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Development of a Method for Processing Eye Images for Use in Biometric Authorization in Computer Systems

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Abstract. *This article demonstrates an improved algorithm for processing conjunctival capillary images for use in contactless biometric authentication of computer system users. The algorithm is developed and runs on a Raspberry PI 3 model b, Raspberry Pi High Quality Camera, and a macro lens with a focal length of 8 millimeters. The image processing algorithm is described in detail, including preprocessing, contrast enhancement, edge extraction using a Canny detector, morphological processing, and skeletonization to obtain a clean capillary mesh. The main advantage of the method is its high resistance to spoofing. Unlike facial recognition, which can be fooled by a mask or video recording, a live capillary network cannot be artificially recreated. In addition, this technology offers incredible convenience: the user does not need to touch any sensor (as in the case of a fingerprint) or approach the eye of a particular scanner (as for the iris). Authorization can occur continuously, as long as the user is simply displayed on the screen, without interfering with his work at all. The greatest potential of this technology is revealed when it is combined with behavioral analysis (analysis of eye movement, blinking, gaze). Such a hybrid approach provides not only a high level of protection, but also continuous authentication, when the system constantly checks whether the authorized user is still at the computer. This opens up new horizons for protecting critical information systems.An important advantage of the proposed solution is its energy efficiency and low hardware cost. The use of the Raspberry Pi 4 Model B platform, combined with a specialized high-quality camera and macro lens, makes the system highly accessible for mass deployment. This configuration demonstrates the ability to capture the high-resolution imagery required for precise capillary network analysis while maintaining minimal power consumption and a low hardware footprint. The capability to deploy such a sophisticated biometric system on low-power, single-board computers opens prospects for its integration not only into stationary workstations but also into mobile and embedded devices, significantly broadening the potential application scope of this technology beyond traditional computing environments.*

Keywords: *biometric authorization, computer system, conjunctival capillaries, Raspberry PI, High Quality camera, image processing, skeletonization, Canny edge detector, CLAHE, identification accuracy.*

Introduction

In today's digital world, two key areas of active development in the field of computer technology and cybersecurity are: the improvement of network technologies (including IoT) and wireless networks [1–3]. Based on this trend, data security is emerging as one of the most important priorities. Traditional authentication methods, such as passwords or PIN codes, are increasingly vulnerable to hacking and social engineering.

In response to these challenges, science is turning to biometric technologies that identify a person based on unique physiological or behavioral characteristics [4, 5]. Among the promising areas, identification based on the vascular pattern of the eye, namely the capillaries of the conjunctiva [6]. Image processing methods play an important role in such systems.

The effectiveness of using modified image quality improvement algorithms (e.g. CLAHE), as well as deep neural networks (CNN) for segmentation tasks [7], opens up wide opportunities for their use in biometric pipelines. It is also important to add that the device that implements this biometric protection method can simultaneously perform other functions - such as interacting with computer systems as an additional manipulator [8–10], or monitoring eye behavior. The latter technologies can also be used as additional parameters when assessing the user's general condition [11].

1 The aim of the study

The aim of this study is to develop and implement an effective algorithm for processing images of the capillary network of the conjunctiva of the eye

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to create a fast, contactless, and reliable biometric authorization system in computer systems (CS).

2 Materials and research results

The era of digitalization and the COVID-19 pandemic have dramatically increased the requirements for the security and hygiene of authorization systems in the CS. Traditional biometric methods, such as fingerprint scanning, face or iris recognition, have a number of significant drawbacks: vulnerability to counterfeiting (using 3D models or deep fakes), dependence on static physiological features, as well as the inability to be effectively used by people with disabilities or patients in critical condition. Obtaining and interpreting visual information can be crucial for the integration of such people with our surrounding three-dimensional world and interaction with it [2].

The answer to these challenges may be the use of dynamic biometric parameters. The capillary network of the conjunctiva, the thin mucous membrane of the eye, is unique for each person and has dynamic characteristics (pulsation, density changes), which makes it difficult to forge it. This work is devoted to the development and research of the full cycle of authorization technology in the CS based on this parameter, from hardware to image processing algorithms.

Despite the existence of developments in the field of biometric identification based on the vascular pattern of the eye (sclera, conjunctiva), most of them face the problem of combining accessibility, ease of use, and a high level of security. Many solutions require specialized and expensive equipment (e.g., near-infrared cameras), which limits their widespread use. Other methods that use Purkinje mapping for gaze tracking can block the user's vision during use.

The approach proposed in this paper avoids these drawbacks by using the capillary network image obtained from the corner of the eye for both gaze tracking and authorization. It does not interfere with the visual field and is implemented on affordable hardware.

To implement the method, a hardware platform based on the Raspberry Pi 4 Model B single-board microcomputer was developed. The Raspberry Pi High Quality Camera was used as the main sensor. To obtain a clear image of small capillaries, a macro lens with a fixed focal length of 8 mm was installed. The current prototype is assembled on a bracket for ease of testing, but a compact housing for mounting on the head like glasses is being developed.

The image processing algorithm is implemented in Python using the Open CV and Num Py libraries. It works in real time and consists of the following key steps.

2.1 Frame capture and pre-processing

To implement continuous and user-invisible authentication, the system operates in real-time, continuously capturing a high-resolution video stream from a specialized camera. Each individual frame of this stream (Fig. 1) is obtained in the BGR (Blue, Green, Red) color space. The BGR space is the standard for most image processing libraries (e.g., Open CV). Such a frame immediately undergoes a pre-processing stage.

Fig. 1 - Original image of the eye

The first step is to convert the color image to a single-channel grayscale image.

This transformation is computationally critical for several reasons:

Data reduction: A three-color frame (three channels) requires three times more memory than a single-channel frame. This transformation instantly reduces the amount of information that needs to be processed by a factor of three. This fact is key to ensuring the performance level of a real-time system.

Emphasis on structure, not color: For further detection of linear capillary structures, brightness contrast is a much more important and informative factor than information about the color. Thus, removing color not only does not harm the analysis, but on the contrary – increases the visual contrast between vessels and surrounding tissues, simplifying the task for subsequent algorithms.

After obtaining the grayscale image, a cropping operation is applied to optimize computational resources further. Instead of analyzing the entire eye image, the algorithm selects a small rectangular region of interest (ROI) based on predefined coordinates. This area is selected in the inner corner of the eye (canthus). It is in this area that the capillary network is the densest, most distinct, and least prone to overlap by the eyelids or other obstacles (Fig. 2).

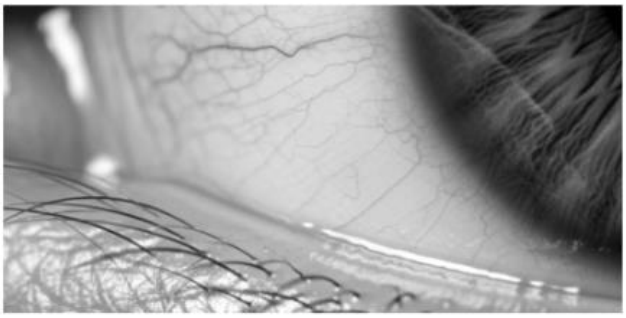

Fig. 2 - A grayscale image of an eye with a limited ROI.

Such cropping allows you to significantly reduce the computational load by removing most of the unnecessary data (skin, eyelids, eyebrows), and at the same time, increase the accuracy of further processing by focusing the system's attention on the informative area.

2.2 Contrast enhancement and filtering

To improve the accuracy of further capillary network extraction, a critically important step is image contrast enhancement. For this purpose, the Contrast Limited Adaptive Histogram Equalization(CLAHE) method is used.

Unlike classic global histogram equalization, which evenly stretches the brightness across the entire image, CLAHE works differently. It divides the image into small, non-overlapping contextual blocks and calculates its own histogram for each block. This prevents oversaturation and noise amplification in homogeneous areas of the image (e.g., the white of the eye).

Histograms display the intensity distribution in an image and can help increase contrast through smoothing. The discrete histogram function is defined as:

$$h(r_k) = n_k \,, \quad (1)$$

where$r_k - k$-thintensity level;n_k–number of pixels with intensityr_k. For normalized histograms, each value is divided by the total number of pixels, which gives:

$$p(r_k) = \frac{n_k}{MN}, \quad (2)$$

where *M*and*N*–image dimensions. Histogram smoothing is applied as follows:

$$s_k = T(r_k) = (L-1) = \sum_{j=0}^{k} p_r(r_j) = \frac{(L-1)}{MN},$$

where$T(r_k)$is a transformation that increases contrast by redistributing pixel intensity. As a result, CLAHE effectively extracts scarcely noticeable capillaries against the background of the sclera, making them clearly visible, while avoiding the artifacts and noise inherent in global methods.

After optimizing the contrast, it is necessary to detect the capillaries themselves. For this, adaptive threshold filtering is used (in this case, the AGAST algorithm - Adaptive and Generic Accelerated Segment Test). This method adaptively calculates the optimal brightness value (threshold) for each pixel separately, taking into account the brightness of the pixels in its closest circle, which allows you to effectively take into account the unevenness of lighting throughout the image, which is critically important when working in real conditions.

The result of this two-step process (CLAHE + adaptive thresholding) is a clear binary image (Fig. 3).

Fig. 3 - Image transformed using the CLAHE method.

In this image, black pixels correspond to potential capillaries and white pixels to the background. This is an ideal basis for further morphological operations and skeletonization, which will transform this mass of pixels into a clear vector model of the capillary network.

2.3 Edge detection and morphological processing

The previous step leaves behind a binary image, but it may still contain small residual noise and tiny pixels that prevent accurate shape analysis. To finally remove it and smooth the contours, a Gaussian Blur filter is applied. This filter smooths the image by weighting the value of each pixel with the values of its neighbors according to a Gaussian function. This effectively suppresses high-frequency noise and small artifacts while preserving the overall shapes of the objects, which prepares a clean basis for accurate boundary detection.

In Fig. 4 one of the most effective algorithms is used to directly detection the precise contours of capillaries – the Canny Edge Detector (CED). Since the result of the Kenny detector may be contours with breaks, the morphological closure operation is used to eliminate them and obtain solid lines. Closure is the sequential application of two main morphological operations: first dilation, and then erosion. Thus, this final processing stage ensures the receipt of perfectly complete, crisp and clean contours of the capillary network, ready for further skeletonization and vectorization in order to build a unique biometric template.

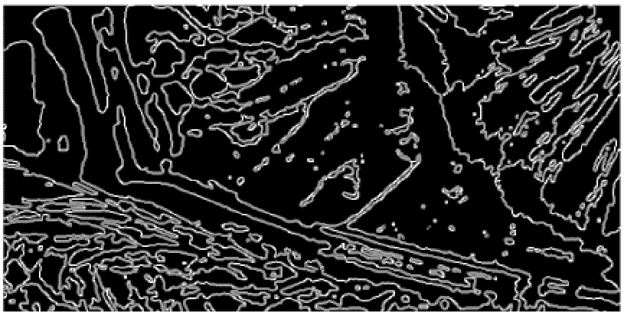

Fig. 4 - The found boundaries of capillaries

After morphological closure, which has formed integral contours, the algorithm proceeds to the stage of analysis and classification of the found objects. At this stage, all contours without exception are found in the processed binary image using contour analysis algorithms.

In order to separate the useful signal from the noise, the contours are filtered by size. The algorithm calculates the area of each contour and compares it with the specified threshold values. Contours whose area is too small are considered noise and are permanently removed. Similarly, contours whose area is too large and does not correspond to the real physiological dimensions of the capillary are classified as artifacts and are also filtered. The contours remaining after such filtering are considered capillary structures (Fig. 5).

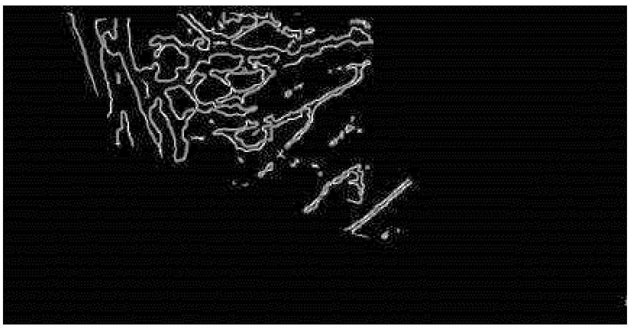

Fig. 5 - Filtered sample

The resulting image is unique and fairly stable for each user and can be used for authorization as an analogue of a fingerprint or other biometric recognition methods.

Conclusion

The proposed data processing pipeline (from frame acquisition to skeletonization) is highly optimized for real-time operation. Steps such as grayscale conversion, ROI definition, and binarization significantly reduce the computational load, which was confirmed by the result of 0.32 ms per frame.

The use of a cascade of specialized methods (CLAHE, adaptive threshold, Gaussian blur, etc.) instead of a single approach allowed to effectively increase the contrast of the target structures (capillaries), while simultaneously suppressing noise and uneven illumination. This is a key factor in achieving the claimed identification accuracy of 84.8%. The combination of the Kenny edge detector with morphological closure turned out to be optimal for the formation of continuous and integral capillary contours, minimizing the number of breaks and artifacts. Further filtering of contours by size finally separates the useful signal from the noise.

The entire pipeline is not only a theoretical model, but also a practically implemented and tested solution, demonstrating the viability of conjunctival capillary identification technology. Its high speed and accuracy make it suitable for implementation in security systems requiring contactless and unobtrusive authentication.

Thus, the algorithm comprehensively solves the problem of converting a grayscale eye image into a clean, structured digital template suitable for instant and reliable user identification in CS.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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Розробка методу обробки зображень ока з метою використання при біометричній авторизації в комп'ютерних системах

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Анотація. *У цій статті запропоновано вдосконалений алгоритм обробки зображень капілярів кон'юнктиви ока для використання в процесі безконтактної біометричної авторизації користувачів комп'ютерних систем. Алгоритм розроблений та працює на базі Raspberry PI 4 model b, Raspberry Pi High Quality Camera, та макрооб'єктиву з фокусною відстанню у 8 міліметрів. Детально описано алгоритм обробки зображень, що включає попередню обробку, покращення контрасту, виділення країв за допомогою детектора Кенні, морфологічну обробку та скелетонізацію для отримання чистої капілярної сітки. Головною перевагою методу є його винятковa стійкість до спуфінгу. На відміну від розпізнавання обличчя, яке можна обдурити маскою або відеозаписом, живу мережу капілярів неможливо відтворити штучно. Крім того, ця технологія пропонує неймовірну зручність: користувачеві не потрібно торкатися до жодного сенсора (як у випадку з відбитком пальця) або прилаштовувати очі до певного сканера (як для ірісу). Авторизація може відбуватися безперервно, поки користувач просто дивиться на екран, абсолютно не перешкоджаючи його роботі. Найбільший потенціал цієї технології розкривається при її поєднанні з поведінковим аналізом (аналізом руху ока, кліпання, напрямку погляду). Такий гібридний підхід забезпечує не лише високий рівень захисту, але й безперервну аутентифікацію, коли система постійно перевіряє, чи досі за комп'ютером знаходиться той самий авторизований користувач. Це відкриває нові горизонти для захисту критично важливих інформаційних систем.*

Ключові слова: *біометрична авторизація, комп'ютерних систем, кон'юнктивальні капіляри, Raspberry PI, High Quality камера, обробка зображень, скелетонізація, алгоритм Кенні, CLAHE, точність ідентифікації.*

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