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A comprehensive review on iris image-based biometric system

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Abstract
Iris image-based biometric systems are commonly used in applications that demand security, authentication, recognition and faster login access. In solving these real-time problems, the impact of soft computing techniques which employ cognitive skills is very high. Although this system has been commercialized, the scope for improvement is still plenty. This paper introduces the reader to different segments of an iris recognition system and reviews the techniques involved with each segment. It reports on how research articles validate the robustness of an iris-based recognition system. As these systems are fallible, it also shows the vulnerabilities associated with each segment and provides insights to develop much better intelligent and robust techniques which will make the system more accurate. This paper also shows that in spite of versatility of soft computing techniques, it is not fully exploited for iris recognition systems. The present challenges and directions for future research are also discussed.

Keywords Iris images · Feature extraction · Feature selection · Biometrics · Pattern recognition · Machine learning

1 Introduction

In an era where security and authentication have become more crucial, biometric systems have gained a lot of potential interest. Biometrics are the measurement of physical or behavioural characteristics of a living being. These systems use biometric features of human to recognize them. Iris is one such physiological biometric trait which is universally unique and distinct even between twins. Moreover, it has attracted many biometric research engineers and industrialists to deploy it into the global market because of its non-invasive nature. Iris image-based biometric system has a broad area of applications as follows:

- To provide secure access to classified documents.
- To render authentication in ATMs.
- To maintain attendance report in large corporate systems.
- To prevent infiltration across borders and inside highly secured government buildings.
- To procure access to personal automobiles and electronic gadgets like smartphones, laptops
- To lend access to premises like a laboratory, home, office room
- To trace missing or wanted persons in forensics.

Earlier, the personal identification of individuals was done through a secret password, encoded cards and personal identification number. The quest for a non-invasive method of identification leads to the ground breaking concept of iris recognition. It was first patented by US ophthalmologist Flom and Safir (1987). Later, an automated system for iris recognition was developed at Los Alamos National Laboratories, CA (Johnson 1991). Followed by it, Daugman and Wildes have worked independently and developed prototypes. Wildes (1997) has also discussed briefly on the emergence of this iris-based biometric technology. Based on the table of information furnished in Nandakumar et al. (2008), Iris seems to be a better biometric trait in terms of having less false rejection rate and false accept rate.

Research laboratories across the globe like CyLab, Idiap Research Institute, CVB lab, National Physical Laboratory, Mitsubishi Electric Research Laboratories and companies like Iritech, Eyelock, CMI Tech, IBM, LG, Iridian Technology, Siemens, British Telecom, IriScan, Iridian and Oki work at various levels on designing hardware and software

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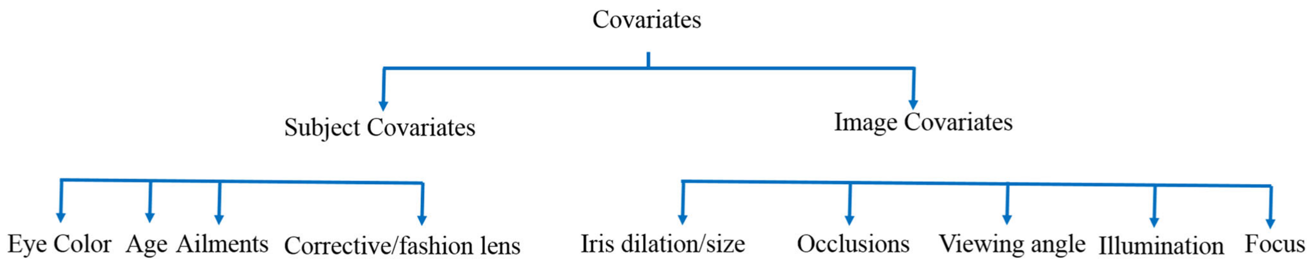

Fig. 1 Variety of iris covariates that has a significant impact on recognition rates

to develop a better iris biometric system. Many smartphone vendors like Samsung, Microsoft, Fujitsu, Vivo, ZTE, Alcatel UMI and LG in their flagship models are looking forward to integrate iris scanners with the mobile phone.

A brief statistics on the usage of iris biometrics is discussed in Unique Identification Authority of India (2012). Iris-based recognition systems are being deployed by government agencies too. India is the first and largest country to use Iris as a national ID. This project was launched to facilitate good governance and to maintain equality in distributing subsidies to each citizen without being partial (Howard and Etter 2014). A similar deployment for public has been used also in countries like the Netherlands, UAE, UK, USA and Canada (http://www.bbc.com/news/uk-england-17058448; http://www.schiphol.nl/Travellers/AtSchiphol/Privium.htm; http://www.irisid.com/productssolutions/irisaccessinaction/; Daugman 2004). The ambiguity in the identity of a woman in a refugee camp was resolved with Daugman's iris recognition software (http://www.unhcr.org/3f86b4784.html; Rathgeb et al. 2012). It is also used in tracing children lost due to children trafficking (The Child Project 2007). The scope of this iris technology seems to grow day by day.

Unlike laboratory conditions, the circumstances in the real world may cause the image of the iris to vary substantially over different degrees of freedom. These differences may be due to subject covariates (Burge and Bowyer 2013) like eye colour, race, sex, the type of corrective or fashion lens worn during acquisition or due to image covariates due to iris size, iris dilation, occlusions due to eyelid or eyelashes, focus quality, illumination and viewing angle as shown in Fig. 1. These are the covariates that majorly contribute to the recognition error.

Although iris biometric systems are commercially available in the market, still there are open issues yet to be addressed. A few of them are as follows:

- To benchmark the consistency of the iris recognition regardless of ophthalmic ailments, state of mind and age.
- To obtain the best descriptor that defines the features and that would enhance the performance of the system.
- To counterbalance the effects of spoofing by imposters and other covariates.
- To project the iris image captured at an improper angle to orthographic perspective.
- To explore the possibilities of enhancing the computer vision through artificial intelligence and deep neural networks.

Although many techniques have been proposed and flaws in iris image-based biometric systems have been addressed by various researchers, a common repository for new researchers is hard to find. This review will give young budding researchers a common platform to perceive iris image-based biometric system as a whole and work in their relevant fields to develop a robust system. Hence, the motivation of this article is to pave way for providing solutions to the above challenges experienced in the iris image-based biometric system.

The structure of the remainder of the article is organized in the following way. Section 2 gives an outline of the iris image-based biometric system and algorithms common in practice. Section 3 gives an idea of the set-up of image capturing device for iris image acquisition and few readily available databases for researchers. Section 4 deals with removing pre-processing for removing artefacts. Section 5 describes different segmentation schemes for segregating iris from the surrounding background. Section 6 brings out the normalization methods to change segmented annular iris into a predefined rectangular structure. Section 7 untangles different features extraction methods that describe the normalized iris. Section 8 unravels the concept of choosing the best descriptors for reducing complexity. Section 9 point out different classifiers associated with recognizing the iris. A discussion on present challenges and directions for future research is summarized in Sect. 10. And at last conclusions are drawn in Sect. 11.

2 Iris image-based biometric system

With the evolution of iris technology, it has gained acceptance and adoption into gadgets over the past 15–20 years. The processing flow of any typical iris image-based biometric system is illustrated in Fig. 2.

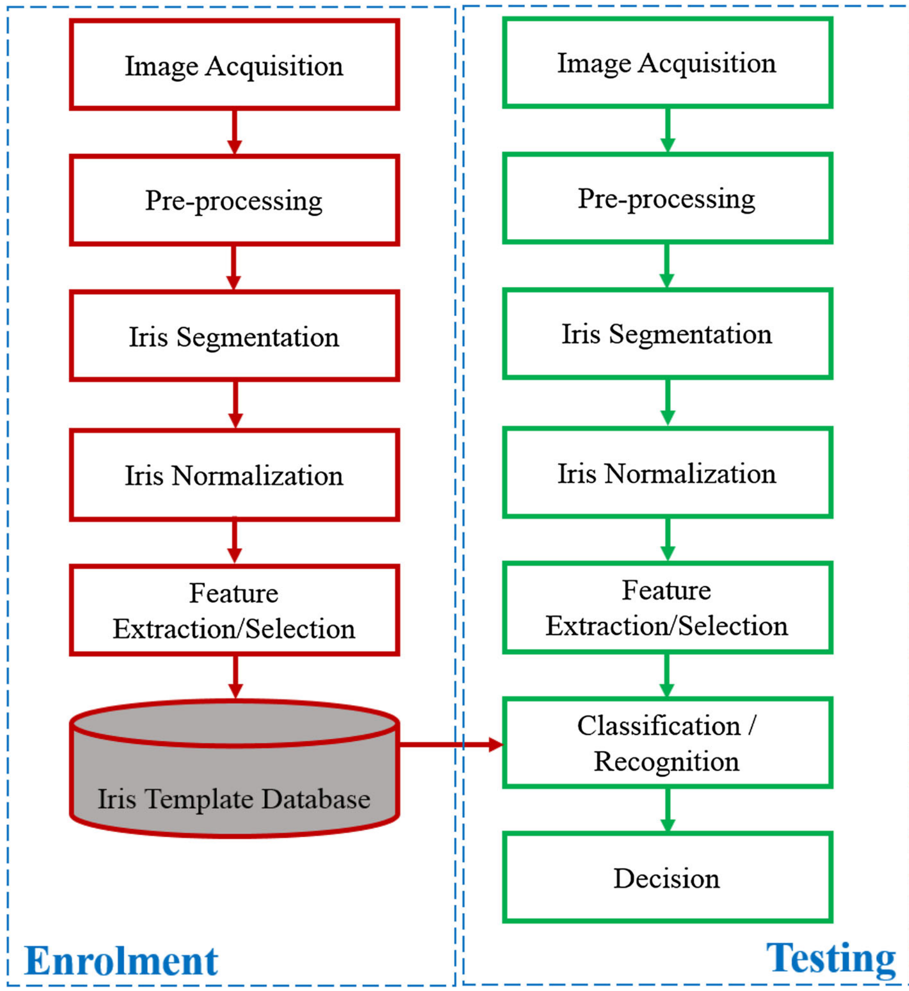

Fig. 2 A basic flow of the iris recognition system

Enrolment phase is associated with creating a database, and testing phase is associated with recognizing either the real-time images or the pre-stored images. The biometric machine based on iris for recognition can be typically fragmented into following distinct segments (Grabowski and Napieralski 2011) for analysis:

- Iris image acquisition
- Pre-processing
- Iris image segmentation
- Feature extraction
- Feature selection
- Iris image classification

Table 1 mentions the degree of difficulty faced by different covariates in crucial segments of iris recognition system.

In the above table, '*' denotes the level of difficulty in the respective stages of the iris image recognition system. The more the number of '*', the higher the difficulty level faced by the algorithms in their respective stages. Based on the level of severity of the covariate, more effort has to be taken at the pre-processing stage to nullify the negative impact on the robustness of the recognition system.

The working of the iris recognition algorithm is explained by Daugman (2007). In human–computer interface for real-time applications, the hardware complexity, cost and size are significant parameters in the design of such systems. With many technical advancements in the semiconductor industry, integration of CMOS with FPGA has seen several milestones in image processing to develop embedded systems which incur low power (Tan et al. 2012; Hematian et al. 2013; Si et al. 2012; Amir et al. 2005). The challenge in the design of mobile phones having this iris recognition system is to place these limited number of infrared illuminators in the limited board space and acquire good iris image quality. An empirical study on the effect of fast eye detection algorithm for the mobile platform with different design constraints is discussed in Kim et al. (2016). Rather than dedicated portable devices like ASIC, computers which operate at higher clocking frequency can increase processing speed (Liu-Jimenez et al. 2011). In security point of view, microprocessor remains less malicious than computer-based solution because it is

Table 1 Impact of covariates on different stages of iris recognition

Stages	Eye colour	Ailments	Lens	Occlusions	Viewing angle	Illumination	Focus
Segmentation	*	****	**	***	**	****	*****
Feature extraction	*	****	*	*	*	***	**
Classifier	*	***	**	***	***	***	****

not open to program new applications. GPUs offer more advantages by parallel processing for iris recognition (Rakvic et al. 2016). With increasing the number of cores, we can reduce processing time drastically and also improve energy efficiency from 12.5 to 272.2 per cent. Chipsets of modern smartphones are enabled with GPUs, which widens the scope for integrating iris recognition. A machine vision system prototype for automated recognition of individuals through their instant captured iris image is discussed in Wildes (1994).

Many algorithms have been discussed in the literature to provide a suitable solution for iris recognition system. Most of these algorithms used in iris recognition can be grouped into multi-resolutional analysis, entropy-based coding, local texture, multi-lobe differential filters, SVM-based learning and neural network-based learning techniques. A dyadic wavelet transform to extract features from the iris signature is introduced by Sanchez-Avila (2002). An analysis, among Euclidean, Dz and hamming distances, shows hamming distance performs better in giving higher classification success. Sequential steps involved in a statistical independent testing of the iris on over 9.1 million comparisons across eye images of different geographical regions are discussed briefly in Daugman (2004). The execution time by each segment of the algorithm on a 300-MHz RISC processor is also analysed. The author also hints the benefit of parallel computing for rapid identification. This iris recognition framework proposed by Daugman is still used in many real-time iris recognition systems. With experimental results, Ma et al. (2004) have drawn conclusions to rank local variation analysis-based methods over texture-based analysis in both accuracy and speed. The author also envisions to improve the robustness against deformation of iris image due to pupil movement of the algorithm by combining local features and global features. The concept of choosing global features for noisy images and local features images for good quality images is studied in Sun et al. (2005). This method of cascaded classifier improves the recognition accuracy.

With interest to reduce the computation speed, author in Monro et al. (2007) has replaced wavelet-based features with 1D DCT which has asymptotic decorrelating properties compared to KL transform. Apart from increasing the speed by reducing the complexity, it also has no false accepts/rejects. The author also adds that in non-ideal situations pre-processing can improve the performance. To avoid spoofing in automated systems, iris liveliness detection methods are used. The author in Hu et al. (2015) uses two methods, namely spatial pyramid model which computes the feature distribution over varying sizes and a relational measure model which computes the feature distribution over varying shapes. At the end, individual results of the two methods are fused at the score level and then the final decision is made. The error rate of this method is relatively higher. Computer vision and machine learning is another supporting tool which has accelerated the recognition framework. An experimental study has been made by Shervin Minee et al. (2016) for recognizing individuals using VGG-Net architecture. A multi-class SVM is used with a hyperplane separating the linearly separable classes to identify the iris. This method of classification does not need segmentation or iris localization. And moreover, due to the richness of the features, the accuracy is high. To overcome the ill fortunes caused due to occlusions, pre-processing is done to enhance the performance in Zhang and Wang (2017). Still, more probe is needed to reduce the training time required by the network to predict the iris correctly.

Any pattern recognition system involves two phases, namely enrolment and testing. Figure 2 describes the sketch of a basic iris recognition system. Enrolment phase involves all the preliminary steps to build the database sets for classification. In the testing phase, the system computes the features of the test image and computes the similarity score against the database sets. At last, the one with best match score is taken as a recognized pattern.

Iris biometric has a huge opportunity in the industrial market. In such systems, the level of expectation of performance expected is very high. In the literature, a connectivity between the primitive techniques and the present state-of-the-art techniques is missing. Moreover, a common repository of techniques on each segment of the iris recognition system for early researchers is not available. To bridge this gap, this paper explores all the conventional and the state-of-the-art techniques associated with each segment of iris-based recognition system.

3 Iris image acquisition and database

Iris images are captured in the visible spectrum as well as NIR spectrum. The visible spectrum is more prone to noise than images captured in NIR spectrum. Although cameras are

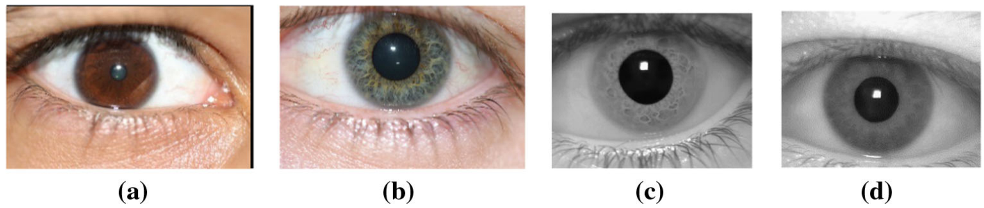

Fig. 3 Iris image captured **a**,**b** in the visible wavelength, **c**, **d** in the NIR wavelength from UTIRIS database

available for capturing images of iris, many open databases are there to facilitate researchers all around the globe to use them and develop state-of-the-art algorithms. Figure 3 shows the example of iris images in visible and near-infrared wavelength from UTIRIS database (University of Tehran 2018).

3.1 Real-time iris image acquisition

The first step in the iris-based biometric recognition system is the capture of iris image using suitable acquisition device. The subsystems of this acquisition module includes

- Illuminators
- Lens
- Sensor
- Control unit

3.1.1 Illuminators

Illumination is one of the important factors to obtain images of good quality. It can enrich the textural information in the image. The wavelength of visible spectrum ranges from 390 to 700 nm, and the wavelength of near infrared ranges from 750 to 950 nm. Images captured in the visible spectrum are more prone to noise and reflection rather than in NIR spectrum. Hence, systems which operate in the NIR spectrum are mostly preferred. However, prolonged exposure can damage ophthalmic tissues. It is important to take care in designing NIR capture system such that standards like IEC 60825-1 are satisfied. According to American standards on the safety of NIR LEDs in healthcare, care has to be taken such that the luminous intensity on NIR LEDs does not exceed 10 mW/cm^2 (American National Standards Institute 1988). Ordinary filament lamps can be used for illumination in the visible range. With the degree of illumination, the reflection in the captured image varies. Much of the texture information gets lost on illuminating over 900 nm (He et al. 2006). It is necessary to keep illumination under control for getting a good quality image.

3.1.2 Lens

The lens focuses the image onto the image sensor. Manufacturers like Huvitz, Carl Zeiss and Haag Streit are pioneers in manufacturing lens for imaging systems. The sensor has to be placed at the focal length of the lens. The theory of image formation from ray optics states that the magnification is the ratio of image height to object height (Saleh and Teich 1991). This magnification factor depends on the focal length of the lens. Acquisition systems come with both fixed focus and variable focus. Auto-focusing lens helps to get sharp image quality without the disturbing the subject's cooperation (Gong et al. 2012).

3.1.3 Sensor

Sensor is the gateway which transforms the real-world image into digital images. High-resolution image sensor like charge-coupled devices and complementary metal oxide semiconductor has heralded the antique techniques like photomultipliers and video tubes. The phenomenon of photoelectric electric effect converts the incident photons into a variable amount of electrons. The output of CMOS is digital, whereas the output of CCD is analog. CCD needs an ADC to convert the signal into digital. With improvements in sensor technology, the sensitivity of the CCD seems increasing (Lulé et al. 2000). Another advantage of CMOS over CCD is that its active sensor technology makes it integrate with pixel level signal processing and provide better image quality (Gamal and Eltoukhy 2005). By introducing dopant regions for pixel design into the pinned photodiode, the author in Rizzolo et al. (2018) has increased the charge transfer and reduced the power consumption in CMOS-based image sensors. These characteristics attract CMOS-based imaging devices for biometric applications.

3.1.4 Control unit

The control unit balances the hardware and the software together in the embedded system. The hardware design and instruction sets make ARM-based processor more intelligent and energy efficient (Neagoe et al. 2010). These processors are the platform which runs the algorithm over the captured

Table 2 List of cameras for iris recognition

Company	Model	Spectrum	Connectivity	Sensor technology	Distance	Power input	Resolution
HQCAM	HQ-176212133	NIR	Mini USB	CMOS	2–3 m	5 V DC/100 mA	1280 × 720
Galaxy	SM-T1161ZKRINS	Visible	Integrated	CMOS	1 m	5 V DC	1280 × 720
LG	IrisAccess 4000	NIR	Ethernet	CCD	26–36 cm	12 V DC/2 A	640 × 480
Panasonic	BM-ET100	NIR	USB	CCD	50 cm	5 V DC/500 mA	640 × 480
OKI	IRISPASS-h	NIR	USB	CMOS	3–12 in	300 mA	640 × 480
Hoyos	HBox	NIR	Ethernet	CMOS	147 cm	100–240 V AC	720 × 480
Securimetrics	HIIDE	NIR	Ethernet/USB	CMOS	8–10 in	12–24 V DC	640 × 480

iris image and help in recognition. The prototype design of a low-power, less-weight and smaller system using the ARM for iris recognition is detailed in Wang et al. (2008). Instead of sequential processing, a parallel processing approach using FPGA speeds up by 19 times when compared to the CPU-based system design (Rakvic et al. 2009). In mobile phones which are more prone to get blurred images, pre-processing is introduced to support iris recognition (Kang 2010). Details of a typical image capturing camera for iris recognition are tabulated in Table 2.

The researchers interested in experimenting with the real-time iris recognition can purchase above cameras from the manufacturers mentioned in the table.

3.2 Iris database

Apart from iris capturing devices, there is ample amount of database around the world to help researchers to test run their algorithm and validate its robustness. Most of the databases are captured in the near-infrared spectrum, and few databases are available in visible spectrum. Databases have their images stored in uncompressed and compressed formats. Some are captured in a constrained environment, while others are captured in an unconstrained environment. Table 3 gives the list of few of the iris image databases available.

Specifications of the iris image in the database available for conducting research are briefly mentioned in the above table.

The readily available images for testing your algorithms can be downloaded from the URLs mentioned in Table 4.

4 Pre-processing

Pre-processing is the primary step involved in the execution of any proposed algorithm. This would help remove the artefacts that occurred during the image capturing process. Without pre-processing, it would be unsuitable for recognition. Literature survey shows many image pre-processing techniques accessible for iris recognition. Iris images captured usually suffer many artefacts like noise, illumination reflections, blurring, gazing and occlusions from eyelashes. Several methods are recorded in the literature to remove these artefacts. Removing the artefacts through pre-processing will enhance the recognition accuracy. Table 5 shows the method available to clear away different artefacts.

4.1 Denoising

Some of the primitive methods used in pre-processing by researchers are discussed for insight. Zheng et al. (2005) use low-pass filter based on Gabor kernel to alleviate noise from the iris image. It helps in finding the edges of the eye without embarrassment. This is because the Gabor features highlight the iris structures with the appropriate selection of filter coefficients. Ross and Shah (2006) have used 2D median filters in the segmentation process and also used anisotropic diffusion to enhance the image. This helps in getting better iris code and improves accuracy.

4.2 Deblurring

In real-time application, cameras with a small degree of field causes images to blur because of optical defocusing. Kang and Park (2007) propose a kernel to measure the focus scores. With coefficients of constrained least square restoration filter computed based on the focus score, this method deblurs and restores the image focus. Obviously, this restoration improves the accuracy. Liu et al. (2013) have introduced two methods, namely deblur and blur mask for motion-blurred iris image. The author has done a systematic study on the influence of motion blurring on accuracy. The disadvantage of this method is that the training-based blur mask generation would not be suitable for real-time application as it takes time for convergence.

4.3 Discarding of reflections

The intensity values across the cross section of the eyes give the map of reflections present in the iris region. Kong and

Table 3 Summary of iris image database

Database	Camera	Spectrum	Resolution	Number of subjects	Number of images	Format
UBIRIS V1	Nikon E5700	Visible	800 × 600	241	1249	.jpeg
UBIRIS V2	Canon EOS 5D	Visible	400 × 300	522	11,101	.tiff
BATH	ISG LW-1.3-S-1394	NIR	1280 × 960	400	16,000	.j2c
IITD	Jiris JPC1000	NIR	320 × 240	224	2240	.bmp
WVU	IrisPass	NIR	640 × 480	945	220	.bmp
MMU	IrisAccess 2200		320 × 240	1445	289	.bmp
CASIA V1	CASIA camera	NIR	320 × 280	108	756	.bmp
CASIA V2	CASIA-Iris	NIR	640 × 480	120	2400	.bmp
CASIA V3	OKI irispass-h	NIR	640 × 480	1614	22,548	.jpeg
CASIA V4	IKEMB-100	NIR	640 × 480	3284	32,537	.jpeg
UPOL	SONY DXC-950P 3CCD	Visible	786 × 576	128	384	.png
ICE	LG2200	NIR	640 × 480	244	3953	.bmp
BioSec	LG Iris Access Eq. 3000	NIR	640 × 480	200	3200	–
UTIRIS	Canon EOS 10D/ISG lightwise LW	Visible/NIR	2048 × 1360/1000 × 776	79	1540	.jpeg/.bmp
COEP	Crossmatch I-Scan 2	NIR	–	–	4800	–

Table 4 URL of iris database

Database	Web links to download	Access date
CASIA	http://biometrics.idealtest.org	Accessed April 30, 2018
IITD	http://www4.comp.polyu.edu.hk/~csajaykr/IITD/Database_Iris.htm	Accessed April 30, 2018
UBIRIS	http://iris.di.ubi.pt/ubiris2.html	Accessed April 30, 2018
MobBIO	http://paginas.fe.up.pt/~mobbio2013	Accessed April 30, 2018
Biosec baseline	http://atvs.ii.uam.es/databases.jsp	Accessed April 30, 2018
VSSIRIS	http://www.nislab.no/biometrics_lab/vssiris_db_2	Accessed April 30, 2018
MMU	http://pesona.mmu.edu.my/~ccteo/	Accessed April 30, 2018
UTIRIS	https://utiris.wordpress.com/	Accessed April 30, 2018
ND IRIS 0405	http://www3.nd.edu/~cvrl/CVRL/Data_Sets.html	Accessed April 30, 2018
VSIA	http://www.nislab.no/biometrics_lab/vsia_db	Accessed April 30, 2018

Table 5 List of artefacts and pre-processing

Author	Artefacts	Remedial method
Dehkordi and Abu-Bakar (2013)	Noise	Multiple thresholding
Huang et al. (2009)	Blur	Blur kernel estimation
Aydi et al. (2011)	Reflections	Linear interpolation
Kennel et al. (2006)	Low illumination	Histogram equalization
Schuckers et al. (2007)	Gaze angle	Angular deformation calibration
Zhang et al. 2006	Occlusions	Nonlinear conditional filtering

Zhang (2003) have set a threshold to eliminate the reflections around the iris. The main inconvenience of this method is that it is a hard threshold. It has lacked to compute the threshold adaptively. In an unconstrained environment, eye is more likely to exhibit corneal reflections. The authors in Wang et al. (2008) have smoothed out the reflections by choosing empirical coefficient based on radial autocorrelation function. Since it is empirical, it again remains vague for systems where things have to be automated. Moreover, along with reflections some good amount of texture information of the eye is also lost, which can cause a reverse effect in recognition.

4.4 Contrast stretching

To aid proper segmentation of the iris from sclera and other surrounding tissues, the author in Saad et al. (2014) has investigated several methods and highlights the importance of pre-processing. It is always good to have good illumination to get images with more textural features. On failing to do so, pre-processing has to be done to enhance the contrast of the image. One of the methods of Daugman (1993) adapts histogram equalization. It helps to stretch the contrast of the image across different intensity levels and enhances the segmentation process.

4.5 Occlusion removal

Occlusions from eyelashes can hinder the visibility of textural information in the iris. Zaim (2005) uses morphological operators to remove the tiny eyelashes. Although this method removes the eyelashes, the structural element of the morphological operator has to be oriented with the eyelash to get better results. The method to compute the orientation is not discussed and is taken randomly.

4.6 Gaze angle correction

One of the challenging issues among researchers to improve the recognition performance is to gaze angle correction. An analysis of the performance of iris recognition for different angles of gazing is done by Karakaya (2016). The study shows that the textural information degrades with an increase of off-angle and significantly affects the accuracy of the system. The author in Abhyankar and Schuckers (2010) focuses on conventional affine-based off-angle correction and also the biorthogonal wavelet network. The major disadvantage of this method is the computational complexity involved and the limitation to system performance in 2-D. Moreover, the iris template size is greater than in conventional methods.

Few artefacts remain difficult to address and need to be further explored. Although several techniques have been discussed in removing each artefact, a unified approach could help systems automate the iris recognition. This can essentially improve the performance of the system.

5 Iris image segmentation

Immediately after the pre-processing stage, the region of interest is extracted. This is referred to segmentation or localization in the literature. The objective of the segmentation is to separate the iris region from the remaining background. The iris recognition algorithm is based on the features of this segmented region. Hence, it is apparent that the accuracy of the system largely depends on the preciseness of segmentation. Figure 4 shows the groups under which the work of the researcher is majorly classified.

5.1 Transform-based segmentation

The texture information of the iris region is exploited by using transforms in Cui et al. (2004) to locate the region of interest. The low-frequency components of the wavelet transform help to locate the pupil. The boundary of the iris is found using differential integral operator. Edge detection along with Hough transform helps to locate the eyelids and eyelashes. The results show that this method computes the location at a faster rate. The system specification to benchmark the computation time is not specified, and it remains unclear on what basis the computation is reduced. The author in Daugman (2007) has approximated the boundary of the iris using Fourier coefficients. The fidelity of the approximation depends on the number of coefficients. Further weights

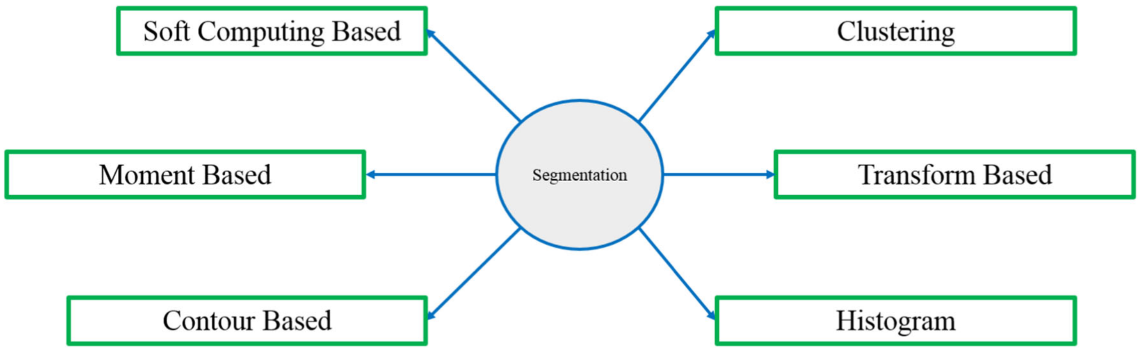

Fig. 4 Methods of iris segmentation

are assigned to improve the resolution of the approximation. However, there is not enough information on choosing weights and number of coefficients to make it adaptable for automatic systems.

Energy distribution using Fourier spectral density is used to explore the iris region of the captured eye image by Puhan et al. (2011). The iris is computed by binarizing the Fourier spectral density, and few regions are labelled together to remove reflections. And then, the edge pixels are connected to find the inner and outer boundaries of iris. This technique seems efficient as it reduces the number of scans to figure of the iris boundary. An improved version of Hough transform is used to find the centre and radius of the iris in Bendale et al. (2012). In this, a circular integro-differential operator is used to trace the outer boundary and extended 1D Hough transform is used to trace the inner boundary. The influence of parameters like threshold and angular range on segmentation has been experimentally analysed. The drawback of this method is that the threshold has to be chosen manually to improve the accuracy of recognition. Variants of Hough transform are used to find the iris boundary in Farihan et al. (2013). Here, the author uses circular Hough transform to find the iris boundary and occlusions due to upper and lower eyelids are removed by linear Hough transform. With reflections in the captured image, this method found it difficult to localize the region.

5.2 Clustering

It is obvious that in real time, iris capture occurs in an non-ideal environment. In such cases, authors in Pundlik et al. (2010) have used prior knowledge of iris in terms of texture, intensity and geometry to segment the iris region. It has to improve much more on knowledge of iris. And moreover modelling of occlusions due to eyelids and eyelashes can be even more precise to achieve much better segmentation. And also much more insights to improve the geometry solvers are needed to improve the efficiency of the system. In order to reduce the search time of locating the iris here in Sahmoud and Abuhaiba (2013), authors have used a k-means clustering and edge map followed by a circular Hough transform. Morphological operators are used to remove noise under non-ideal conditions. Although k-means clustering is faster than hierarchal clustering, the disadvantage would be in predicting the optimal k value. And a wrong prediction can lead to segmentation errors.

Based on the degree of similarity, the seed points are grouped into different regions. This method predominantly called as the watershed algorithm is discussed in Abate et al. (2015). The difficulty with this type of segmentation is that as the seed points are many, it would be grouped into multiple regions and all the regions have to be merged mandatorily. This method has also failed to explore the methods for reducing the outliers. With Shannon's theory and distance parameters, a cross-entropy-based clustering for segmentation is discussed in Misztal et al. (2015). Arbitrary Gaussian functions are used in calculating entropy to segregate the iris and pupil. Later with distance constraints, they best fit the iris and remove occlusions. Still, this method needs improvement in optimizing the Gaussian functions automatically. This can improve the performance of automatic systems.

5.3 Histogram-based segmentation

In an algorithm for iris image processing (Lili and Mei 2005), authors have taken the help of histogram to plot the location of the pupil and then least squares method with curve fitting for optimizing the iris boundary. The drawback with this mechanism is that curve which fits best may be a flaw. Therefore, careful attention has to be given in choosing methods for iris segmentation. Two circular edge detectors along with colour information are handled by authors Sik et al. (2010) to segment the iris regions. The Adaboost technique is also adapted to overcome errors in segmentation. The specular reflections are also taken care by interpolating the region. Although specular reflections are taken care, in noisy images Adaboost may experience under fitting problem due to outliers.

The authors in Talal et al. (2012) have used local histogram over a circular window instead of the global histogram. And then, with statistical parameters, they identify the pupil and iris regions. The author has failed to explore much of the statistical parameters to locate the pupil and iris in the presence of dense eyelashes. Instead of hard threshold, an adaptive threshold is recommended by authors in Mehrotra et al. (2013) as it may affect the segmentation results at varying degrees of illumination. Later, an edge map is used to compute the radii. Then, after few pre-processing, the iris is located using concentric circles. As it uses rigid circles, it would be difficult to eliminate the occlusions due to eyelids and eyelashes. Based on the gradient descriptor of iris that describes the structure of iris and SVM, the iris region is localized in Radman et al. (2017). Here, the shadow around the iris region hinders the segmentation accuracy. Prior attention has to be paved for the removal shadow to enhance the segmentation process.

5.4 Contour-based segmentation

Rather than using conventional circular contours here in Ryan et al. (2008), authors have proposed a starburst algorithm which uses contours of the ellipse model. The advantage of this method is that it can simultaneously detect both pupil and limbic boundary. The removal of eyelids and eyelashes has not been paid attention which affects the iris boundary detection. An active contour method based on geodesics is suggested by authors in Shah and Ross (2009). This method can fit into any shape and can trace multiple objects simultaneously. It employs a median filter followed by circle fitting procedures which enclose maximum black pixels and detects it as the pupil. Further with computation of the minimal length curves, the iris boundary is segmented. But if the iris information in weak, this method may lead to over-segmentation problem. Constraints have to be made to confine the contour within edge points.

In Koh et al. (2010), the centre of the pupil is estimated from the histogram. The errors are corrected using an active contour model. The drawback of this would be that in NIR illumination it becomes difficult to handle the intensity inhomogeneity. The accuracy depends on the tighter convergence and hence may consume heavy computation. This work also fails to investigate the performance on a large dataset. In situations where we do not get an orthogonal perspective view of the iris image, circular contour fitting is not a good idea. The authors in Zuo and Schmid (2010) have proposed a translated ellipse contour to distinguish the iris and pupil boundary with pre-processing steps to avoid inaccuracy. The drawback of this structural contour is that the boundaries traced are rigid and may miss some information. And as the operations are sequential, much analysis has to be done on the computation time. The importance of active contours and its gaining interest in segmentation is pressed by authors in Ouabida et al. (2017). Here, an optical correlation measured by VanderLugt correlator is used to support active contours in the demarcation of iris and pupil from the background. A detailed analysis of this method spotlights the dominance of this technique in iris segmentation. The dependency of the matched filter in this concept makes it unsuitable for scaled and rotated versions of the dataset. Certain probing on circular harmonics or coordinate transforms can make this method as scale and rotation invariant.

5.5 Moment-based segmentation

The textural features extracted from Zernike moments are recommended by authors in Tan and Kumar (2012) to part iris from the background. They also envision the use of moments suitable for both images captured in NIR wavelength and visible wavelength. The Zernike moments of each pixel are used to train the neural network or support vector machines to grasp information about the iris pixels. But, the segmented output shows the limitation of this method and demands post-processing like circle fitting from the edge map of the iris region.

5.6 Soft computing-based segmentation

The authors in Proenc (2010) have come up with supervised machine learning method for the bisection of iris from the background. The neural network is trained by the feature sets computed for each pixel. Constrained polynomial fitting is used to parameterize the boundary. The course edges are then interpolated. However, this method needs more inspection on optimizing the feature sets as it would load the computation process. To address the noisy edges which mislead iris segmentation, the authors in Li et al. (2012) have urged to use learned boundary detection method based on a number of features. Adaboost is engaged to select the best boundary features. The least squares fitting is done to localize the iris boundaries. Like the previous method, more efficient features can be designed and elastic models can be used for curve fitting.

In Liu et al. (2016), the authors have claimed the benefit of using the convolutional neural network in the segmentation process. It does not need any pre-processing or post-processing stages and does not need user function to create a feature set. The biggest snag for this technique is the involvement of convolution as it is a slow process. It increases the learning time. But, a multi-stage fully convolutional method proposed by the author can reduce the time by parallel processing. It also shows promising results compared to the traditional network. A deep learning-based iris segmentation is suggested by authors in Arsalan et al. (2017). Convolutional neural network produces two features

Table 6 Error rate of segmentation

Year	Author	Database	Method	Average error rate (%)
1993	Daughman (1993)	CASIA	Integro-differential operator	4
2002	Camus and Wildes (2002)	CASIA	Multi-resolution strategy	7.61
2004	Hanho Sung et al.	Realtime	Edge detector	5.46
2006	Proenca and Alexandre (2006)	UBIRIS	Fuzzy clustering + edge detector + circular Hough Transform	2.12
2010	Zuo and Schmid (2010)	WVU	Ellipse fitting	2.08
2011	Bakshi et al. (2011)	CASIA, BATH	Circular Hough transform	4.24
2011	Sundaram et al. (2011)	UBIRIS	Edge detector + modified CHT	14.18
2012	Fernandez et al. (2012)	HID, MMU, IREX	Contour fitting	7.7
2015	Han et al. (2015)	NICE.II	HT + ellipse fitting	8
2015	Zhao and Kumar (2015)	UBIRIS, FRGC, CASIA	Circle fitting	1.27

on the rough boundary traced by Hough transform. Based on this, the true boundary is identified. The biggest challenge is the non-availability of the large public dataset for exploring deep learning approaches. And yet, it uses the pre-processing stage, which loads the computation. The computation of these deep learning methods can be very well implemented in software with appropriate priorities for each task based on (Sangaiah et al. 2017) fuzzy multi-criteria. Table 6 shows the performance error associated with different segmentation techniques.

As seen from Table 7, the performance of different segmentation algorithms on different hardware varies. Along with the complexity of the segmentation algorithm, the time for segmentation also depends upon hardware.

6 Normalization

Normalization is the process of unwrapping the circular iris into a rectangular pattern. It comes after the segmentation process. The dimension of the segmented iris differs based on various degrees of illumination, from person to person and standoff distance. Hence, with an objective to have common dimension to ease the feature extraction process normalization is done. From the literature, the methods employed for normalization can be broadly classified as the linear method and nonlinear method. Nonlinear approaches are preferred in scenarios where the iris and pupil are non-concentric.

6.1 Linear method

A well-known iris normalization procedure called rubber sheet transform is suggested by Daugman (1993). This method linearly maps the iris region from Cartesian coordinate to polar coordinate. It recoups the effects of pupil dilation, scale and translation. The disadvantage of this method is that it is more sensitive to rotation. Since the radii of the pupil and radii of iris are different, the normalization makes some of the pixels to be repeated to occupy the empty space of the image plane. In order to overcome this issue, a trapezoidal approach is prescribed by authors in Shamsi and Rasouli (2011). The iris region is split into a number of concentric discs and then unwrapped. There is no need for repetition as it is a one-to-one mapping. The unwrapped image looks like a trapeze. And hence, this method reduces false acceptance. The challenge in this method would be to fit it into an unchanging structure. An elastic model is suggested by authors in Hilal et al. (2014) for non-circular pupil images. Here, instead of circular discs, elastic discs are used to trace the curvilinear nature of the iris. The difficulty of this method is to locate the centre of the pupil. As an error in locating the centre would cause the elastic contours to over segment and makes the feature extraction difficult.

6.2 Nonlinear method

A nonlinear normalization model is presented by authors in Yuan and Shi (2005) where the region between pupil bound-

Table 7 Computation time for segmentation approaches

Author	Database	Method	System	Segmentation time (ms)
Daugman (1998)	CASIA	Integro-differential operator	Intel 486X66, 66 MHz	577
Vatsa et al. (2008)	ICE 205	Modified ellipse fitting	Pentium IV, 3.2 GHz	908
Fatt et al. (2009)	CASIA	Hough transform	ADSP-BF561, 525 MHz	683.16
Shin et al. (2012)	NICE II	Circular edge detector	Intel i7, 3.33 GHz	48.1
Ngo et al. (2012)	Real-time	Edge detector	Stratix IV EP4SGX530 FPGA, 159 MHZ	7.42
Radman et al. (2013)	UBIRIS	IDO + CGF	Intel dual core, 2.4 GHz	1090
Li and Huang (2017)	MICHE	MIGREP	Dual core Cortex A-9, 1.2 GHz	10
Abdullah et al. (2017)	UBIRIS, CASIA	Active contour	Intel i5, 3.2 GHz	500
Kumar et al. (2018)	CASIA	Edge map + CHT	Zynq xc7z020lclg484, 200 MHz	4.24
Sardar et al. (2018)	CASIA, IITD, MMU	Rough entropy + CSA	Intel i7, 3.4 GHz	1060

ary and iris boundary is nonlinearly translated to a reference annular zone and then mapped into a fixed-size rectangular zone. This method exploits the nonlinear property of the iris deformation. More push has to be given in explicit prediction of deformation and boost the recognition performance. To save time in the method presented by Yuan, a closed-form expression by applying decree of cosine is discussed in Li (2009) The deformation caused due to hippus is further exploited by authors in Wei et al. (2007) by correcting the deviation using Gaussian model. This method tends to reduce the error rate and improve the accuracy of the recognition system. Apart from learning the wear and tear around the iris region, if more exploration can be done on image quality, the performance of the system can still improve. The radial displacement of the feature point in iris due to pupil dilation has been addressed by the biomechanical approach in Tomeo-Reyes et al. (2015). Here, the iris region is translated into uniformly discretized annular zones. The deformation is computed iteratively, and then the mapping is done onto a rectangular zone. But this method is more susceptible to segmentation irregularities and affects the accuracy of the system.

7 Feature extraction

The anatomy of eye reveals a lot of observable rich features in the ciliary and pupillary zones of iris. The success of feature extraction lies in aptly representing these textural features for differentiating the iris significantly during the classification process. Features vectors can be broadly grouped under phase, zero-crossing, texture and seed points. A few studies under these groups are discussed below.

7.1 Wavelet transform-based features

Daugman (2004) uses 2D Gabor kernel to extract the texture feature of the normalized iris image. The kernels are multiplied over the image and integrated to get the 1024 phasor coefficients. These coefficients are later translated into two-bit codes. Altogether they give a 2048-bit binary iris code which characterizes the texture pattern of iris. The richness of the iris texture still can be perceived more if orthonormal bases are used in 2D Gabor wavelets. A 1D wavelet that incorporates quadratic spline bases is recommended by authors in Ma et al. (2004) to locate the sharp features of iris structure. Apart from locating the iris features, it is also computationally efficient. As this method is designed with local features, it is very unstable to glitches of segmentation and other covariates.

Zero-crossing of discrete dyadic wavelet signature is recommended by authors Sanchez-Avila and Sanchez-Reillo (2005). The sign changes of the iris signature are used to project the zero-crossing, and interpolation between samples of different signs is used to locate the zero-crossing location. A modified log Gabor is suggested by authors in Yao et al.

(2006). Log-Gabor filters do not have DC components. They are like a bandpass filter extended towards high frequency. Bases chosen are a logarithmic function of frequency and angle. This property preserves the iris phase information. The limitations of Gabor filter is overcome by this log Gabor wavelet filter.

A two-layer sparse filter layer which learns sparsity among feature vectors generated by 2D Gabor filter is proposed by authors in Raja et al. (2015). This work is employed on images captured using smartphones. Each of the filtered response is binarized and then encoded. Later histogram of the encoded sub-image is taken as the iris code. Even more quantitative analysis over a large database can be done to analyse the computation efficiency of the proposed method. Cohen–Daubechies–Feauveau wavelet mel-frequency cepstrum is endorsed by authors Barpanda et al. (2018a). Here, the power spectrum of the wavelet transformed image is computed, and then discrete cosine transform is computed to get the cepstrum coefficients. These features are compact and can highlight the features well because of the non-uniform weights which emphasize the high-frequency component. The sensitivity of this method to segmentation error makes it difficult to extract features. A haar bases wavelet is suggested by authors in Krichen et al. (2005). As it is not continuous, it may not extract the fullness textural feature of iris.

7.2 Curvelet transform-based features

To translate most of the textural features of iris into spectral information, the authors in Rahulkar et al. (2012) have proposed two different algorithms for feature extraction. The first one is the fast discrete curvelet transform through unevenly distributed fast Fourier transform, and the next one is fast discrete curvelet transform through wedge-wrapping of appropriate Fourier specimen. The later seems faster in computation as it is simple. These curvelet coefficients are very responsive to directional and anisotropic nature of iris because of its bases function which provides parabolic scaling and has oscillatory behaviour. Although this method extracts the richness of iris texture, its setback would be the time for computing the curvelet coefficients.

Statistical features of curvelet transform are suggested by authors in Guesmi et al. (2012). The transform is computed across 5 different scales, accumulating a total of 164 sub-bands. From each of the sub-band, 4 statistical features like energy, entropy, standard deviation and mean are taken as the feature vectors of 648 integer values. Selective sub-band coding is advised by authors in Ahamed and Bhuiyan (2012). The 4th level sub-band coefficient is alone chosen and binarized to depict the textural features of iris of length 472 bits. As the feature vector is small, it aids in faster recognition. To exploit the curvy features of iris, the authors in Arivazhagan et al. (2011) have prescribed ridgelet transform. The ridgelet coefficients are computed on the sub-image of the normalized iris structure. Then, from co-occurrence matrix computed on each of the sub-band, parameters like contrast, dissimilarity, homogeneity, correlation, mean and standard deviation are figured out as the feature vectors. The delicacy of this method to the large dataset is a drawback.

7.3 Energy sum-based features

Logical iris code formed by the localized cumulative sum of normalized iris image is introduced by authors in Ko et al. (2007). The cumulative sum along the column on average of each sub-block is used to form the iris code. This method consumes less time for extracting the iris feature vector. However, this method fails to extract the abundance of iris feature. An entropy-based feature vector characterizing the features of iris is proposed by Proenca and Alexandre (2007). The entropy of overlapping angular spaces is calculated to generate one-dimensional iris feature vector. The performance of these features looks good in an unconstrained environment for iris recognition. But the degree of overlapping is not examined as it would affect the feature vector and also the computation adds to the drawback of this method. In another article (Viriri and Tapamo 2017), authors have suggested the iris code generated from the cumulative sums. The inhomogenity in the pixel levels represents the textural features of iris using logical functions. But, the author has not validated the fidelity of this method to a noisy environment.

7.4 SIFT-based features

Scale-invariant feature transform (SIFT) was introduced by Zhu et al. (2006). Here, seed points which are unsusceptible to change in rotation, scale and illumination are chosen for feature extraction. These points as a reference, gradient features are extracted using a Gaussian function. The complexity of this approach depends on the number of seed points. Its increase in seed points increases the number of computations to generate the feature vector. 2D images of the 3D iris patterns deform due to non-cooperation from the subject. It becomes more challenging to correct the deformations. Here, in Belcher and Du (2009) authors have suggested region-based invariant descriptors. The iris region is partitioned into three regions. On each region, feature points are selected based on the difference of gradient. Moreover, the stability of these points is tested using 3D quadratic function. Later, the stable points are translated as feature vectors by corresponding gradient orientation. This method performs well in the unconstrained environment, but the performance slumbers in the constrained environment compared to other traditional methods.

A 128-element feature vector is recommended by authors in Alonso-Fernandez et al. (2009). For different degrees of

Gaussian blur, a difference of Gaussian is computed to find the local extrema key point. Then, the descriptors around this point are denoted by orientation histograms. This work has hinted at the challenge of this technique for feature extraction on people moving with pedestrian speed. A similar method with segmented key points only around the iris region for bovine is studied by authors in Bakshi et al. (2012). Like other methods, this method also fails to address the time consumption.

7.5 SURF-based features

An improvised version of SIFT is referred as speeded-up robust features (SURF) in Bay et al. (2008). Unlike SIFT, this method acts upon an integral image to get feature points. Authors in Mehrotra et al. (2013) have taken up this SURF method to extract iris features. Laplacian functions are used to enhance the noticeable difference between foreground and background. Later, key points are identified with the help of the Hessian matrix. Around each key point, windowed Haar wavelet coefficients are computed and their directional sums are taken as feature vectors. Each point has a 64-element feature descriptor. This approach reduces the computation time drastically because of the reduced feature elements, but still gives better accuracy. In Ali et al. (2016), Gaussian approximations are used to get a rough Hessian determinant from which feature point is interpolated. Sum of Haar wavelet coefficients around this point serves as the feature vector. But, this method needs illumination correction for better performance.

7.6 Deep features

The success of deep learning in computer vision has created interest in exploring features extracted from deep neural networks. In Abdolrashidiy (2016), the authors have used VGG-Net to extract deep features. It performs a sequence of convolution to draw deep features. Later, a dimensionality reduction is done using the PCA method. The challenge in this method is the need for heavy computation to learn the deep iris features. In Nguyen et al. (2017), the authors have extracted deep features using CNN. The various layers in the network help in extracting coarse and fine features of the iris. With a lesser number of layers, it can generate millions of parameters and improve the recognition performance.

Table 8 shows the different features of describing the uniqueness of iris pattern and their performance in a recognition system.

8 Feature selection

The size of the feature vector can increase the computation complexity and can cost much. In large feature set, sparse representation (Kumar et al. 2017) can help identify the discriminatory features. With this ideal amount of features, it would be still possible to attain the level of accuracy as that with full features. So feature selection is a process of finding out those ideal features that can reduce computation but still achieve good accuracy. A reduction in computation will certainly speed up the recognition process (Sahu et al. 2018).

8.1 Adaboost

Edge-type features generated from filter bank were used in Chen et al. (2007) for feature extraction. However, the best part of this work has come from selecting appropriate filters that would effectively contribute to the feature selection. An appreciative weight is given for proper classification and a depreciation for misclassification. At last out of 1045 filters, the best 20 filters are selected to give the finest edge-type descriptors. The author could have explored much on the quantitative analysis of the method to validate better. In He et al. (2009), the authors use Adaboost learning for local binary patterns over different scales. The most significant binary patterns that identify spoofing are given confidence value during the learning phase. With drastically reduced feature set, this method is simple and efficient. Adaboost learning for feature selection is revisited by authors in Wang et al. (2012). Based on the segmentation errors, this method chooses best orientation features computed from Gabor filters. This method gives significant results in noisy iris recognition.

8.2 Genetic algorithm

A GA-based hybrid approach for selecting outstanding features is discussed by authors in Roy and Bhattacharya (2008). Based on several feature selection yardsticks, the prominent subset of features that improve the accuracy of classification is chosen to satisfy the fitness function. This helps to get the best features from the pool of features. A multi-objective genetic algorithm for feature selection is examined by authors in Roy and Bhattacharya (2008). Here, the 1D Gabor wavelet features are initially computed. A wrapper-based GA with the objective of reducing the wavelet feature set and minimizing the error rate by Pareto optimization is done. The setback of this approach is heavy computation. In order to increase the performance of the recognition system, a four-criterion GA-based feature selection is experimented in Roy et al. (2011). From the conventional feature set of size 2048, the proposed method reduces the feature set to size 105. However, it has not

Table 8 Features used for iris recognition

Year	Author	Database	Descriptor	Accuracy	Comment
1996	Wildes et al. (1996)	David Sarnoff Research Center	2D bandpass decomposition	–	Laplacian decomposition of iris into four different levels helps in effective storage and representation of iris features
2008	Nabti and Bouridane (2008)	CASIA	Multi-scale feature	Acc = 99.60%	Statistical features and moment invariants of Gabor-filtered wavelet maxima are the feature vector. Most precise information is preserved
2010	Huang et al. (2010)	CASIA, UPOL, UBIRIS	Gaussian Markov random fields	FRR = 1.56% FAR = 0.001%	Requires marginally less time for feature extraction
2010	Zhou and Kumar (2010)	IITD, CASIA	Localized radon transform	EER = 2.82%	Despite reducing the computation burden, conserves the multi-spectral iris features
2012	Costa and Gonzaga (2012)	Real-time	Dynamic features	Acc = 99.1% EER = 0.049%	This helps in live video iris recognition and has scope for detecting the liveliness of iris
2012	Zhang et al. (2012)	CASIA, ICE 2005	Correlation filter	EER = 0.40%	Sustains both local and global features and is immune to illumination changes
2013	Abidin et al. (2013)	CASIA	Edge traits	–	Preliminary edge detectors like canny can provide the fine details of iris, and it is more immune to noise. But, difficult for real-time one because of heavy computation
2016	Alvarez-Betancourt and Garcia-Silvente (2016)	CASIA, MMU, UBIRIS	SIFT	Acc = 99.05% EER = 3.50%	As multiple features are computed at each seed point, it has computation complexity. However, it is more robust to non-ideal imaging scenarios
2017	Kaur et al. (2018)	CASIA, UPOL, UPOL, UBIRIS	Moment features	Acc = 97.50% EER = 0.10%	Perpetuating the local and global traits, it is more robust for both visible and NIR images
2017	Galdi and Dugelay (2017)	MICHE-I	Colour descriptors	EER = 0.48%	Parallelism of the logic makes it more suitable for portable devices
2018	Nguyen et al. (2017)	ND-CrossSensor-2013, CASIA	CNN features	Acc = 98.8%	The biggest burden of CNN is the computation complexity loaded with the addition of each new layer

compensated with accuracy as this method helps to identify the pertinent features.

8.3 Component analysis

Independent component analysis (ICA) is used as a method to extract features from Iris in Bae et al. (2003). Here, the 1D signature of the normalized iris is computed using a Gaussian function. Next, we approximate this signature as a weighted linear combination of multiple bases function. Later, based on the polarity of the weights, iris codes are formed. This helps in largely reducing the feature set representing the characteristics of the iris. The local statistical independent features of iris are further exploited using ICA by authors in Wang and Han (2005). The sensitivity of this method to approximation error in computing independent components makes it unsuitable. Iris has the varied richness of texture. This varied richness is extracted by two-dimensional weighted principle component analysis. This method does not need 1D conversion of image, and hence, the dimension of the covariance matrix reduces, which improves the speed of computation of features. Eigen decomposition of approximation band of Coiflet wavelet transform is suggested in Kumar (2011). The eigenvectors are multiplied with zero mean vectors to get the feature vectors. These methods help in reducing the feature set without compromising the accuracy of the system. The authors in Liao et al. (2018) have taken careful attention in selection of distinct feature set. A cost function is used to signify the best feature set. The comparison shows the significance of this approach in the performance of the system.

8.4 Swarm intelligence

Swarm intelligence technique like PSO requires less memory and computation in selecting optimal features from a large dimension space. Here, in Eskandari et al. (2014) a face-iris multi-modal recognition, the global and local descriptors of the iris region are concatenated to form a huge feature set. To select the choicest features from this set, authors have employed a PSO-based intelligence technique. Further, a weighted sum of these features is taken to authenticate the identity. The crypts in the iris region are more genuine features. These crypts are traced from a normalized iris region using PSO technique by authors in Hashim et al. (2015). Then, through interpolation, the visible quality of crypts in the iris is increased. In Subban et al. (2017), the authors have applied PSO technique to select the best features from the Haralick measures of iris region. The PSO is further optimized by fuzzy rules. This method achieves a faster and accurate recognition.

9 Classifier

Classification is the final step in the recognition system. Classifier computes the degree of similarity between the test image and the image in the database and helps the system recognize between an authentic person and an imposter. Details of these classifiers are shared below.

9.1 Distance-based classifier

Daugman (1993) generates a 2048-bit iris code. This code is compared bitwise to measure the degree of similarity by the normalized EX-OR operation. This measure is called hamming distance. The test iris matching with the lowest distance in the database reveals the identity. With parallel processing in dedicated hardware available, this exhaustive comparison can be done swiftly over a large database. Apart from the hardware demand, this method accounts for a high accuracy rate. Sanchez-Avila and Sanchez-Reillo (2005) have given a qualitative analysis on three different distance measures, namely Euclidean distance, hamming distance and dissimilarity function, to classify the iris with the best accuracy. It is found that hamming distance performs better in classification. The authors have reduced the feature size as well, hence less computation burden on the hardware. Further, the hamming distance-based classifier is used in Monro et al. (2007) over binary code generated from optimal DCT coefficients. Here, again the authors emphasize the swiftness of the algorithm. A machine learning approach with Mahalanobis distance measure for training the classifier is proposed in Liu et al. (2014). This method seems to work well for low-resolution iris images than any other computer vision techniques.

9.2 Support vector machine-based classifier

With statistical parameters as input, the SVM is trained to detect the fake iris in He et al. (2007). Parameters like angular second moment, homogeneity, correlation and contrast from the co-occurrence matrix are taken as the feature set of the iris. With radial basis function, the machine is trained to identify the fake iris. However, the criterion of the basis function is not clear as the performance of the machine largely depends on the radial basis function. In Vatsa et al. (2008), two distinct feature sets, namely texture and topological feature, are used to train the machine. Training helps to find the hyperplane which differentiates the iris. The indexing given for the iris images in the database helps to recognize the iris very quick. The fusion of match scores of local and global features using SVM helps improve the accuracy as well.

A multi-class kernel function helps extract the features, and SVM helps to segregate them into linearly separable groups. Later, hidden markov model is used to reiterate the classification decision. The accuracy of this method suggested in Tallapragada and Rajan (2012) depends on a large number of features taken for training phase. A cascaded classifier approach is suggested by authors in Rai and Yadav (2014). Haar wavelets are used to train SVM models for each class. Since SVM has high false rejection ratio (FRR), we have still some scope for improving the performance. Hence, 1D log Gabor features of size of 2048 bits is extracted from falsely rejected iris and further subjected to classification based on hamming distance. This method has excellent performance characteristics. But, as it is a sequential classifier, it causes a penalty of time.

9.3 Neural network-based classifier

A probabilistic neural network along with bio-inspired optimization technique is proposed by authors in Chen and Chu (2009). It is a four-layer neural network, namely input layer, a pattern layer, a summation layer and an output layer. The input layer just passes on the data to the pattern layer. The pattern layer performs computation on the feature vector. And the summation layer finds the maximum likelihood of the feature vector with the appropriate class. Finally, the output layer classifies the iris based on the Bayesian decision. PSO-based optimization method is used for the classifier to learn on the smoothing parameter. It is computationally efficient because of the reduced feature size. A probabilistic neural network is recommended by authors in Chen and Chu (2009). The complexity of the PNN is reduced by introducing PSO-based learning into the network. This enhances the performance of the iris recognition system.

A multi-dimensional artificial neural network which operates on 2D Gabor wavelet features is suggested by authors in Farouk et al. (2011). It has one hidden layer, one input and output layer with a total of 21 neurons. The network is trained by back propagation algorithm. This method gives better recognition rate. However, the trade-off between database size and the recognition speed has to be optimized. A multi-layer perceptron neural network along with PSO is recommended by authors in Ahmadi and Akbarizadeh (2018). This network structure employs PSO in the inner layer to optimize the weights that minimize the training error and another PSO at the output layer for optimizing the weights for classification. However, the accuracy of the classifier is relatively low and needs improvement.

Deep learning has also gained interest among researchers for providing solutions for iris recognition. Authors in Tapia and Aravena (2017) have experimented with two different convolutional neural network structures for gender classification using iris image. This method performed well even with a simple model and a smaller dataset. A modular deep neural network is suggested for iris recognition by authors in Gaxiola et al. (2018). In this method, they have adopted three network modules. The recognition is done finally by the gating network integrator. A good optimization of each network module can further improve the recognition rate.

9.4 Fusion-based classifier

In a less invasive approach for biometric recognition, with constraints on strong acquisition due to user cooperation or the sensor limitation, we look for an opportunity to increase the performance in commercially deployable systems. This opens the opportunity to try fusion-based hybrid approaches. Fusion can happen at various levels inside a biometric system, namely signal level, feature level, score level, rank level and decision level. Table 9 gives different possibilities of possibilities of fusion-based techniques and their performance measures.

The possibility of combining parameters at various levels tabulated above shows the scope of fusion-based hybrid classifiers to aid iris-based biometric recognition. A great scope is there for researchers to work in these fields and optimize the system performance. The table given below shares few other classifier techniques and their performance (Table 10).

The critical and the most influential part of any machine learning algorithm to aid computer vision is the classifier that can help the machine recognize the authenticity of any given object or person. The above classifiers give a glimpse on performance measures of different classifiers used in iris recognition.

10 Discussion

This survey provides information on different segments associated with iris-based biometric recognition system. It also vividly narrates the performance of each technique and spotlights the scope for improvement to interested researchers. Firstly, with the advent of CMOS technology, the image sensors have helped in capturing high-quality images with less power consumption. Moreover, the FPGA-based system performs faster than CPU-based systems, enabling quicker recognition process. The available database needs huge datasets to encourage researchers working for solutions through deep learning techniques. All the glitches in the captured image are removed with pre-processing techniques. The removal of occlusions due to eyelashes needs to be further investigated as it blocks the visibility of textural pattern of the iris region. Segmentation process segregates the region of interest from the surrounding tissues. Curve fitting techniques help in both accurate and faster segmentation. This region of interest is then reshaped to a fixed block size. Variants of rubber sheet transforms are commonly employed in this process. The descriptors of the region of

Table 9 Performance of classifier on fusion-based techniques

Level	Author	Database	Feature	Fusion method	Classifier	Performance
Signal	Hollingsworth et al. (2009)	MBGC	Binary code from log Gabor-filtered image	Average of iris over multiple frames	Hamming distance	EER = 6.99×10^{-3}%
	Wild et al. (2015)	CASIA, IITD	Wavelet transform	Sum rule on N segmented iris	Levenshtein distance	EER = 0.64%
Feature	Zhang et al. (2004)	Self	Log Gabor wavelet	Combining of local and global features	Hamming distance	FAR = 0.3%, FRR = 1.1%
	Wang et al. (2009)	CASIA, ORL, Yale	Iris-Gabor filter + Face-Fisher	Parallel fusion	Complex Fisher discriminate analysis	EER = 0.07%
Score	Park and Park (2007)	CASIA	Short gabor filter and long gabor filter	HD of short and long Gabor filter	SVM	EER = 0.047%
	Kang and Park (2009)	Self from Samsung SCH-V770 mobile phone	Gabor filter	HD measure of iris left and right iris code	SVM	EER = 0.561%
Rank	Radha and Kavitha (2012)	FVC2000, CUHK	Iris and fingerprint eigen projection	Linear discriminate	Hamming distance	FAR = 0.06%
	Basha et al. (2011)	CASIA	Minutiae	Logistic regression approach	Minutiae matching	FRR = 0.25%
Decision	Saleh and Alzoubiady (2014)	Self	Iris—contourlet transform + signature—LDA transform	Fusion of decisions of AND, OR and weighted majority voting	Ant colony optimization	Acc = 93%
	Benaliouche and Touahria (2014)	CASIA, FVC 2004	Minutia descriptor	Fuzzy it-then rules	Fuzzy logic-based matching	FRR = 0.05%, Acc = 99.975%

interest are then represented by suitable feature extraction methods. Multi-resolution features give ample information on these features. And the convolutional neural network features mostly need heavy computation. So the best way would be to choose the best features. Genetic algorithms and swarm intelligence methods can be opted for choosing optimal features. Classifiers help the system to take a decision on recognition. SVM-based classifiers generally perform well than neural network-based classifiers. However, with an optimal tuning of parameters, the performance of neural network methods can be further improved. Other hybrid techniques like fusion-based classifiers can also improve the recognition rate of classifiers. Collectively, this article draws interest to work on different segments of iris image-based biometric system that can be helpful in personal as well as public systems.

Table 10 Classifier approaches for iris recognition

Author	Database	Feature	Classifier	Performance	Comment
Sun et al. (2005)	CASIA	Zero-crossing of DWT	Cascade of local feature classifier and Blob matcher	FRR = 0.016%	Cascaded classifier makes the best use of both matching techniques
Harjoko et al. (2009)	CASIA, MMU	Coiflet wavelet transform	Hamming distance	FAR = 0.067%, FRR = 0.472%	Among distance-based classifiers, Hamming distance gives a good measure of similarity
Kumar et al. (2011)	CASIA	PCA-based DWT	K-nearest neighbour	Acc = 99.07%	City block distance among feature set yields good results
Rashad et al. (Shams et al. 2011)	CASIA, MMU, LEI	Local binary pattern and histogram	Learning vector quantization	Acc = 99.87%	As it is based on Hebbian learning, it is simple and fast
Rahulkar and Holambe (2012)	UBIRIS, MMU, CASIA, IITD	Multi-resolution feature from triplet half-band filter bank	k-out-of-n	Acc = 99.84%	It is robust against segmentation errors and reduces false rejection
Tsai et al. (2012)	CASIA, UBIRIS	Gabor filter	Fuzzy matching	EER = 0.1482%	It is customizable, simple and does not need large data to train
Zhenan (Sun et al. 2014)	CASIA, Q-FIRE	Hierarchical visual codebook + SIFT	Spatial pyramidal matching	EER = 0.54% Acc = 99.26%	As matching is done at multi-resolution level, it has better accuracy
Liu et al. (2015)	CASIA, Q-FIRE	Pairwise filter bank	Convolutional neural network	EER = 0.31%	Requires more learning time for large dataset
Bhateja et al. (2016)	CASIA, IITD	Binarized average of local intensity	Genetic algorithm + K-nearest subspaces, sector-based and CSCI-based classifier	Acc = 99.43%	As it decides on the weighted sum of 3 classifiers, it reduces the false acceptance rate
Barpanda et al. (2018b)	CASIA, UBIRIS, IITD	Tunable filter bank	Canberra distance	Acc = 91.65%	It is more sensitive and hence can support classification over a large dataset

11 Conclusion and future scope

Iris recognition has gained huge interest worldwide as an authentic biometric system because of its uniqueness. A collective idea of iris image recognition system is shared in this paper along with the virtues and shortcomings of some approaches for automating iris recognition. The system was divided into different subsystems, namely iris image acquisition, pre-processing, segmentation, normalization, feature extraction, feature selection and classification. It also highlights the significant contribution of researchers in signal and image processing techniques associated with these units of iris recognition systems. This article also helps researchers to try some hybrid approaches to improve the performance of the iris recognition system in terms of both increasing accuracy and reducing computation. Deep learning techniques can also be employed for iris image-based biometric systems. This can enhance the performance of automation in the iris recognition system.

The major limitation of this biometric system is the increase in false rejection due to age, pupil dilation, occlusion due to drooping of eyelids in moving targets, highly reflective environment and wearing of cosmetic lenses. Moreover, in a number of methods found in the literature, the performance level does not seem to be same across databases. A thoughtful investigation has to be done to know the reason for this variance of performance. As single-core processors are getting upgraded to multi-core processors, researchers can also think on grabbing multiple iris images in a sequence and create techniques to improve the recognition rate. The segmentation in the presence of eyelid and eyelash is still challenging and can be worked upon to improve the automatic segmentation algorithm. This can speed up the real-time recognition systems. Some techniques in deep learning have skipped the segmentation and normalization process. But, including them in the technique can improve the performance significantly. As artificial intelligence is becoming more compatible in present ubiquitous systems, soft computing and deep learning techniques can be further explored to aid seamless iris recognition. Methods to alleviate the anomalies due to fake iris pattern need to be researched more for avoiding unauthorized recognition. The future of this iris image-based biometric system will be more interesting if it can work on the above paradigms and give suitable solutions.

Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest.

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