FEATURE EXTRACTION METHODS ON A PARTIAL SECTION OF THE IRIS REGION FOR IRIS CLASSIFICATION

by

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$I(x,y)$	Grey intensity level
$G_{\delta}(r)$	One dimensional Gaussian smoothing filter
$C(s:r,x_0,y_0)$	Circular closed curve with radius r
$\sigma_w^2(t)$	The weighted within-class variance
$G(x,y)$	2D Gabor filter over an image (x,y)
$\oplus$	Exclusive-OR
Θ	XNOR operation
$\cap$	AND operator
$\overline{f_A \cap f_B}$	NOT operation
$p[x]$	Probability function
$cdf_x[k]$	The cumulative distribution function

LIST OF ABBREVIATIONS

ALBP	Average local binary pattern
ANN	Artificial neural network
ASM	Active shape models
AUC	Area under the curve
BEMD	Bi-dimensional empirical mode decomposition
BLOB	Binary large object
CASIA	Chinese Academy of Sciences' Institute of Automation
CMC	Cumulative match curve
DCB	Difference cumulative bin
DoF	Depth of field
DWFB	Directional wavelet filter bank
EE	Equal error
EER	Equal error rate
FA	False accept
FAR	False accept rate
FMR	False match rate
FNMR	False non-match rate
FPC	Fourier phase code
FR	False reject
FRR	False reject rate
HD	Hamming distance
HOG	Histogram of oriented gradient

IITD	Indian Institute of Technology Delhi
k-NN	k-Nearest Neighbour
LBP	Local binary pattern
LED	Light emitting diode
LoG	Laplacian of Gaussian
MLBP	Modified local binary pattern
MRA	Multi-resolution analysis
NIR	Near infrared
OMI	Overlap mean intensity
OVA	One versus all
OVO	One versus one
PILP	Phase-intensive local pattern
PTZ	Pan tilt zoom
RDWFB	Rotated directional wavelet filter bank
ROC	Receiver operator characteristic
SCB	Sequential cumulative bin
SIFT	Scale invariant feature transform
SIFT	Scale invariant feature transform
SMT	Sign magnitude transform
SVM	Support Vector Machine
THFB	Triplet half-bank filter bank
ULBP	Uniform local binary pattern
WBCT	Wavelet-based contourlet transform
WFOV	Wide field of view

KAEDAH PENGEKSTRAKAN CIRI PADA SEBAHAGIAN KAWASAN IRIS UNTUK KLASIFIKASI IRIS

ABSTRAK

Klasifikasi iris adalah satu sistem biometrik untuk mengklasifikasi manusia menggunakan corak iris individu. Salah satu langkah yang penting dalam sistem ini adalah untuk mengekstrak maklumat iris daripada bahagian iris yang telah disegmenkan. Walaupun terdapat banyak kaedah yang menghasilkan kadar pengecaman yang sempurna tetapi ianya memerlukan pemprosesan intensif yang melibatkan proses untuk mengasingkan maklumat iris dan juga lain-lain maklumat seperti kelopak dan bulu mata semasa penjanaan templat. Proses pemisahan dua bahagian ini adalah amat diperlukan supaya tiada data kelopak dan bulu mata diakui sebagai data iris semasa padanan. Untuk menyatakan isu ini, pendekatan kaedah pengekstrakan ciri yang digunakan secara meluas sebagaimana dicadangkan oleh Daugman telah diselidiki dalam kerja penyelidikan ini. Kemudian, satu teknik alternatif pengekstrakan ciri dengan menggunakan bahagian separuh atas kawasan iris yang berupaya melangkau proses pemisahan antara maklumat iris dan kelopak atau bulu mata semasa penjanaan ciri dicadangkan yang bukan hanya dapat mengurangkan masa pengiraan tetapi berkebolehan mengekalkan kadar ketepatan. Skim yang dicadangkan adalah berdasarkan kepada perbezaan bin terkumpul (DCB), jujukan bin terkumpul (SCB) dan pertindihan keamatan min (OMI) yang menggunakan pengiraan tempatan untuk menukar nilai piksel kepada bit binari. Kaedah ini dinilai menggunakan pengkelas Mesin Vektor Sokongan (SVM), k-NN and Naïve Bayes pada pelbagai saiz kawasan dan elemen kejiranan. Keputusan menunjukkan walaupun ketepatan purata untuk kaedah yang dicadangkan pada

penilaian individu (94.27%) adalah sedikit rendah berbanding kaedah Daugman (95.77%) tetapi kadar pengklasifikasinya meningkat kepada 96.26% jika penilaian menggunakan set mod ciri bersambung dan juga mampu mengurangkan masa pengiraan iaitu 0.030ms berbanding dengan kaedah Daugman yang memerlukan 0.166 ms.

FEATURE EXTRACTION METHODS ON A PARTIAL SECTION OF THE IRIS REGION FOR IRIS CLASSIFICATION

ABSTRACT

Iris classification is a biometric system to classify a person using the individual's iris pattern. One of the important steps in this system is to extract the iris information from the segmented iris region. Although several methods have produced a perfect recognition rate, they require intensive processing that involves the process of isolating the iris information as well as other information such as eyelid and eyelashes during template generation. The process of separating these two parts is crucially needed so that no eyelid or eyelash data are acknowledged as iris data during matching. To define the issue, the widely used approach of the feature extraction method as proposed by Daugman is studied in this research work. Then, an alternative feature extraction technique by using the upper half of the iris region that is able to skip the process of separating between iris information and eyelids or eyelashes during feature computation is proposed which is not only able to reduce the computation time but is able to preserve the accuracy rate. The proposed schemes are based on difference cumulative bin (DCB), sequential cumulative bin (SCB) and overlap mean intensity (OMI) that utilize the local texture analysis computation for transforming pixel value to a binary bit. The methods are assessed using Support Vector Machines (SVM), k-NN and Naïve Bayes classifiers on various region sizes and neighbourhood elements. The result showed that although the average accuracy for the proposed methods on individual assessment (94.27%) was slightly lower than by the Daugman method (95.77%), the classification rate for the proposed methods has improved to achieve 96.26% accuracy if the assessment uses a concatenated

mode set of features and also has managed to reduce the computation time which is 0.030 ms compared to Daugman's method that required 0.166 ms.

CHAPTER 1

INTRODUCTION

1.1 Preliminaries

High-security areas such as airports require a particularly high-level form of safety measures. Similarly, in cases where fraudulent or unauthorized usage needs to be prevented such as in banking institutions, a reliable and accurate security system is fundamental. With current advancements of computer vision, pattern recognition and optics, a new way to implement the recognition system using human traits has been initiated. Biometric recognition, also known as biometrics, is an automated system that recognizes individuals based on their unique biological or behavioural characteristics (Latman and Herb, 2013; Koong et al., 2014).

The degree-of-freedom across the population, individual uniqueness, being less immutable over time and resilience to any intervention are issues that have to be taken into consideration when implementing biometrics based on personal recognition (Jain et al., 2011). Face, fingerprint, palmprint, iris, voice and veins are examples of biological traits that have been successfully applied in biometric systems (Jain et al., 2016; Oloyede and Hancke, 2016). The systems are used to verify the claimed identity by comparing the biometric sample with the template of the corresponding claimed identity.

1.2 Iris Biometrics

A biometric system based on the iris of the eye provides a convincing criterion for human identification due to the fact that the iris of one individual is highly distinctive from that of another (Latman and Herb, 2013). In the past 20 years, researchers have developed many automatic systems for classifying or recognizing an individual based on the human iris (Iridian Technology, 2008; LG, 2008; Sagem, 2008). One of the largest system deployments was the system that was located in the United Arab Emirates (UAE). This country had signed a contract with John Daugman who was the inventor of the iris recognition system to perform the comparison of 632,500 different irises (Daugman, 2004).

Known as the iris recognition system, it is one of the most stable biometric systems due to the unalterable nature of the iris patterns over a lifetime (Jain et al., 1991; Ma et al., 2003; Ma et al., 2004; Wildes, 1997). Applying the irises for person identification was initially proposed by Flom and Safir (1987) who claimed that no two irises are alike (left and right), even between identical twins. Based on this concept, John Daugman further investigated the opportunity of using irises for individual recognition and developed algorithms that were able to automate the identification process. As an internal organ of the eye, the irises are well isolated and protected from the external outlier, which makes iris pattern challenging to modify unless a surgical process such as cataract surgery is performed (Roizenblatt et al., 2004).

The iris is the annular part between the white sclera and the black pupil, and it usually contains unique characteristics such as freckles, coronas, stripes, furrows, crypts, and a region of zigzag collarettes. The combination of these features forms differences in the iris texture between individuals. In the recognition scenario, a person who claims an identity will be matched with the enrolment templates and the acceptance or rejection of the claimed identity will typically be decided by this system.

Despite the successful progress of the iris biometrics system, the study of this kind of biometrics approach is still ongoing. Research in this field mainly focuses on finding alternative methods which are primarily engaged to improve the segmentation of algorithms and feature extraction, and encode the features to a particular meaning for matching schemes (Nguyen et al., 2017; Naseem et al., 2017; Frucci et al., 2016; Umer et al., 2015; Vatsa et al., 2008; Donald et al., 2007; Ko et al., 2007; Birgale and Kokare, 2010; Du et al., 2006; Khan et al., 2011; Ibrahim et al., 2012). The challenging part of the abovementioned processes is how to tackle the presence of the eyelids or eyelashes which are unavoidable in any captured iris image.

With unique physiological properties that remain stable throughout life and the fact that it is difficult to forge and imitate the authentic person, irises offer a major advantage as a method for person authentication (Daugman, 2003; Ahmadi and Akbarizadeh, 2017; Kumar and Passi, 2010; Raja et al., 2015). In addition, the iris capturing process is not too intrusive to the subject as there is no direct contact between the subject and the camera (Daugman, 2004; Aloudat et al., 2016; Kim et al., 2016; Liu et al., 2012). Compared to others, such as a fingerprint that requires direct contact with the screen, the iris is quite hygienic and no transmissible diseases can be spread from one person to another as no contact is required during its acquisition (Aloudat et al., 2016). Moreover, the substances of the sensor surface used in thumb print identification could degrade and it may eventually reduce the performance of the touch sensor. Apart from that, the current fingerprint systems such as those used in smartphones are vulnerable to fake fingerprints (Charles, 2014; Diaz, 2013, Yang and Han, 2014).

Iris-based technology is the most accurate and fastest compared to all available biometric solutions (Thomas et al., 2016; Aloudat et al., 2016; Nalla and Kumar, 2017). In addition, the iris biometrics are difficult to be affected by the use of a fake iris as the iris is acquired from a non-cooperative user (Kim et al., 2016). Huge improvements in image sensors enable these sensors to be operated at longer standoff distances of up to 60 m and this offers high user convenience and improves the throughput (Nguyen et al., 2017; Jain et al., 2016). One of the main reasons why the iris is convenient as a biometrics trait is because the iris itself does not change over time (Daugman and Downing, 2013; Mehrotra et al., 2013; Fenker and Bowyer, 2012). The iris remains the same except after surgical procedures or due to medical conditions that change the colour and shape of the iris (Roizenbalt et al., 2004).

Several research works from simple to complex algorithms for segmentation, feature extraction and matching have been proposed in the iris recognition or classification field (Soliman et al., 2017; Daugman, 2016; Thomas et al., 2016; Desoky et al., 2012). Rather than the front-end processing stage in the iris recognition system which is the iris segmentation, feature extraction is also one of the crucial stages that outline the accurate region of the iris that will be used for feature extraction.

1.3 Problem Statements and Motivation

Although the extraction method such as 2D Gabor wavelet first proposed by Daugman (1993) have produced impressive results, it requires intensive processing that involved the process to separate the iris information as well as other information such as eyelids and eyelashes during template generation.

Employing specific algorithms to detect the eyelids and eyelashes before the extraction process is another solution that has been proposed in several previous research works (Soliman et al., 2017; Sahmoud and Abuhaiba, 2013; Jan et al., 2013a; Min and Park, 2009; Jang et al., 2008; Han et al., 2012). Although some of the existing methods are able to detect the eyelids and eyelashes efficiently, their effectiveness is reduced when the quality of the image is poor (Daugman, 1994) specifically when the iris image is not perfectly wide open which causes the iris region to be covered by the eyelids or eyelashes.

Typically, the iris is almost partially occluded by the eyelids and eyelashes which consequently reduces the amount of iris texture that is needed for extraction. It is very difficult to develop efficient eyelid and eyelash localization and also a challenging stage due to the irregular shape of the eyelids (Thalji and Alsmadi, 2013; Ibrahim et al., 2012). Moreover, it is hard to define a suitable threshold of the eyelashes due to the variation and the volume of eyelashes in the iris images.

If not properly excluded, they will increase the risk of false rejection and false acceptance due to the likelihood that the undetected eyelids or eyelashes will be considered as a part of the iris texture. The probability of such an incident happening during the extraction is high if the entire normalized iris image is considered (Daugman, 2004; Ma et al., 2004; Monro et al., 2007; Miyazawa et al., 2008), and the outcome will directly influence the classification's accuracy (Huang et al., 2009; Sankowski et al., 2010; Proenca and Alexandre, 2010, 2010(a); Puhan et al., 2011; Radman et al., 2013).

There are two kinds of approaches to deal with the eyelid and eyelash problem in iris recognition. Segmenting and excluding the occlusion regions and then labelling the regions using a mask in iris matching is mainly the widely used approach to deal with the problem. However, this approach needs an accurate and efficient iris extraction method and it will also increase the double size of the iris template. This masking iris strategy will also increase the computational cost in both iris image processing and iris matching (Poornima et al., 2010; Sun et al., 2014; Chen et al., 2014). So a more realistic method that is able to identify and exclude the heavily occluded iris images is needed so that it is beneficial to both accuracy and efficiency of iris recognition systems.

Therefore, to overcome the abovementioned problem, a sub-pattern based method in which the iris image is partitioned into different sizes of equal or unequal sub-images has also been proposed (Chen et al., 2014; Belcher and Du, 2009). The iris image is divided based on the upper, middle, or bottom sub-regions which are then used to find the best matching score respectively. This approach is also plagued by problems, specifically in choosing the appropriate size of the sub-image that gives an acceptable accuracy (Wang et al., 2010) and also this method has a tendency to include the undetected eyelids or eyelashes during extraction specifically for the bottom sub-regions.

In order to elude the undetected eyelids and eyelashes from being considered as a part of the iris texture or to skip the process of masking the detected eyelids or eyelashes that is possible to reduce the computation time, the promising approach that can be applied is by extracting the feature of the iris region that is near to the inner part of the pupil for both the left and right of the eye images. However, the size of the region is small and may contain a limited richness of the iris texture for features and may require a comprehensive extraction method so that the features are enough to represent the texture in order to obtain satisfactory accuracy. The reason why the region that is closer to the pupil can be used as a possible option to extract the feature is because the region contains more local discriminating iris information (Ma et al., 2003; Du et al., 2005; Chen et al., 2006; Proenca and Alexandre, 2007; Rahulkar and Holambe, 2012; Ali and Tahir, 2014). As the lower and right parts of the rectangular form an image (the outer limbic boundary) which sometimes contains information about the eyelids or eyelashes, the option of selecting the region that is closer to the pupil provides a safe situation to avoid incorrect computation of the features as long as the extracted region is consistent (Hofbauer et al., 2016).

In order to reduce the computation time but maintain the performance, an extraction process based on texture analysis can be used to extract the iris features. For feature extraction that employs a texture analysis-based approach, the abundant frequency information of the spatial iris texture is extracted according to the significant local structure of the iris. Local texture analysis has been comprehensively applied because of its computational efficiency, it is unaffected by partial occlusion, and has better discriminability of the feature descriptions and tolerance to changes of illumination (Li et al., 2015; Viriri and Tapamo, 2017).

1.4 Research Objectives

1. To assess the performance of iris feature extraction approaches in terms of computation time and accuracy in order to reduce the processing time without affecting the performance rate.
2. To propose enhanced iris feature extraction approaches based on texture analysis to reduce the computation time while preserving the performance rate.

1.5 Scope of the Research

This research presents several approaches for feature extraction using texture analysis pertaining to the iris texture. The scope of research will cover on a study of Daugman's method to assess the accuracy and computation time at the feature extraction stage before furthering to the proposed feature extraction methods. The experiments are tested only to the databases from the Center for Biometrics and Security Research (for CASIA Version 1 and CASIA Version 3) and Indian Institute of Technology Delhi (IITD). This is due to limited access to other public databases. All the feature extraction methods are only applied on the unnormalized rectangular based iris region instead of the normalized iris region. However, to evaluate the proposed feature extraction methods, no algorithms are applied to remove the eyelid or eyelashes on the rectangular iris region. This is due to the proposed extraction methods are only applied at the upper half partial area of iris region which is contains more iris texture with less or no information of the eyelid or eyelashes.

1.6 Thesis Contribution

In this thesis, there are three new variants of LBP approaches suggested for feature extraction. The approaches use local information of the iris texture from the upper half of the iris region. First, an approach called Difference Cumulative Bin (DCB) is suggested in this thesis. This technique is similar to the conventional 2-D LBP regarding the choice of the reference pixel and the computation to find the difference between the neighbourhood pixels. However, for the final descriptor, the proposed methods prefer the binary bit based on determination rather than decimal value to the referenced pixel.

For a similar reason and also applying several partial irises' information as in the DCB variants for feature extraction, the second variant of LBP called Sequential Cumulative Bin (SCB) is suggested where the method will partially process the selected iris region in a one-dimensional path of the neighbouring pixels. The variant processes the local information by considering the pixel difference values before assigning a bit number to the respective neighbourhood pixels. Using a similar selected iris region as in the SCB method, the third variant, called the Overlap Mean Intensity (OMI), is suggested in this thesis. However, the computation between the neighbouring pixels is different where the mean between the neighbourhood pixels is considered for bit projection. Both the SCB and OMI methods perform a bit assignment scheme for reference after calculating the majority bit in the corresponding neighbourhood pixels.

The proposed methods use the local information of iris where the neighbourhood pixels are considered interconnected and contains information required for block of processing. Therefore, respective processing block provides appropriate observation of data which can be used as descriptive features for a particular iris image. Therefore, the proposed methods are promising alternative for feature extraction and to distinguish descriptor between images.

In order to extract the iris feature, a segmentation method to localize the pupil and iris region on the iris images is also presented and discussed. However, this method is not the primary contribution of the thesis as the method is reformulated from previously established works.

1.7 Thesis Outline

The remaining parts of this thesis are outlined as follows. Chapter 2 provides a brief background overview of iris recognition (or classification) and highlights several previous and recent works in this field. The approach and methods that are commonly applied for developing an iris recognition or classification system are comprehensively explained in this chapter. This chapter also discusses several iris image processing steps consisting of iris localization or segmentation, normalization, feature extraction and matching methods. Chapter 3 presents an overview of the research methodology including Daugman's method, and then discusses three major research works consisting of the segmentation and feature extraction methods for further explanation. This chapter also briefly explains the experimental work on how the training and testing samples are prepared for the matching stage using traditional Support Vector Machine, k-NN and Naïve Bayes classifier. The experimental results and discussion of the thesis contribution are explained in Chapter 4. Finally, Chapter 5 provides the conclusion and suggestions for future works.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter presents the background and a literature review on the iris biometrics and highlights some previous and recent exploration in the study of iris recognition and classification. An overview of iris anatomy and application of iris recognition and its deployment is provided in Section 2.2 and Section 2.3 respectively. The overview of iris recognition and iris image acquisition is described in Section 2.4. Detailed reviews of the existing methods for iris segmentation including Daugman's method and other methods of iris segmentation are discussed in Section 2.5, while Section 2.6 reviews iris normalization. The feature extraction method including Daugman's method and other methods are discussed in Section 2.7. The half iris region and texture-based feature extraction according to local binary pattern method is also reviewed in Section 2.7. Then, detailed reviews of matching methods are described in Section 2.8. Finally, the conclusions obtained from this literature review and the significance of the proposed works are expressed in Section 2.9.

2.2 Iris Anatomy

The human iris is an internal organ located between pupil and white sclera. A typical part of the iris is depicted in Figure 2.1. It has an annular shape containing various structures such as collarettes, crypts and furrows. These unique structures are the elements that form iris patterns which are dissimilar between individuals, even identical twins. The iris pattern is observable from a short distance and contains elastic connective tissue where the dilator and sphincter muscles control the size of the iris according to the amount of light entering the eye.

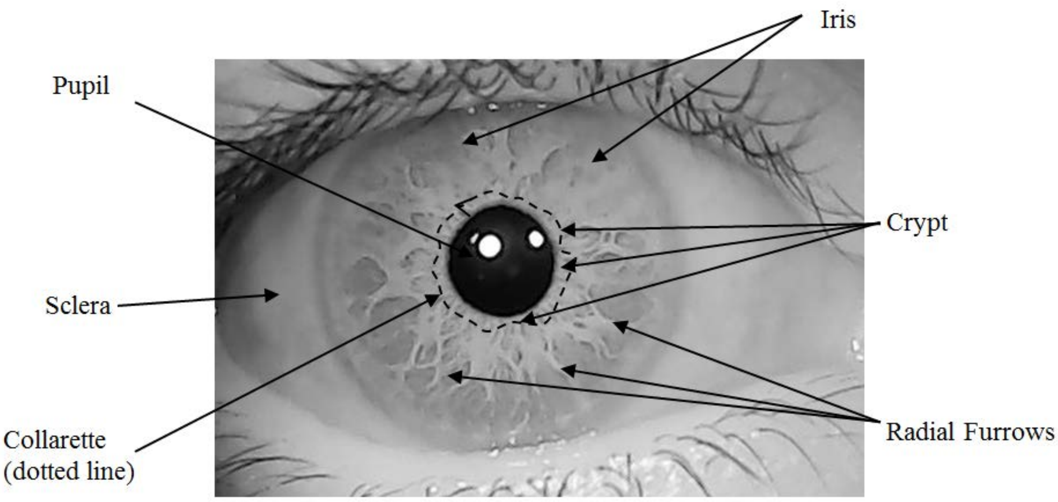

Figure 2.1 Sample of iris image

The human iris begins to form in the third month and continues its development up to the eighth month for a complete structure. The process for colour and pigmentation typically continues through the first year after birth (Muron and Pospisil, 2000). After that, the texture remains stable throughout one's life, unless there is something that causes direct damage to the eye or eye surgery is performed.

However, there exists a report saying that iris recognition can still be applied to individuals who have had cataract surgery but requires re-enrolment for a possible result (Roizenblatt et al., 2004). With unusual characteristics, iris modality may provide a stable and reliable route for personal authentication. Its circular shape also contributes to the capability for automatic detection by using current image processing algorithms and acquisition devices.

2.3 Application of Iris Recognition and Its Deployment

Research based on the iris pattern for the iris biometrics system has been expanded and is rapidly growing since the first modern automatic iris recognition system was introduced by John Daugman in 1994 (Daugman, 1994). However, before Daugman's work, in 1986, Leonard Flom and Aran Safir filed a patent for iris recognition but without proposing specific algorithms (Flom and Safir, 1986). Based on this idea, many successful systems have been practically implemented, showing the power of iris biometrics. At the same time, many works have been explored to expand the fundamental issues or propose new approaches in this field.

Since the early days of the iris recognition, several extensive studies have been performed to assess the effectiveness of iris biometrics regarding products, systems, performance evaluation, and the basis of research activities. Among the studies conducted were those by the AuthentiCorps' Iris Recognition Study 2006 (Authentic Corp Report, 2007) and the Technology Assessment for the State-of-the-Art Biometrics Excellence Roadmap in 2009 (Wayman et al., 2009). The Iris Exchange (IREX) that was initiated at the National Institute of Standard and Technology, US (NIST) has performed the study for evaluating the capabilities of iris recognition in various activities such as iris image quality assessment (IREX II) (Tabassi et al., 2011), performance of one-to-many algorithms (IREX III and IV) (Grother et al., 2012; Quinn et al., 2014), compression (IREX IV) (Quinn et al., 2014), guidance for collecting and handling iris images (IREX V) (Quinn et al., 2014) and the study regarding the stability of iris recognition over time (IREX VI) (Grother et al., 2013).

The approach of iris recognition has been explored from theoretical studies to applied research for the last 20 years. Iris recognition or classification is a combination of image processing and computer vision processes. The unique structure on the iris will be mathematically processed and compared to the registered templates for identifying the person. An iris recognition system is simply a contactless approach and may be incorporated in the near future into smartphones or wearable devices as long as a camera is attached to it. There are several recent reports mentioning that iris patterns change over time (Fenker et al., 2013; Mehrotra et al., 2013; Czajka, 2013; Bowyer and Ertiz, 2015; Hofbauer et al., 2016). The iris recognition or classification field still invites many researchers to propose and evaluate the new concepts and algorithms for various iris image situations such as off-angle iris images (Abhyankar et al., 2010; Li et al., 2013; Schuckers et al., 2007), noisy iris images (Marsico et al., 2012; Tan et al., 2012) and similar cases.

While the primary concern regarding iris recognition is security, nowadays the technology is also being adopted for applications that require productivity enhancement such as employee attendance. In current development, the iris recognition technology is progressing for the purpose of application rather than security environments such as inventory control and more growth is focused on the complex tasks that use IT and wireless communication. The world's largest biometric operations that has employed iris and fingerprints are the Aadhaar project by the Unique Identification Authority of India that launched in 2009 (UIDAI, 2013). This project was purposely deployed for providing each Indian resident with a unique identification number according to this multi-biometric configuration. The United Arab Emirates also used iris biometrics for border control in all 32 airports, land and seaports for screening people entering the country. This option makes up to 2.7 billion iris cross-comparisons every day (Al-Raisi and Al-Khouri, 2008). On the UAE border control which used Daugman's approach, a report in 2004 stated that

200 billion iris comparisons had been made using this assessment (Daugman and Malhas, 2004). Since the year 2000, frequent travellers in the UK have to present their iris instead of their passport at almost 10 UK Airport terminals as well as at Amsterdam's Schiphol Airport. In Afghanistan, UNHCR has also used irises for refugee registration for aid and food.

The formulation of the new products that are reliable for the security market includes significant advances in the field of iris recognition after the expiration of the patents of Flom and Safir and John Daugman in 2005 and 2011 respectively (Rathgeb et al., 2013). Iridian Technologies, currently known as L-1 Identity Solutions, is one of the iris recognition system providers. The company has licensed the technology to several big companies such as LG Electronics, Panasonic and IBM, among others for hardware and camera platform development. Starting from the evolution, currently the technology has gone through a series of changes and is more focused on various applications such as financial transactions, healthcare, consumer or residential purposes. For example, IrisID, formerly known as LG Iris, has deployed iris recognition technology since 1997, and now uses the 4th-generation systems to benefit the security industry. Another leading iris recognition system provider is SRI International which produces several products such as RapID-Cam II and the IOM PassThru[TMh] Drive-up Iris Recognition System. The company uses the concept of the iris on the move where the iris is captured and authenticated when the subject is on the move or in a vehicle.

2.4 Iris Recognition: An Overview

With the development of the recent technology and acquisition sensors, iris recognition technology has undergone significant achievements for person identification. Iris recognition is a method for iris biometrics that differentiates between individuals using tiny textures and unique patterns in the human iris. Each person has different patterns, even between the left and right eye. It is a non-invasive process and is stable over one's lifetime. Iris recognition has been accepted as one of the successful systems for individual identification (Wildes, 1997; Mehrotra et al., 2013).

There have been various methods to perform iris recognition. The one that inspired many researchers to work in this field is the approach that was proposed by Daugman (1994, 2001, 2004, 2007). After many years, there exist new ideas regarding which the results are comparable with Daugman's work.

2.4.1 Typical Iris Recognition System

The illustration in Figure 2.2 shows a typical stage of the iris recognition or classification system. It consists of image acquisition, pre-processing including segmentation, feature extraction and template matching. The standard system starts with the image acquisition and finishes with the decision to either accept or reject the claimed identity. To achieve satisfactory performance of iris recognition or classification, the incoming image to the system must be of high quality, and it frequently depends on the camera sensors which may operate in the visible or near infra-red spectrum (Matey et al., 2006; Yuniol et al., 2014).

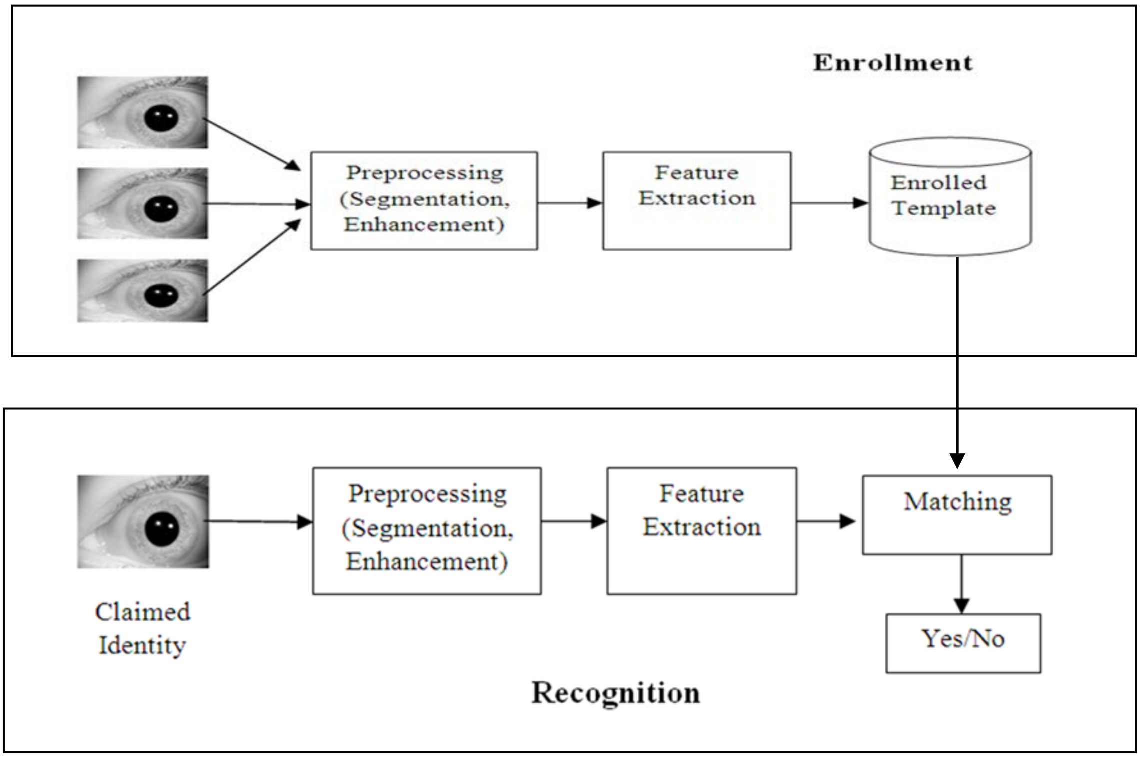

Figure 2.2 A typical stage of an iris recognition or classification system

In current practice, most of the iris recognition systems require the subjects to retain their distance to the camera sensor, and this process needs the full cooperation of the subjects in order to obtain not only a good quality image but also to achieve the right edge and position of the eye image. However, there is a system where the iris image can be captured at a distance while the subject is on the move and requires little cooperation from the subject during the acquisition (Matey et al., 2006).

Image quality enhancement, segmentation and normalization are the typical steps in the pre-processing stage. Iris segmentation, also known as iris localization, is the process of finding the iris region on the eye image. Discovering the inner and outer boundaries of the iris area is the most common practice in iris localization. The inner boundary is the area near to the pupil whereas the outer boundary is at the sclera area. Besides that, the segmentation process also involves the upper and lower eyelid and eyelash artefacts detection. These unwanted elements must be eliminated if they occlude the iris pattern. Several techniques have been proposed for segmenting the iris such as the Hough Transform (Wildes, 1997), integrodifferential operator (Daugman, 2004), active contour (Daugman, 2007) and so on.

During acquisition, it is difficult for the subjects to keep a constant distance from the camera and this will cause pupil variation even if the image is on the same subject. This situation will make the iris dilate or contract, and will therefore lead to inconsistent sizes of the iris region. Pupil variation is also caused by illumination sources and tilting of the eye and head which is hard to avoid during image acquisition. For dealing with the problem, the detected iris region must be normalized in order to have a uniform dimension of the iris region. The rubber sheet model is the extensively used technique for normalizing the iris region from circular to rectangular forms (Daugman, 2004). However, there have been several works where the iris recognition system is developed without the normalization approach (Lelina and Kokare, 2010; Ramkumar and Arumugam, 2014).

Feature extraction is the subsequent process which aims to extract the most distinctive characteristics from the textural information of the iris. Encoding the features to the constructive element is needed so that a comparison can be made between several iris patterns. There are various encoding approaches which have been developed such as 2D Gabor wavelets (Daugman, 2004), Discrete Cosine Transforms (Monro et al., 2007), ordinal features (Sun and Tan, 2009), multiscale combined directional wavelet filter bank (Rahulkar and Holambe, 2012) and many more.

Comparing the claimed identity to any of the enrolled templates is the last stage in the iris recognition system. Similarity measures such as Hamming Distance (Daugman, 2004) and the machine learning approach such as Support Vector Machine (Roy and Bhattacharya, 2006) or Artificial Neural Network (Sibai et al., 2011), Euclidean Distance (Sanchez-Avila and Sanchez-Reillo, 2002) and BLPOC function (Miyazawa et al., 2008) are among the methods widely used in the matching stage. The claimed and the enrolled template identities can be accepted as the same identity if the measured degree of similarity fulfils the predefined threshold.

2.4.2 Iris Image Acquisition

With a diameter of around 1 cm and being dark coloured, the image acquisition system must be designed with vigilant engineering practice. Sufficient resolution and sharpness of the image frequently depend on the Depth of Field (DoF) of the camera which is the range between nearest and farthest distance of the eye image to the camera. The subject must position their eye within this range and should keep the eyes wide open so that the image will appear sharp with visible iris textures. The subject should also position their head in the camera's field of view. To avoid centre deviation to the left or right, the angle of the area of view should not be more than 100 (Kalka, 2012).

The image must be centred well without requiring the subject to employ much contact for positioning the eye which may seem invasive (Wildes, 1997). A captured iris image is considered acceptable if the image contains at least 150 pixels across the diameter of the iris (Kalka, 2012). Most of the systems utilize the visible light spectrum for the lighting but in the current system, a near infrared light source

(NIR) is used instead of the visible spectrum. A near-infrared LED provides a sufficient amount of illumination to obtain the minute and complex textures from stromal regions rather than visible light sources which only disclose the ligament meshwork (Xie, 2007).

With the advancement of the current technology and considering both Daugman (1994) and Wildes' (1997) system as a benchmark for the iris acquisition system, many commercialized iris products have been developed such as OKI's IrisPassWG, LG's IrisAccess, Panasonic's BM-ET300, Irisguard's IG-H100 and so on (Dong et al., 2009). Near Infrared cameras are most commonly used in commercialization and research. Other cameras are the high-resolution colour cameras, and the most sophisticated one is the telescope-based type iris camera which can capture an iris image from a distance of up to 10 feet. Table 2.1 shows the summary of the operations of the iris cameras (Du, 2006).

To date, there are several systems that can operate and acquire the iris image at long distances (Nguyen, et al., 2017; Thavelengal et al., 2015). The L-1 Eagle Eyes system that was developed by Bashir et al. (2008) in has the longest capturing distance of up to 10 metres. Yoo and Kang (2015) proposed an integrated acquisition system combination of low- and high-resolution cameras for capturing facial and non-intrusive iris images. A system based on the pan-tilt-zoom (PTZ) camera (Yoon et al., 2009) and stand-off-based acquisition (Wheeler et al., 2008) has also been introduced to capture images at a distance of 1.5 to 3 meters in less than 3.2 seconds, respectively.

Iris on the Move is another system that is able to capture iris images from subjects who walk at normal speeds through a gateway that is installed with a high-resolution camera (Matey et al., 2006). Another effort for the same scenario was also suggested by Venugopalan et al. (2011) who developed a system that can capture iris images from up to 8 metres with the resolution of 200 pixels. Self-adaptive systems (Dong et al., 2008), multispectral iris cameras (Gong et al. 2012), autofocus settings (Park and Jim, 2005) and wave-front coding technology (Hsieh et al., 2013) are among the approaches that have been integrated into the current iris acquisition system.

Table 2.1 Summary of the camera for the iris acquisition system (Du, 2006).

Camera	Characteristic
NIR	-Can operate from up to 2 feet -Using NIR LED (700 – 900 nm) for the illuminator -The image can be captured with a resolution of 640 x 480 - It is commonly used for iris identification and has commercialization value. - Requires non-cooperative users for successful acquisition.
High-resolution	- It can operate from only up to 2 inches. - Uses visual light for illumination - The size of the acquired image can be up to 6144 x 4096 -Used for iris pattern analysis and also has commercialization value. - Due to the operational distance being too short, this kind of camera is intrusive to users.
Telescope type	- Can operate with acceptable images obtained from up to 10 feet away. - Uses NIR medium for illumination - There is no commercialization value. Only in lab usage. - Used for iris surveillance and offers the eye safety.

2.5 Iris Segmentation

Iris segmentation is the early stage that is important for the success of the remaining processes in the iris classification system. A recurring issue in this stage is how to find the exact region of the iris with the help of finding the localization of the pupil region. Different camera-to-eye distances will cause inconsistency in the size of the captured iris images which do not only occur for different subjects but also for the eyes from the same subject. Normally, it is hard to obtain iris images that are free from non-relevant elements such as sclera, pupil, eyelids, reflections and eyelashes (Ma et al., 2003; Li et al., 2010; Jillela, 2015; Jan, 2017). Segmentation is a kind of process to partition the image into several elements, and it is an important front-end stage before advancing to feature extraction. It outlines the appropriate region that will be used for feature extraction which directly affects the classification accuracy (Hofbauer et al., 2016). Figure 2.3 shows the states of inner, outer and upper or lower eyelid boundaries that are typically considered for segmentation.

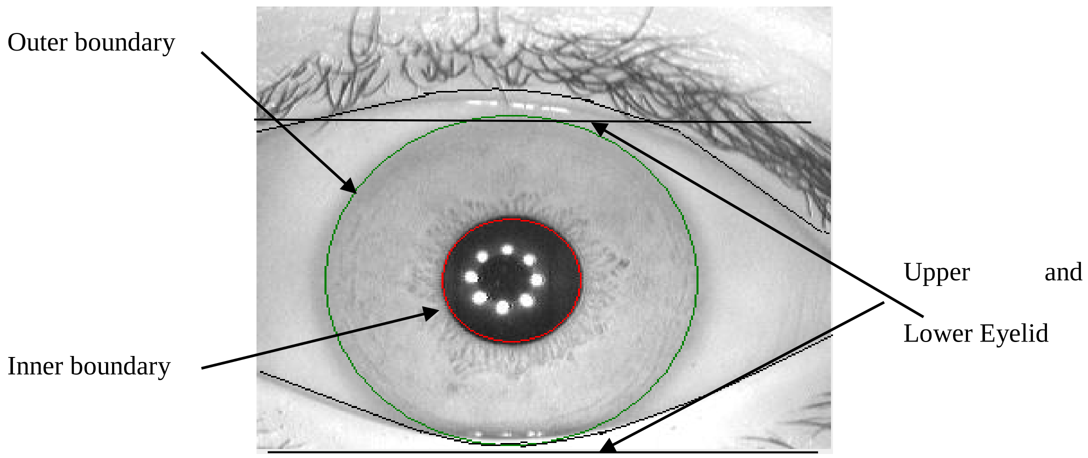

Figure 2.3 State for inner, outer and upper and lower eyelid boundaries

From the literature (Ng et al., 2008; Jang et al., 2008; Li et al., 2015; Thomas et al., 2016), the iris segmentation process can be summarized and divided into several major steps as listed below.

1. *Specular reflection removal*. Specular reflections are the noisy attributes which are usually constructed within a small region of an iris image (pupil) due to high pixel intensity values. Typically, improper lighting is the primary cause for the presence of this element in an eye image. Specular reflections that are found in the iris region can be categorized as noise, and should be eliminated before continuing any further processes. If not, it may cause low recognition performance. Handling specular reflections by employing removal schemes such as simple thresholding and region filling is the most focused technique in iris segmentation.
2. *Detecting the pupillary and limbic boundary*. The heart of iris segmentation is to find the iris region, and can be done by detecting the pupillary and limbic boundaries. In the majority of cases, the boundary is assumed to be circular; however, this assumption is not applicable for images with a deviated gaze. Usually, in this stage, the process begins with detecting the pupillary boundary because this region contains substantial intensity values compared to the surrounding parts. Once the boundary is detected, it can be propagated to the next limbic boundary searching process before finalizing the iris region which is located between pupillary and limbic boundaries.
3. *Eyelid detection.* The presence of an eyelid in an eye image is typically minimal in normal conditions when the eye image is captured with a wide-open eye. However, the majority of the captured eye images are

enclosed with an eyelid at the top and the bottom. The occlusions will partly cover the iris textures on eye images. Eyelid detection is commonly done by modelling the boundaries with parabolic arcs, and the noise is defined if the attributes fall outside of the arc but within the limbus boundary.

4. *Eyelash removal.* This process faces similar problems as with eyelid removal. The occlusions due to eyelashes are usually minimal when the eye captured is wide open. However, the segmentation process can be more challenging when the images are not in a wide-open eye as the iris region may contain both eyelids and eyelashes. This not only contributes to an uneven interruption of the limbus boundary but may also reduce the number of abundant iris attributes, especially in the upper part of the eye image.

2.5.1 Daugman's Iris Segmentation

The segmentation approach based on integro-differential operators is the most cited since it was proposed by Daugman (Rankin et al., 2010; Radman et al., 2013; Jamaludin et al., 2017). The operator has to find both the inner and outer boundaries in order to locate the iris and pupil regions with the assumption that both the iris and pupil are circular. The Daugman operator is based on the fact that the difference values of pixels between inside and outside the iris edge are maximum. This approach also employs an operation to find the arcs of the upper and lower eyelids. The segmentation process using this method is depicted by Equation (2.1) (Daugman, 1993).

$$max_{(r,x_o,y_o)} \left| G_\delta(r) * \frac{\partial}{\partial_r} \oint_{C(s:r,x_o,y_o)} \frac{I(x,y)}{2\pi r} d_s \right| \qquad (2.1)$$