with the addition of the reflection caused by light source compared to the same movement without reflection.

This test was developed to simulate the response of the induced inclined negation stimulus movement of the patient’s head, which produces a horizontal oscillatory movement of the pupil in response to the vestibulo-ocular reflex.

Following, the center of the pupil was directed to the point of origin and the oscillatory motion of the eye was produced in the lower area of the image. This test was developed to simulate the response of affirmation movement to the patient's head, which produces a vertical oscillatory movement of the pupil in response of the vestibulo-ocular reflex.

The measured pupil centers without light source reflection during movement, compared with the same movement with light source reflection has produced the maximum error of 1 pixel in the pupil center location at the Xcenter and Ycenter axis.

5) Movement including tests 1 to 4 in a single video sequence without light source reflection, compared to the same video with light source reflection, repeated 100 times.

This test aimed to insure the robustness, accuracy, and repeatability of the pupil center calculation algorithm with several repetitions. Figure 5 shows the grap that represents the measurement of the center of the pupil several combined simulated situations.

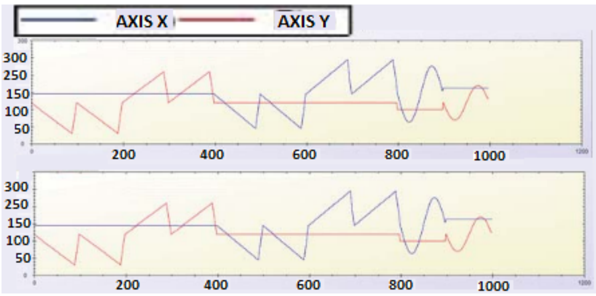

Fig. 5. Image of the graphics with complete eye movement. (A) Eye Movement without light source reflection (B) Eye Movement with light source reflection.

The measurement of the pupil center without light source reflection during movement, compared with the same movement with light source reflection and repeated 100 times has produced the same output error of 1 pixel at the Xcenter and Ycenter axis.

Related Works

The methods previously used by the research group for eye movement quantification were based on digital image processing techniques to calculate the location the center of the pupil [3] [5]. Pupil segmentation was achieved in several steps: thresholding, binarization, object feature extraction and classification. Pupil features were automatically extracted from the histogram. Artifacts (such as blinking and light source corneal reflections) were automatically detected and compensated for.. A variation of the current pupil center calculation was to sweep the eye image with four lines (from left to right, right to left, up-down and down-up), until each line would enclose 10 pixels inside pupil. The lines would execute a back movement until they became tangent to the pupil [3], forming a rectangle. The center of the rectangle is assumed to be the center of the pupil. This technique showed a measurement error in the pupil center calculation of 1%.

Result	Occur 1	Occur 2
Exact Coord	37.4%	75.2%
Neiboard Coord	44.1%	24.8%
1% Error	18.5%	0%
Miss	0%	0%
Drop	0%	0%

Table 1: Table of comparison of the two different methods of estimation of the synthetic pupil`s center. The column Occur 1 demonstrate the results of the method developed in the reference [3]. The column Occur 2 demonstrate the results of the method developed in this research.

Conclusion

Based on the evaluation test results of the interactive eye movement quantification algorithm herein in presented, we can confirm that it is capable of calculating the center of the pupil with greater precision than previous methods it is also capable of plotting the curve representing its position in each video frame for posterior analysis.

O sistema foi avaliado introduzindo-se ruído nas fontes de alimentação das câmeras e mostrou-se robusto, com a mesma taxa de erros de um pixel.

During the tests with the synthetic eye, we carried out several simulations of combined eye movements and interfering artifacts that could cause errors in the calculation of the center, such as: eye movements to the left, right, lower, upper and sinusoidal orbital border with and without light source reflections. The algorithm during the tests was shown to be precise and stable in its response, obtaining a maximum error of 1 pixel per axis. This error can be considered negligible, approximately 0.25% of the area of the object in the worst case scenario.

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