КОМПЬЮТЕРНЫЕ ИССЛЕДОВАНИЯ И МОДЕЛИРОВАНИЕ 2020 Т. 12 № 3 С. 629–639

DOI: 10.20537/2076-7633-2020-12-3-629-639

Ки&М

МОДЕЛИ В ФИЗИКЕ И ТЕХНОЛОГИИ

УДК: 004.942

Математическая модель биометрической системы распознавания по радужной оболочке глаза

Н. В. Суворов[a], М. П. Шлеймович[b]

Казанский национальный исследовательский технический университет им. А. Н. Туполева — КАИ, Россия, 420111, г. Казань, ул. К. Маркса, д. 10

E-mail: [a] n.suvorov.v@gmail.com, [b] shlch@mail.ru

Получено 18.11.2019, после доработки — 22.01.2020.
Принято к публикации 12.03.2020.

Автоматическое распознавание личности по биометрическому признаку основано на уникальных особенностях или характеристиках людей. Процесс биометрической идентификации представляет собой формирование эталонных шаблонов и сравнение их с новыми входными данными. Алгоритмы распознавания по рисунку радужной оболочки глаза показали на практике высокую точность и малый процент ошибок идентификации. Преимущества радужки над другими биометрическими признаками определяется ее большей степенью свободы (около 249 степеней свободы), избыточной плотностью уникальных признаков и постоянностью во времени. Высокий уровень достоверности распознавания очень важен, потому что позволяет выполнять поиск по большим базам данных и работать в режиме идентификации один-ко-многим, в отличии от режима проверки один-к-одному, который применим для небольшого количества сравнений. Любая биометрическая система идентификации является вероятностной. Для описания качественных характеристик распознавания применяются: точность распознавания, вероятность ложного доступа и вероятность ложного отказа доступа. Эти характеристики позволяют сравнивать методы распознавания личности между собой и оценивать поведение системы в каких-либо условиях. В этой статье объясняется математическая модель биометрической идентификации по радужной оболочке глаза, ее характеристики и анализируются результаты сравнения модели с реальным процессом распознавания. Для решения этой задачи проводится обзор существующих методов идентификации по радужной оболочке глаза, основанных на различных способах формирования вектора уникальных признаков. Описывается разработанный программный комплекс на языке Python, который строит вероятностные распределения и генерирует большие наборы тестовых данных, которые могут быть использованы в том числе для обучения нейронной сети принятия решения об идентификации. В качестве практического применения модели предложен алгоритм синергии нескольких методов идентификации личности по радужной оболочке глаза, позволяющий увеличить качественные характеристики системы, в сравнении с применением каждого метода отдельно.

Ключевые слова: биометрическая система, радужная оболочка, математическая модель, коэффициент ложного доступа, коэффициент ложного отказа доступа

Исследование выполнено в рамках государственного задания № 2.1724.2017/4.6.

COMPUTER RESEARCH AND MODELING
2020 VOL. 12 NO. 3 P. 629–639
DOI: 10.20537/2076-7633-2020-12-3-629-639

Ки&М

MODELS IN PHYSICS AND TECHNOLOGY

UDC: 004.942

Mathematical model of the biometric iris recognition system

N. V. Suvorov[a], M. P. Shleymovich[b]

Kazan National Research Technical University named after A. N. Tupolev — KAI,
10 K. Marksa st., Kazan, 420111, Russia

E-mail: [a] n.suvorov.v@gmail.com, [b] shlch@mail.ru

Received 18.11.2019, after completion — 22.01.2020.
Accepted for publication 12.03.2020.

Automatic recognition of personal identity by biometric features is based on unique peculiarities or characteristics of people. Biometric identification process consist in making of reference templates and comparison with new input data. Iris pattern recognition algorithms presents high accuracy and low identification errors percent on practice. Iris pattern advantages over other biometric features are determined by its high degree of freedom (nearly 249), excessive density of unique features and constancy. High recognition reliability level is very important because it provides search in big databases. Unlike one-to-one check mode that is applicable only to small calculation count it allows to work in one-to-many identification mode. Every biometric identification system appears to be probabilistic and qualitative characteristics description utilizes such parameters as: recognition accuracy, false acceptance rate and false rejection rate. These characteristics allows to compare identity recognition methods and asses the system performance under any circumstances. This article explains the mathematical model of iris pattern biometric identification and its characteristics. Besides, there are analyzed results of comparison of model and real recognition process. To make such analysis there was carried out the review of existing iris pattern recognition methods based on different unique features vector. The Python-based software package is described below. It builds-up probabilistic distributions and generates large test data sets. Such data sets can be also used to educate the identification decision making neural network. Furthermore, synergy algorithm of several iris pattern identification methods was suggested to increase qualitative characteristics of system in comparison with the use of each method separately.

Keywords: biometric system, iris recognition, mathematical model, false acceptance rate (FAR), false rejection rate (FRR)

Citation: *Computer Research and Modeling*, 2020, vol. 12, no. 3, pp. 629–639 (Russian).

This work was supported by the state task No. 2.1724.2017/4.6.

Introduction

The development of reliable automatic recognition of personal identity has become an attractive goal for a huge number of researches for a long time. The scope and range of solvable tasks by the systems has been expanded at the same time with technical progress. Automatic biometric recognition is a solution to the problem of pattern recognition, the key issue of which is finding the boundary between the variability of instances in a class and interclass variability. This means that objects can be reliably classified only if this intra-class (same objects) variability is less then inter-class variability. In addition, the stability of the compared signs has to be considered. As an example, the facial images taken a year ago, at least, lead to a strong degradation in accuracy of facial recognition systems. Due to the fact that on the one hand the face is a changeable social organ and at the same time it is a complex 3D object there are differences in the images for a one person depending on the shooting angle, equipment and external factors. It is also important to take into account the degree of uniqueness of biometric features, as far as the comparison of the geometric shape is the basis of face recognition and the different faces possess the same basic set of features so that it leads to the fail result for similar people.

Iris biometric identification is one of the most promising ways of reliable automatic contactless identification of a person. Although small and difficult to image, especially in visible light, the iris is an organ that has the great mathematical advantage that its pattern variability among different persons is great. The degree of freedom of the iris pattern and the density of unique features are several times higher than the degree of freedom of other biometric features. But from practical point of view taking iris images is far more complicated process than of facial features. For example, taking iris images requires a special system of infrared spectrum cameras. Based on tests of personal identity iris recognition system mentioned above we can emphasize that iris recognition system provides higher quality of identification compare to face recognition, although false recognition and excess failure cases should be considered herewith.

Designing of more precise iris based identification methods with application of new algorithms of signs differentiation and their comparison, is one of the key areas for development of automatic recognition of personal identity. Along with that, development of machine learning systems finds more areas of application and for modeling such systems a lot of test data sets are required. All of that modeling is an integral part of overall information system security that assesses its sustainability and functioning in different situations.

As a tool for solving these problems, a development of a new model of iris biometric recognition system of personal identity is proposed and its assessment and comparison with current similar systems. Based on different areas of application of such models, it is proposed to consider only those topical approaches that are theoretical (axiomatic) and empirical (frequency, static) levels of interpretation.

Iris recognition principle

There are a number of methods of personal identification according to iris and one of them is widely used in industrial systems and has already recommended itself as one of the precise methods of personal identification, whereas others have only been described in scientific articles and they are subjects for further practical application. Nevertheless, there is an overall principle of iris personal identification which presents as a sequence of actions described in Figure 1.

The first step is to capture an eye using individual cameras or a camera system to take high-resolution images. In industrial systems, cameras in the infrared spectrum are more often used, which makes it possible to obtain a more contrast image even for dark irises, however, the distance to the subject is no more than 1 meter. Currently, recognition methods are being actively developed for images

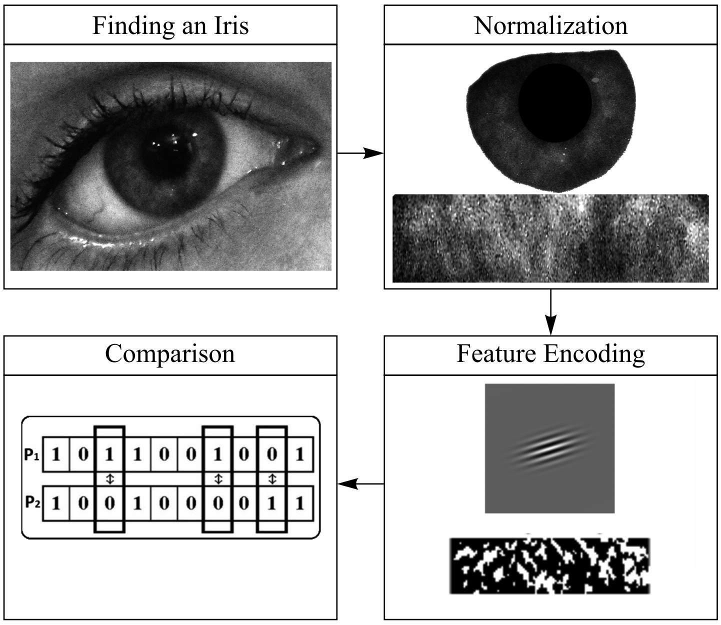

Figure 1. Typical process of eye identification by the iris, presented in the form of a sequence of transformation steps: input image, localized iris, normalization, parametrization (Gabor filter), code comparison

obtained in the visible radiation range [Trokielewicz, 2016]. The resulting image undergoes a series of pre-processing functions, the essence of which is to align the histogram and smooth out bright bursts (glare) to reduce the influence of these areas on the localization stage. In the next step, the iris localization algorithms are applied. The center of the pupil and its borders, the center of the iris and its external borders are calculated. This is an absolute necessity because the centers of the pupil and iris in many tests do not match due to the physiological features of the eye structure. Additionally, localization of unsuitable for recognition areas of the image is used: the eyelids, eyelashes and glares. After finding the borders of the iris, the transformation from a polar coordinate system to a rectangular one is performed, this provides resistance to the angle of shooting of the subject, as well as to changes in the size of the iris due to the expansion and contraction of the pupil. The advantage of this approach can still highlight the same format and size for all images of the iris, regardless of the shooting equipment. One of the key stages is the algorithm for extracting the signs of the iris, also known as parameterization. Depending on the method chosen, the result of this function is the feature vector of the iris structure of a certain length. The purpose of this step is to select features that are independent of contrast, lightness, and angle of shooting, which allows determining the owner uniquely. Depending on the chosen parametrization method, the type of comparison function is determined, the task of which is reduced to interpreting the differences between the feature set as a real number from the [0, 1] value interval, where 0 is a complete similarity, and 1 is a complete difference. Each of these stages is described in more detail in [Daugman, 2004]; within the framework of this article, only the effects of errors at different steps on the final recognition result for the construction of the model will be considered.

Existing iris recognition methods

The active development of the area of identification by the iris of the eye has made a variety of approaches to the identification of unique features and methods for their comparison. A review of the characteristics of the main algorithms is described in detail in [Sunil, 2019]. You can select the basic set of functions on which the selection of signs and the calculation of the distance between the compared feature vectors are based:

- Gabor filter: defined as the result of multiplying a harmonic function by a Gauss function. In this filter, each pixel in the normalized image is modulated into two parts of the binary code in the resulting iris template, which will be used at the stage of matching with the template.
- Wavelet-transformation: here the normalized area of the iris is decomposed into components with different resolutions. The conversion uses a filter bank to search for objects in the image using varying window sizes, and the resulting code will have a resolution in frequency and space.
- Discrete cosine transformation: it is based on the one-dimensional discrete cosine transformation (DCT) as a means of distinguishing features for classification. The iris codes are generated as a sequence of individual parts.
- Gaussian Laplace filter: with this approach, the filter decomposes the image of the iris into an analyzed form called the Laplace pyramid, then a set of Gaussian filters is applied to the resulting image to encode objects.
- Key local variations: it is dealt with a normalized iris image which extracts the features and combines it into one-dimensional signal intensity. Then a discrete wavelet transformation is applied to count the sudden changes of signal intensity, and finally, the points of maximum and minimum are encoded in the feature vectors, which are then transformed into a binary template.
- Hilbert transformation: extracts information from the texture of the iris image, and forms the analyzed frequency, known as the "appearance frequency".

All sorts of functions for comparing feature vectors are also used:

- Hamming distance — Measures the number of bits for which the two iris codes do not match.
- Euclidean distance — Metric for measuring the minimum distance between two vectors iris code.
- Levenshtein distance — Metric for measuring the minimum number of edits required to convert one line to another.
- Series of comparison estimates — Instead of optimally aligning the two aperture codes by maximizing the comparison estimate for several bit shifts, a common series of comparison evaluations is used to avoid loss of information.
- Multimodal merger of coincidences — A method for comparing iris images in visible light using several characteristics of the iris and eye images.

First of all, for the implementation of parameterization algorithms a set of biometric data is necessary for comparison. CASIA and UBIRIS eye image databases are freely available, which contain images of various resolutions and qualities captured on infrared and conventional cameras. The developing methods are tested on different data and measure the main characteristics: recognition accuracy, FAR and FRR.

The following methods will be presented in more detail for further modeling.

1. Daugman's method — for each normalized input image of the iris, a spatial-frequency convolution is applied by a two-dimensional Gabor filter. Each bit of code is determined by the sign of the effect of the two-dimensional Gabor filter on some small area of the iris texture. Thus, the result is a vector of bits, which is compared with the reference method of finding the Hamming distance. Depending on the comparison result from the interval $[0, 1]$, a decision is made where the boundary is the interval $[0.26, 0.35]$, which depends on the system settings.

2. Continuous wavelet transformation (CWT) is a normalized image of the iris, defined as a convolution with a series of wavelet functions that can be converted into multiplication in the Fourier frequency domain. For the resulting feature vector, the Euclidean distance with the reference feature vector is calculated.
3. Discrete wavelet transformation (DWT) — the input image is converted into components that appear in different wavelet resolutions. Texture features can be analyzed at different resolutions using their mulitiscale wavelet decomposition. Haar wavelets can reveal sharp changes in spatial texture by repeatedly applying low and high frequencies. Filters are separately applied to the rows and columns of the iris image. The recursive application of this decomposition is used to construct a higher level of decomposition. To determine the compliance of the distance between the feature vectors, the Hamming distance is used.

The choice of these particular methods is justified by the presence of a detailed distribution function of the comparison values obtained in real identification systems by the iris of the eye.

The quality of the distance distribution function affects the construction of a probability function that directly determines the quality of the model. Characteristics of recognition methods were obtained for images from the UBIRIS database.

Mathematical model of a biometric identification system

To describe and simulate the system of eye identification by the iris, let us present the recognition process as a set of input data, transformation functions, and possible variants of the system result (Figure 2).

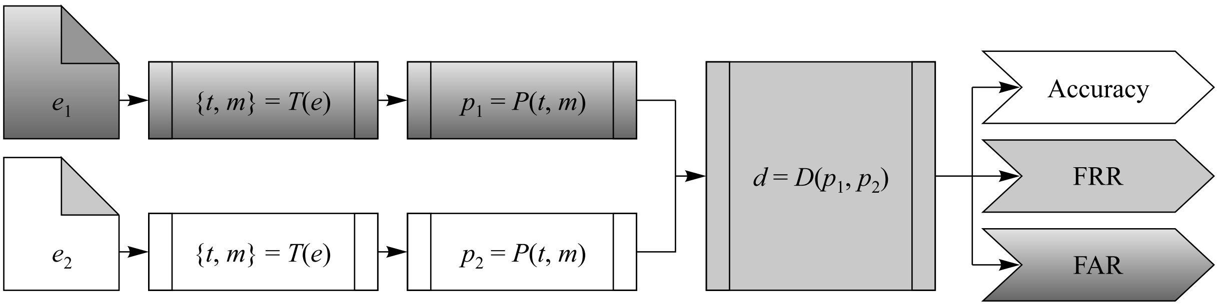

Figure 2. Typical process of eye identification by the iris, presented in the form of input data: the reference image e_1 and the image compared with the reference e_2, sequences of application of functions $T(e)$ — localization/normalization, $P(t, m)$ — parametrization and $D(p_1, p_2)$ — comparisons of vectors symptoms and possible results of work: the right decision, access failure error and access granting error

As input data we will consider images of the eyes e_1 and e_2, taking into account the varying quality parameters of the shooting. The variability of the image parameters introduces a probabilistic characteristic into the system, which is complemented by the influence of the conversion and comparison functions. To simplify the scheme, and combine the stages of preprocessing, localization and normalization together, and get: $\{t, m\} = T(e)$, where t is the template of the iris in a cartesian coordinate system, specific size, m is the mask unsuitable for recognition areas. The parameterization stage is a transformation of the form $p = P(t, m)$, the result of which is the vector of signs of the iris. Depending on the selected feature extraction method, a function of the form $d = D(p_1, p_2)$ is defined, which is a measure of the comparison of the distance between the feature vectors p_1 and p_2. The normalized value of d varies in the interval $[0, 1]$, where 0 corresponds to a complete match, and 1 to a full difference. We define the intervals of values as $[0, x_1]$ — for the same iris, $[x_2, 1]$ — for

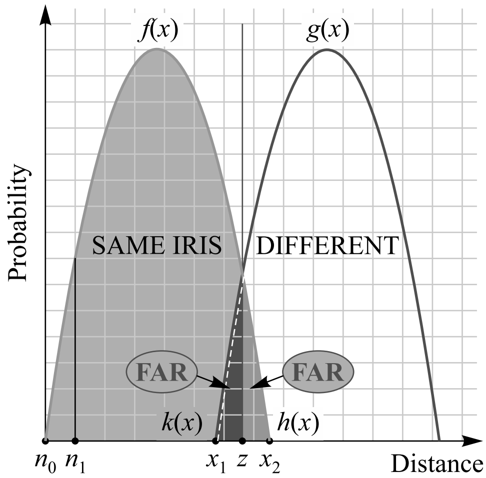

Figure 3. Graph of probability of obtaining the distance between the vectors of the eye iris signs, divided into $f(x)$ — successful identification of the same irises, $g(x)$ — successful access denied for different iris, $k(x)$ — erroneous access for different iris, $h(x)$ — access failure error for identical iris and indicated by the boundaries x_1, z, x_2

different. This separation allows you to analyze the options of the system. Since the biometric system of identification on the iris of the eye works with a certain probability of errors, then we will only consider the case when $x_1 > x_2$. We introduce the point z, which is chosen from the interval $[x_1, x_2]$ and is the separator for the identification decision. Thus, we obtain the interval $[x_1, z]$, in which the error of a false access (FAR) can occur with a certain probability,

$$FAR(x) = \int_{x_1}^{z} k(x)\, dx, \tag{1}$$

and the interval $[z, x_2]$, in which the error of a false access failure (FRR) can occur with a certain probability.

$$FRR(x) = \int_{z}^{x_2} h(x)\, dx. \tag{2}$$

Knowing the probabilities of FRR and FAR, one can calculate the accuracy of the system:

$$P_{\text{accuracy}}(x) = 1 - FAR(x) - FRR(x). \tag{3}$$

Graphics can also determine the types of functions: $f(x)$, $g(x)$, $k(x)$, $h(x)$. When describing the characteristics of the eye recognition method on the iris, a graph of the distribution of distance values is plotted, by which it is possible to determine the probabilities as following:

$$P_{\text{accept}}(x) = \int_{0}^{Z} f(x)\, dx - FAR(x), \tag{4}$$

$$P_{\text{reject}}(x) = \int_{Z}^{1} g(x)\, dx - FRR(x), \tag{5}$$

$$P_{\text{accuracy}} = P_{\text{accept}}(x) + P_{\text{reject}}(x). \tag{6}$$

Thus, choosing mathematical functions corresponding to the statistical ones, one can construct a model of identification of the person from the iris of the eye.

Quality model recognition system

To assess the mathematical model, 3 different methods of eye identification by the iris were selected, the parameters and characteristics of which are presented in Table 1 [Bodade, 2014].

Table 1. Characteristics of various methods based on discrete wavelet transform (DWT), continuous wavelet transform (CWT), gabor filter

Parameter method	Accuracy (%)	FAR (%)	FRR (%)
DWT method	91.5	4.25	4.25
CWT method	95.5	2.25	2.25
Gabor filter method	97.5	1.25	1.25

We will generate a set of recognition results that satisfies the configurations for each identification method. Each record will be a pair of values $\{x, t\}$, where x from [0, 1] is the normalized distance between feature vectors, t from $\{0, 1\}$ is a sign of successful system operation, where 0 is erroneous recognition (FRR or FAR), and 1 — the correct recognition. Thus, using these configurations, we will simulate the operation of the system for 1 million comparisons and the resulting data sets are comparable with the actual system performance.

Figure 4 shows graphs of statistical data of real systems and graphs of the work of the developed model. Comparison of characteristics between them shows that the deviation of the data distribution of the model does not exceed 0.01%, which is sufficient for its further practical application.

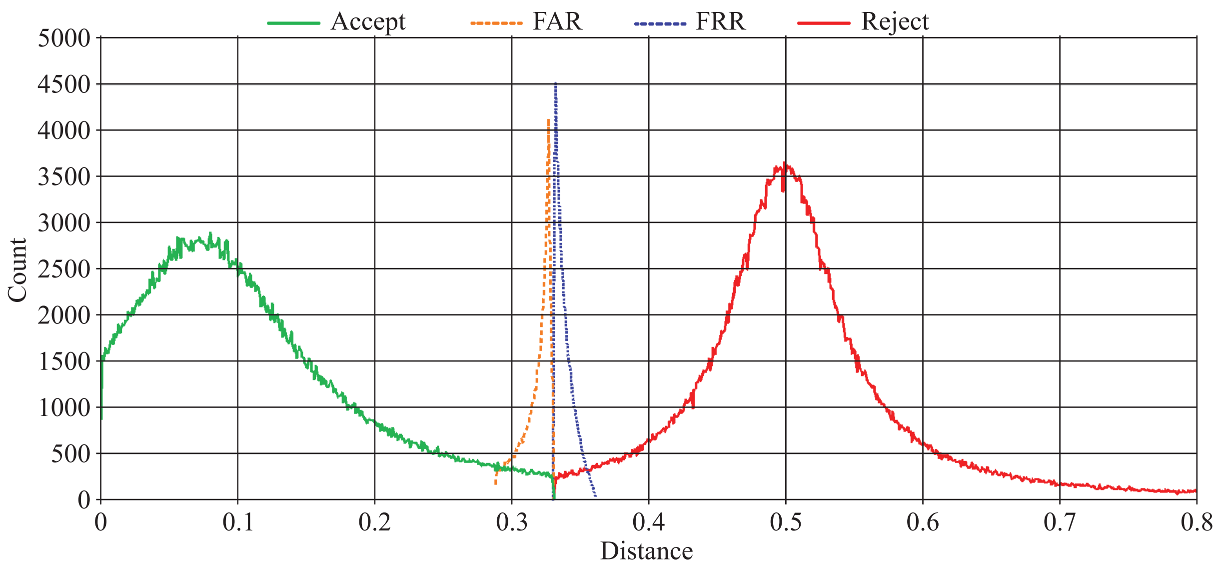

Figure 4. The graph reflects the dependence of the number of occurrences of the distances between the vectors of eye iris signs for the simulated parametrization methods. Accept — shows the distribution of comparison results, where the solution to the system is the successful identification of the iris. Reject — shows the distribution of comparison results, where the solution for the system is a successful denial of access for different users. FAR — shows the distribution of false access for different users. FRR — shows the distribution of false access denials for the same user

Intellectual synergy coefficient for several recognition methods

We first determine the theoretical possibility of the appearance of a synergy effect when using several methods of eye identification by the iris in the automatic recognition of people. Let us analyze in more detail the process depicted in Figure 2. Consider each function in terms of the impact on the quality of identification as a whole and the next step in particular. To do this, we construct a graph (Figure 3) of the quality deviation dependence level of the function on the probability of accurate identification in general. We introduce x_1 as a boundary to which there is no influence on the quality of identification. We also denote x_2 as the boundary after which the identification quality is 0. Thus, we obtain the interval $[x_1, x_2]$, where the identification probability can be represented as a function of $F(x)$, the form of which varies based on the characteristics of the considered implementation stage. Consider the sequence of normalization $T(e)$, parametrization $P(t, m)$ and comparison of $D(p1, p2)$, as dependent functions. Thus, x_1, x_2 and $F(x)$ will be determined for each stage both by its own characteristics and by the parameters of the entire chain of functions. As an example, in Figure 4 we will present possible options for identifying several methods of normalization, parameterization, and comparison. As you can see, you can select the chains C_i, on which a more accurate recognition is possible for a specific case. Based on the fact that the parameters x_1, x_2 and $F(x)$ vary for each chain, from a theoretical point of view it is possible to choose such factors, as for the set $[C_1 \ldots C_n]$ the identification accuracy is higher than the maximum value of the individual $(C_1 \ldots C_n)$. This is the result of the synergy effect.

$$S = \cup_{i=1}^{n} C_n \cap (\sum_{i=1}^{n} (d_n * k_n) < z), \quad d_n \in \mathbb{R} = [0, 1]. \tag{7}$$

As one of the practical applications of the mathematical model, it is proposed to use the generated data in neural network training, which will allow you to make an optimal identification decision based on synergy coefficients for several methods of recognition by the iris.

Model performance summary

Table 2 presents a summary of the model performance and accuracy for a workstation with the specifications: CPU 2.4 GHz, RAM 16 GB. The software implementation is made in the Python 2.7 programming language. The model input parameters are: the number of comparisons, the sampling step, recognition accuracy, the percentage of false access errors, the percentage of false access denials and the types of distribution of these functions over the interval $[0, 1]$. The algorithm of the program can be described as follows:

1. Construction of a probability function for each value on the interval $[0, 1]$, with a given sampling step.
2. Generation of a new entity of comparison.
3. Determining the type of comparison (true or false).
4. Decreasing counters of a specific type.
5. If not all entities are generated, then return to step 2.

Improvement of eye shooting instruments and increase in power of computers allow using more advanced methods of image preprocessing, localization, parameterization and comparison of codes without a significant loss in identification speed, as well as to combine several identification methods for better recognition. The model can generate about 6,000 full comparisons between different irises per second, because of the efficient implementation of the matching process in terms of elementary

Table 2. The speed and accuracy of the model, depending on the number of elements of the iris recognition process

Count	Time (s)	Diff accuracy (%)	Diff FAR (%)	Diff FRR (%)
1,000	0.176	0.40916	0.07143	0.25
10,000	1.629	0.26331	0.09489	0.00662
100,000	16.315	0.00429	0.01078	0.00134
1,000,000	165.456	0.00032	0.00899	0.00127
10,000,000	1663.728	0.000016	0.000559	0.00109

mathematics operators. Additionally, the high level of the model's quality allows to use it in the tasks of information security's models, teaching the neural networks of decisions making and testing the new methods of iris recognition.

Conclusion and future scope

The biometric identification of people has now acquired a key importance in the world, in such areas as security, access control and forensics.

Recognition by the iris of the eye is one of the rapidly developing biometric methods that stand out for its unique characteristics and accuracy. Iris recognition is the process of recognizing an individual by analyzing the visible structure of the iris, a comparison of which can be used for biometric authentication and identification of people. This article discusses the various stages of recognizing iris images, which include acquiring, segmenting, normalizing, extracting features, and matching. The model of a typical iris recognition system of the eye is described and the results of its work are presented. The data obtained demonstrate a data generation rate of about 6,000 comparisons per second and a deviation of the output data characteristics from the expected ones of about 0.001% for 1 million comparisons. A method of combining several parameterization methods to obtain the synergy effect is proposed. Tasks and achievements are presented in order to provide a platform for the development of new methods in this area as future work. Also, one of the directions of development is the practical obtaining of the synergy effect and maximization of recognition accuracy by dynamic calculation of coefficients based on machine learning.

References

Bodade R. M., Talbar S. N. SpringerBriefs in Applied Sciences and Technology // Springer India. — 2014. — P. 90–99.

Chen C., Veldhuis R. Extracting biometric binary strings with minimal area under the FRR curve for the hamming distance classifier // Signal processing. — 2011. — Vol. 91, No. 4. — P. 906–918.

Czajka A., Bowyer K. W. Presentation Attack Detection for Iris Recognition: AnAssessment of the State of the Art // ACM Computing Surveys. — 2018. — Vol. 51, No. 86. — P. 1–35.

Daugman J. G. How Iris Recognition Works IEEE Trans // IEEE Trans. on Circuits and Systems for Video Technology. — 2004. — Vol. 14, No. 1. — P. 21–30.

Daugman J. G. Information Theory and the IrisCode // IEEE Trans. Info. Foren. Sec. — 2015. — Vol. 11, No. 2. — P. 400–409.

Daugman J. G. Biometric entropy (summary of IAPR Award Lecture) // IAPR Newsletter. — 2017. — Vol. 39, No. 3. — P. 4–5.

Farmanullah J. et al. Iris localization in frontal eye images for less constrained iris recognition systems // Digital Signal Processing. — 2012. — Vol. 22, No. 1. — P. 971–986.

Farmanullah J. et al. A non-circular iris localization algorithm using image projection function and gray level statistics // Optik-International. — 2013. — Vol. 241.

Galbally J. et al. Iris image reconstruction from binary templates: An efficient probabilistic approach based on genetic algorithms // Computer Vision and Image Understanding. — 2013. — Vol. 117, No. 1. — P. 1512–1525.

Galbally J. et al. An effective biometric cryptosystem combining fingerprints with error correction codes // CExpert systems with applications. — 2012. — Vol. 39, No. 1. — P. 6562–6574.

Rathgeb C., Busch C. Cancelable multi-biometrics: Mixing iris-codes based on adaptive bloom filters // Computers & Security. — 2014. — Vol. 42, No. 1. — P. 1–12.

Trokielewicz M., Bartuzi E. Cross-spectral Iris Recognition for Mobile Applications using High-quality Color Images // Journal of Telecommunications and Information Technology. — 2016. — Vol. 3. — P. 91–97.