

Hand-Based Biometric Recognition Technique - Survey

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ABSTRACT

In today's modern world, reliable automatic personal recognition is a crucial area of discussion, primarily because of the increased security risks. A large number of systems first require the recognition of a person before they can access their services. Biometric recognition can be used, which can be understood as automatic identification or automatic verification of persons based on physiological or behavioural characteristics. Examples of biometric characteristics may be the fingerprint, face, signature, hand geometry. There are many approaches, and each has its pros and cons. However, there is currently no current extensive research and evaluation of hand-based biometric systems. Given the user-friendliness of these systems and the needs of society, this article aims to compare different methods of biometric recognition based on hand, so that the article reduces the entry barrier into this area of research. Furthermore, the article aims to determine the research gap and suggest possible directions for research in the future.

1. Introduction

This paper is an extension of work originally presented in International Conference on Information and Digital Technologies [1]. In today's modern society, there is an increasing emphasis on working with information. Information is one of the most valuable assets we can own, so it needs to be protected. Among the basic requirements for their security are their confidentiality, integrity and availability. The requirement of confidentiality information requires that only authorized entities have access to it. One way to ensure the confidentiality of information is through authentication, during which the identity of the entity to which the relevant rights are subsequently assigned is verified [2].

Authentication can be defined as: "A method of verifying a user's identity on a system to control access to the system or resources." [3] Authentication can be performed using knowledge (password, pin), an authentication object (token, mobile phone), or using what we are physically and mentally (biometric characteristics). The last option is used by biometric recognition systems, which have come to the fore, especially in recent years, thanks to scientific and technical progress.

Biometric systems are applications of biometric technologies that allow automatic identification or verification of a specific natural person, using physical (e.g. face, fingerprint) or behavioural (e.g. voice, gait) characteristics. Biometric

characteristics must be universal (the characteristics must exist for all persons), they must have high external variability (high diversity for different persons) and low internal variability (low diversity for one person).

Identification ("One-To-Many Matching") is understood in this article as the process of comparing a set of biometric features obtained from a scanned biometric sample with all reference templates stored in a database. If there is a reference template in the database that sufficiently corresponds to the set of biometric features, the biometric system identifies the person by the identity associated with this reference template, otherwise the person is not identified [4].

Verification ("One-To-One Matching") is understood in this article as the process of verifying that the person being examined is who he or she claims to be. The set of biometric features obtained from the scanned sample is compared with one own biometric template, which is stored in a database. If the set of biometric features sufficiently matches this reference template, the identity is verified, otherwise it is not verified [4].

Biometric recognition of people is based on their biometric characteristics, and it is their unique physiological and behavioural characteristics. Physiological characteristics are those characteristics with which we were born and include, e.g. iris [5, 6], retina [7], face [8], shape of the outer ear [9], fingerprints [10], palmprints [11] and footprints [12], fingers geometry [13], hand geometry, [14], topography (layout and shape) of wrist veins

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[15], DNA [16]. Behavioural characteristics include, e.g. voice [17], writing [18], signature [19], and gait [20].

From the biometric characteristics, distinguishing repeatable biometric features can be obtained for biometric recognition. Biometric features are numbers or designations obtained from biometric samples that are used for subsequent comparison. Biometric samples are an analogue or digital representation of biometric characteristics before the actual extraction of biometric features [21].

The article aims to provide a comprehensive survey with the inclusion of most recent research papers up to 2020, covering a total of 117 journal publications, conference proceeding, patents, and papers. The aim is also lower the entry barrier to this research area by providing a comprehensive reference for novices. Offer a wide range of comparisons in diverse research angles and perspectives in hand geometry recognition. Identify current trends in this area and the need for future research.

2. Development of Hand-Based Biometric Systems

The first modern biometric systems used the hand geometry as a biometric characteristic, and then it was an authentication system in the verification mode (the user submitted an identity and it was subsequently confirmed or rejected). Robert Miller dealt with the issue of hand-based biometric systems in the 1960s and based on research, and he created a device at the Stanford Research Institute, which he patented in 1971. This device performed the pattern recognition by purely mechanical means, where four spring bars slid towards the user's fingers and subsequently the length of the user's fingers was measured. If the finger lengths matched the pattern embossed on the user's identity card, a simple switch was activated, which was used to operate the electric lock [4, 22].

The first commercial hand scanner was the Identimat, based on the patent Robert Miller's as mentioned above [22]. The measurement of the hand was performed by scanning the photocells located under grooves on which the user placed the hand (fingers). The light source was light with a power of 1000 watts. A reading head with a magnetic stripe was attached to this scanning mechanism, to which a user's magnetic card was attached during verification. If the pulses on the card matched the signal times from the photocell sensors within the threshold value, the user's identity was verified. This system was successfully used in various applications. The first use was of a military nature, and it was the security of nuclear weapons. Later, Identimat was used to access US nuclear power plants and also to control employee attendance at an investment company on Wall Street. The second development line of Identimat was already two-dimensionally oriented, measuring not only the length but also the width of all fingers on one hand [4, 23].

The history of the practical implementation of hand geometry recognition is further associated with the name David Sidlauskas and his company Recognition System Inc., which he founded in 1986. This company was the first in the world to start developing and selling modern hand scanners. In the mid-1980s, David Sidlauskas patented the first biometric system to use a three-dimensional hand image. The patented system consists of a camera and an optical measuring board. The camera has a plan view and a side view of the hand. The identification code is entered using the keypad [24]. Based on this patent, the first commercially successful biometric system using the hand geometry of the Handkey ID3D scanner was created.

BioMet Partners, Inc. developed a two-finger version of the Digi-2 hand scanner and was launched in 1995. The scanner uses a CCD camera to scan only the index finger and middle finger and obtain their 3D image [4].

In the 1990s, biometric hand scanners were used in the INSPASS program, a program at selected US airports that accelerated the check-in of frequent travellers. These persons could apply for inclusion in a program in which their hand geometry was scanned and then obtained an identification card with a reference template. These persons were able to complete check-in quickly at selected airports with the help of installed hand scanners [25].

Another hand-scanner recognition project was an Israeli project that automated motion control on the Israeli-Palestinian border. During the creation of the biometric system, suitable biometric characteristics were selected. Biometric characteristics face, hand geometry and fingerprints were considered. A multi-biometric system was chosen that combined face recognition and hand geometry, which was chosen mainly because most people crossing the border are workers whose fingerprints are not reliable for biometric verification [26].

In terms of security, hand scanners were also used at the 1996 Atlanta Olympics, which controlled access to the Olympic Village. Hand scanners were also used by the Colombian legislature, which voted safely through them [27]. Until 1998, only two scientific articles in the field of hand-based biometric systems were published, namely: "Vital Signs of Identity" a "A Performance Evaluation of Biometric Identification Devices." [2, 23, 28] From 1998 to 2006, there was an almost exponential increase in the number of publications in this area [29].

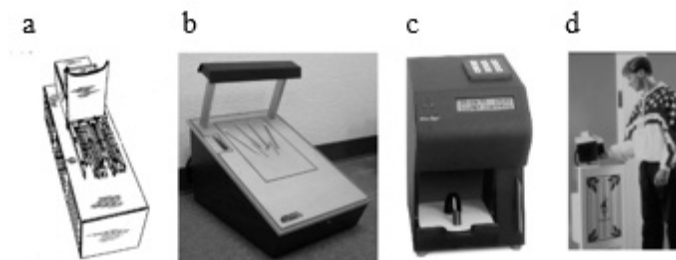


Figure 1: a) Drawing of mechanical hand reader [22] b) Identimat [30] c) two-finger scanner from Biomet [31] d) utilization hand geometry scanner at the Atlanta Olympics [32]

3. Current methods in hand-based biometric systems

Current hand-based biometric systems can be divided into the following groups according to biometric characteristics [33]:

- hand geometry and handshape,
- palmprint,
- fingerprint,
- topography (finger, hand).

At the beginning of the research of hand-based biometric systems, hand geometry was used, e.g. widths, lengths, angles [35-37], later the silhouette of the hand was added as another biometric characteristic [38-40].

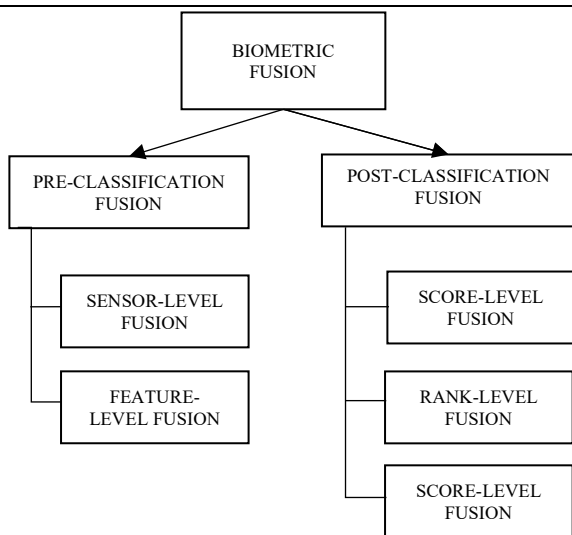


Figure 2: Fusion at various levels of multi-biometric systems (source: [34])

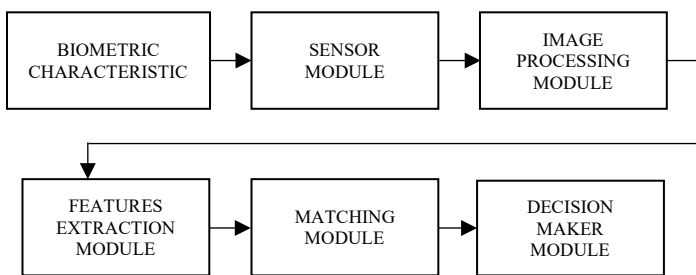


Figure 3: General model of biometric system

Currently, there are also multi-biometric systems that use a combination of multiple biometric characteristics. A palmprint [41-45] or bloodstream topography [46-48] is used in combination with hand geometry or silhouette. The topography of bloodstream is measured either on the palm or back of the hand when the whole hand is scanned. Systems have also been developed that combine more than two characteristics, such as hand geometry, palmprint, and fingerprint [49, 50]. Multi-biometric systems achieve higher accuracy [51] than biometric systems using only one biometric characteristic. Newly emerging biometric systems also use as a characteristic the heartbeat captured on the finger [52], pores on the hands [53], or hand gestures [44].

Combining multiple biometric characteristics in one biometric system requires fusion, which is the interconnection of information. Fusion can be achieved at different levels of the biometric system. Fusion levels can be divided into two large groups: pre-classification fusion and post-classification fusion. Pre-classification fusion include sensor-level fusion and feature-level fusion while post-classification fusion includes score-level fusion, rank-level fusion rank and decision-level fusion [34]. The individual fusion levels are shown in Figure 2.

The biometric recognition system has several modules: the sensor captures the biometric characteristic, followed by image processing, extraction of identification features, comparison with the biometric template and decision. The individual modules of the biometric system are shown in its general model in Figure 3.

3.1. Sensor

CCD chip cameras, a light-sensitive image detector used by digital cameras, camcorders, and webcams, e.g. are most

commonly used to capture biometric characteristics [24, 53]. The scanner can also be a biometric sensor [42, 49, 54]. The sensor captures either a 2D [55-57] or a 3D [48, 58, 59] image of the hand. 3D images are obtained using two cameras, with the help of mirrors, or they can be obtained using a 3D digitizer [60].

Lighting also plays an essential role in obtaining a biometric sample. Some systems have their own light source, mainly commercial biometric scanners. Most sensors acquire images of the hand in visible light, but some also use infrared radiation [47, 61], which achieves a higher accuracy of biometric recognition [62].

Today, commercially available hand readers use spacer pins that firmly determine the position of the hand when scanning [48, 58, 63]. As spacer pins can deform the silhouette of the hand [64], systems without spacer pins have come to the fore in scientific circles [53, 65, 66]. The latest possibilities are contactless systems [38, 61, 67, 68], where, in addition to the spacer pins, direct contact with the reader is not required. These systems are considered to be the most user-friendly, mainly due to the elimination of the need for physical contact.

3.2. Image processing

After obtaining the image of the hand, it is necessary to process the acquired image. The first step in image processing is image pre-processing. It is a set of methods that are applied to an image because only a minimal percentage of hand images are taken under optimal conditions. Almost no captured image is completely noise-free, not entirely focused, obtained in optimal lighting conditions. For this reason, filters are used to sharpen the image or to remove noise. It is also possible to change the brightness using geometric transformation methods. [69]

The second step of image processing is image segmentation, i.e. dividing the image into segments with common properties. The aim of segmentation in hand-based biometric systems is to separate the hand from the rest of the image automatically. The more hand the image is obtained in more limited conditions, the easier the segmentation and can be done by faster methods. Segmentation methods can be divided into groups [69]:

- statistic methods,
- methods based on edge detection,
- hybrid methods (morphological),
- knowledge methods.

If the hand image is acquired on a scanner, the background is constant, and segmentation is relatively simple, then the segmentation method of image thresholding can be used. Image thresholding is the simplest statistical segmentation method based on pixel brightness evaluation. During thresholding, problems arise with rings, bracelets, or dirty skin [70-72].

Segmentation of the hand image can also be performed using edge detection methods. Edges are detected by edge detectors based on significant differences in the values of neighbouring pixels [37, 73].

There are also multi-stage segmentation methods where multiple methods are combined. These multi-stage methods can detect a hand from a crowded background. An example of such a method is a method that first detects the skin by colour (knowledge) and then detects the shape of the hand [74].

Another method of segmentation and at the same time localization of biometric features is AAM (Active Appearance Model) [55]. The AAM method presents the hand using an appearance model, which is created from a shape model and a hand texture model based on a statistical method - principal component analysis (PCA). The advantage of the method is the complexity of the information it contains about the hand [75].

The disadvantage of some segmentation methods is that their use breaks the silhouette of the hand. Mathematical morphology is a mathematical tool that can solve this problem and connect disconnected fingers. Mathematical morphology is also used to remove rings, bracelets or watches [56, 76, 77].

If the position of the hand is not fixed when acquiring the image, it is necessary to align the image of the hand after segmentation within the image processing. This can be done using landmarks, which can be extremes (fingertips, finger valleys) [36, 57, 78], of the centre of gravity, or a fixed reference point on the wrist [79].

Image processing is performed to facilitate the extraction of the region of interest. Biometric features are then extracted from the area of interest.

3.3. Extraction of biometric features

The image processing is followed by the extraction of biometric features. Extraction of biometric features is defined in [21] as: "A process applied to a biometric sample to isolate and obtain a repeatable output of characteristic numbers or designations that can be compared with features extracted from other biometric samples." For the biometric characteristic of hand geometry, biometric features are geometric measurements, such as finger lengths and widths, finger area, radii of circles on fingers and palms, and angles between fingers. Figure 4 shows 17 geometric measurements, but some systems use a different number of measurements, most often 13-50 measurements [35, 49, 80].

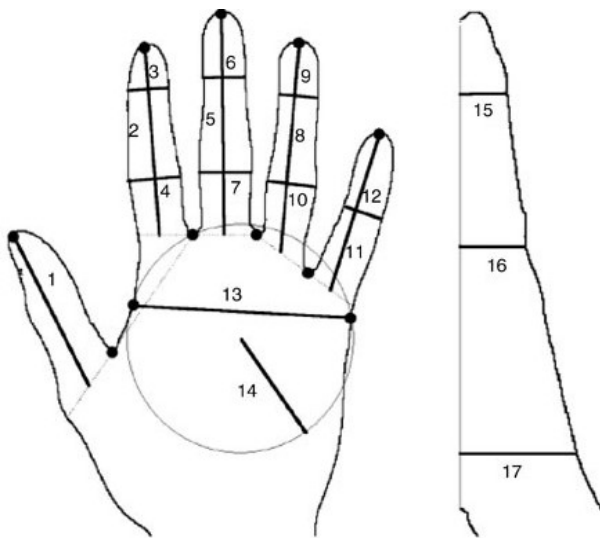


Figure 4: Geometric measurements (source: [81])

More information than hand measurements is provided by the silhouette of the hand, which is used by many systems [40,70]. These systems use biometric features to extract generic or customized feature extractors. For example, customize shape extractors [40, 82, 83] or figure features extractors algorithms

Scale Invariant Feature Transform (SIFT) [82], LBP [84]. They are also used palm-based textures [85]. The silhouette is also distinguishable by its contour pixels; it represents the real shape of the hand [67].

Contours are less explored than geometric features, especially since geometric features are easier to determine from a normalized hand image. The issue of normalization of various hand positions and accurate localization of fingertips and finger valleys in unrestricted and contactless systems requires further research. [67]

Some systems extract biometric features of hand geometry and hand shape at the same time, extractors are specially adapted to the shape and geometry of the hand [86, 79].

Recent research uses deep neural networks, such as convolutional neural networks [87, 88] or Siamese networks, to extract biometric features of the hand [87].

3.4. Comparison with the reference template

In this phase, a set of biometric features obtained from a recognized person's biometric sample is compared with a reference template or templates (stored in a database). The score is then generated using the following methods:

- statistic methods,
 - minimum distance (Euclidean metric, Hamming metric, Chebyshev metric),
 - Kullback–Leibler divergence,
 - correlation coefficient,
 - Gaussian mixture models (GMM),
- machine learning,
 - support vectors machine (SVM),
 - k-nearest neighbours,
 - Bayesian networks,
 - neural networks.

Statistic methods

Statistical methods of comparing a set of biometric features with a reference template when recognizing a person based on the geometry and shape of the hand include a comparison by a minimum distance. If M reference templates are stored in the database $x_{1R}, x_{2R}, \dots, x_{MR}$, the minimum distance of the hand biometric sample x from the reference template is calculated as follows:

$$\min_{s} \|x_{sR} - x\| \tag{1}$$

- $x_{sR} \dots \dots$ reference templates
- $s \dots \dots$ number of reference templates
- $x \dots \dots$ biometric features set (vector)

When recognizing a person based on hand geometry and hand shape, various metrics are used to determine the distance, such as the Euclidean metric [37, 56, 70], the Hamming metric [39], or the Chebyshev metric [80].

- Euclidean metric is defined by the relation:

$$\rho_E(\mathbf{x}_1, \mathbf{x}_2) = \sqrt{\sum_{i=1}^n (x_{1i} - x_{2i})^2} \quad (2)$$

- Hamming's metric, sometimes called Manhattan, is defined by relations:

$$\rho_H(\mathbf{x}_1, \mathbf{x}_2) = \sum_{i=1}^n |x_{1i} - x_{2i}| \quad (3)$$

- Chebyshev's metric is defined by the relation:

$$\rho_C(\mathbf{x}_1, \mathbf{x}_2) = \max_{i} |x_{1i} - x_{2i}| \quad (4)$$

The Kullback – Leibler divergence can also be used to express “distance”, which expresses the degree of dissimilarity between two probability distributions [36]. The correlation coefficient can also be used as a measure of similarity [81, 89].

Gaussian mixture models are located at the interface of statistical and machine methods (GMM). It is a pattern recognition method that is based on the GMM's ability to approximate any probability density using a mixture of Gaussian densities. The probability of the vector of characteristics \mathbf{x}_n is estimated as a weighted sum of Gaussian densities. The result is, therefore, the probability with which the pattern (hand image) belongs to a given class. This method gives better results in the field of recognizing a person based on hand geometry than methods working with distance [37, 59].

The Gaussian mixture model is defined by the relation:

$$p(\vec{x}|u) = \sum_{i=1}^M \frac{c_i}{(2\pi)^{L/2} |\Sigma_i|^{1/2}} \exp \left\{ -\frac{1}{2} (\vec{x} - \vec{\mu}_i)^T \Sigma_i^{-1} (\vec{x} - \vec{\mu}_i) \right\} \quad (5)$$

u identity of the person to whom the hand image is assigned with probability p

\mathbf{x} vector of biometric features

c_i weight of individual Gaussian models

μ_i average vector model

Σ_i covariance matrix

M number of models

L dimension vector of biometric features

Machine learning

Machine learning is a group of algorithms that allow a computer system to learn. Mitchell [90] defined machine learning as follows: “A computer program is said to learn from experience E concerning some classes of T and the measured power P , if its performance P improves with experience E .”

A large and used group of machine learning are algorithms called support vectors or support vector machines (SVM). These are classifiers that use boundaries in image space. SVM aims to find a superstructure that divides the symptom space. SVM used Vinodkumar and Srikantaswamy as a classifier in a multi-biometric system, where the biometric characteristics were hand geometry, fingerprints and palmprint [91]; however, they have also been used in many other hand-based multi-biometric systems [41, 42, 49, 92].

A frequently used machine learning method in hand-based biometric systems is the nearest neighbour (k-NN) method [54, 93]. It is one of the simplest classification methods.

Bayesian networks [93, 94] or random forest [84] can also be used for comparison with the pattern.

Some types of neural networks, multilayer perceptron (MLP) can also be used as classifiers [95]. Generalized regression neural network (GRNN) [96] and convolutional neural network (CNN) were used as classifiers that were not preceded by classical features extraction, classification was performed using SOFTMAX [86].

3.5. Decision

In most systems, the final decision on a user's identity is based on a threshold that is chosen so that the biometric system meets security and throughput requirements. The score calculated in the previous system module is compared with the threshold value. If the score is higher than the threshold, the user is identified or verified, but if the score is lower than the threshold, the user is not identified or verified. The outcome of decisions for hand-based biometric systems is significantly influenced by user training, with the right habits of users, the score increases (agreement of the compared samples) [97, 98].

4. Quantitative evaluation of biometric system

Possible identification results are shown in Table 1.

Table 1: Possibilities of recognition decision

		Decision	
		Accept	Reject
Actual output	Authorized user	Correct acceptance	Incorrect rejection
	Unauthorized intruder	Incorrect acceptance	Correct rejection

Source: [2]

Based on the decision, the performance of biometric systems can be quantified. Selected quantified identifiers are [99].

False Rejection Rate – FRR

The probability that the biometric system does not recognize the authorized user will lead to an erroneous rejection, i.e. a type 1 error. If an error of this type occurs, the user can try to prove his identity again. The FRR is calculated according to the formula:

$$FRR = P(FR/OU) = \lim_{N_{OU} \rightarrow \infty} \frac{N_{FR}}{N_{OU}} \quad (6)$$

FR ... occurrence of a rejection error

OU ... recognition (verification or identification) by an authorized user

N_{FR} ... number of false rejections

N_{OU} ... number of attempts by authorized users to recognize

False Acceptance Rate – FAR

The probability that the biometric system will accept an unauthorized intruder will lead to incorrect acceptance, i.e. a type 2 error.

The FAR calculation is considered according to the formula:

$$FAR = P(FA/NN) = \lim_{N_{NN} \rightarrow \infty} \frac{N_{FA}}{N_{NN}} \quad (7)$$

FA... occurrence of an acceptance error

NN... recognition by an unauthorized intruder

N_{FA} ... number of incorrect acceptances

N_{NN} ... the number of attempts by an unauthorized intruder to recognize

The FAR and FRR rates depend on the threshold and are also inversely proportional. The higher the threshold, the more secure the biometric system, but the more common the type 1 error occurs and the user-friendliness decreases. On the contrary, the lower the threshold value, the more user-friendly the biometric system, but more often an unauthorized intruder, i.e. a type 2 error, is admitted, and the security of the system is reduced. The threshold value must always be set according to the requirements that are placed on the biometric system.

Equal Error Rate – EER

Value where the error rates of both FAR and FRR are equal, (i.e. FAR = FRR). With such a setting, the system incorrectly rejects and incorrectly identifies the same number of people. The lower the EER value, the higher the accuracy of the system. It is the most widely used indicator for evaluating and comparing biometric systems.

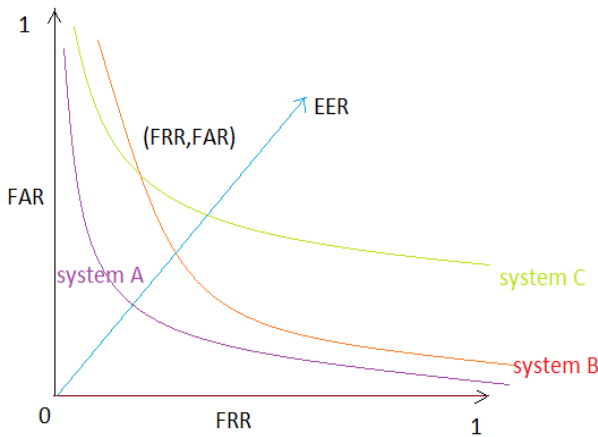


Figure 5: ROC Curves [100]

Receiver Operating Characteristic – ROC

The probability's curve that is given by the relationship between the probability of false acceptance (FAR) on the x-axis and the corresponding probability of correct acceptance on the y-axis for all allowable threshold values. Using ROC curves, multiple models can be compared with each other. Comparison and evaluation of multiple ROC curves are performed using the Area Under Curve (AUC) areas, which are located below the individual ROC curves [101]. Figure 5 shows the ROCs of the three systems, system A being the best system under the circumstances.

EER, FRR, FAR, ROC was selected for this work. They are a good indicator and the most frequently used tool for evaluating and managing biometric systems.

In articles dealing with biometric systems, we also encounter the concept of accuracy. The accuracy is calculated according to the formula:

$$\text{accuracy} = \frac{CD}{NR} \quad (8)$$

CD ... correct decision (correct rejection and correct acceptance)

NR... number of recognition attempts

5. Comparison

The most commonly used physiological characteristics in biometric are fingerprint, face, hand geometry, and iris [102]. Table 2 compares biometric systems that use commonly biometric characteristics based on EER. Of these biometric characteristics, most often the lowest EER is achieved, biometric systems working with the iris, but as can be seen in Table 2, other systems, such as fingerprints, also achieve very low EER. However, in addition to error rates compilation speed, acquirability, privacy, cost and ease of use, should also play a role in choosing a biometric system [102].

Table 2: Comparison of selected hand other biometric systems

Sources	Biometric Characteristic of Recognition	Size of the Database	Performance
Chen et al. [103]	Iris	3 500	EER = 0.43
Yingzi et al. [104]	Iris	610	EER = 0.0295
Wijaya [105]	Face	2 268	EER = 0.0457
Marvadi [106]	Face	427	EER = 0.1525
Liu et al. [107]	Fingerprint	350	EER = 0.0042
Jain & Feng [108]	Fingerprint	449	EER = 0.081
Varchol & Levický [109]	Hand geometry	408	EER = 0.0462
Jain et al. [110]	Hand geometry	500	EER = 0.06

Table 3 summarizes the essential characteristics of some systems and methods that appeared in the journal and conferences. Some systems have been tested in identification mode, some in verification mode. Only some papers report EER, FAR / FRR or Accuracy values, some authors evaluate systems using ROC curves. The selection in Table 3 seeks to compare a representative sample of hand-base systems by characteristics (Hand-base Biometric Characteristic, Mode, Techniques Applied for Features Extraction, Techniques Applied for Recognition, Size of the Database, Performance).

Older systems use geometric measurements as features and are mostly in verification mode [110, 115]. Newer systems [111, 117] use a combination of multiple biometric characteristics such as hand shape and hand texture and use deep learning methods. Today's systems are mainly in identification mode, and FRR or EER has less than 1%.

Table 3: Comparison of selected hand based biometric system

Sources	Biometric characteristic / Mode	Techniques Applied for Features Extraction	Techniques Applied for Recognition	Size of the Database	Performance
Afifi [111]	Hand texture and shape / identification	CNNs + LBP	Support vector machine (SVM)	11 076	EER = 0.009
Kumar & Zang [112]	Hand geometry / identification	discretization of hand-geometry features	SVM	1 000	Accuracy = 0.94
Shanmukhappa & Sanjeevakumar [113]	Hand geometry /identification	Feature vector construct by hand image graph	SVM (Radial basic function)	1 440	FRR = 0.0205
Jain et al. [110]	Hand geometry/ verification	Geometric measurements	Euclidean distance	500	EER= 0.06
Varchol & Levický [109]	Hand geometry/ verification	Geometric measurements	Hamming distance	408	EER = 0.0973
Villegas et al. [114]	Hand geometry /identification	Wavelet Features	Nearest Neighbour	120	FAR = 0.11 FRR = 0.1
Varchol & Levický [109]	Hand geometry/ verification	Geometric measurements	Gaussian Mixture Model	408	EER = 0.0462
Burques et al. [115]	Hand geometry/ verification	Geometric measurements	Distance measure	12 800	EER = 0.0016
Charfi et al. [116]	Hand shape/identification	Scale Invariant Feature Transform (SIFT)	SIFT Matching	1 170	EER = 0.0586
Yoruk et al. [29]	Hand shape /identification	Independent Component Analysis (ICA)	L1/L2 norm of the difference of the feature vectors	458	Accuracy = 0.9731
Yoruk et al. [29]	Hand texture /identification	Principal Component Analysis (PCA)	L1/L2 norm of the difference of the feature vectors	458	Accuracy = 0.9791
Yoruk et al. [29]	Hand texture /identification	Angular radial transform (ART)	L1/L2 norm of the difference of the feature vectors	458	Accuracy = 0.976
Přihodová & Hub [117]	Hand texture and shape / identification	CCN (GoogLeNet)	CCN (Softmax)	456	FRR= 0.001

6. Research gap

It was not possible to cover all the literature dealing with hand biometric systems, but we included a representative sample of modern methods. However, we were able to identify some research gaps. To make hand-based biometric systems more efficient in real-world applications, the following challenges need to be overcome:

A large number of users – In the real world, it is often necessary to recognize millions of identities. However, the variability between some individuals may be minimal.

Quality of input data – Thanks to the progress of sensing sensors, the input image obtained in a real application under standard lighting conditions is correctly exposed. However, the image quality deteriorates in poor lighting conditions. Other problems we face despite the significant progress of the sensors are accurate colour capture and noise.

The permanence of biometric characteristics – Hand-based biometric characteristics have high stability over time but are not 100 %. For the hand geometry and hand shape, the topography of the bloodstream is primarily a problem of biological ageing and injury.

Attacks on systems – Hand-based biometric systems must face attacks at various levels in real-world applications. One of them is an attack on an input device, where the attacker forged a biometric sample, as a defence against this type of attack is the detection of liveness.

Datasets – Small datasets are also a problem in this area of research, most current systems are tested on small datasets.

Costs – Costs should always be considered, and efforts should be made to make systems more accessible.

7. Discussion

Given the current state of hand-based biometric recognition, which was described in previous chapters of the article and due to the unresolved challenges in the field, one of the possibilities for further research is the use of a multi-biometric system, which uses hand geometry and thermal properties of hand. The thermal characteristic can be used in the form of blending two images (thermogram and image from the visible part of the electromagnetic spectrum), this blending creates a multispectral image. The multispectral image provides more significant variability between certain individuals than the mere geometry of the hand. A multispectral image is also advantageous in low lighting conditions, the quality of input data decreases less because the thermogram is not dependent on lighting conditions. When using a multispectral image, some types of attacks on biometric systems are also eliminated, because the thermal map of the hand, which is captured by the thermogram, is complicated to imitate and at the same time liveness is detected. At the same time, the multi-biometric system should increase recognition accuracy.

Another research option is also a multi-biometric system using hand geometry or palmprint in combination with skin colour (soft biometrics). This multi-biometric system could help to solve the problem of low variability between specific individuals.

Conflict of Interest

The authors declare no conflict of interest.

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