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CENATAV
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Reconocimiento de Patrones

SERIE AZUL

Iris Recognition Systems – A Survey

José Luis Gil Rodríguez y Eduardo Garea Llano

RT_066 **octubre 2014**

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Note:

This report is dedicated to the memory of the Dr. Jose Luís Gil Rodríguez, first author of this work, who could not see this report concluded and provided the essence, systematized, analyzed and summarized most of the content and the ideas presented here.

Eduardo Garea-Llano

Nota:

Este reporte está dedicado a la memoria del Dr. José Luís Gil Rodríguez, primer autor del mismo quien no pudo ver concluido este reporte y que aportó la esencia, sistematizó, analizó y resumió la mayor parte de los contenidos y las ideas aquí expuestas.

Eduardo Garea Llano

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Abstract. In this survey, we collect the main procedures on Iris texture detection and isolation used in last decade. In recent years biometric identification of persons has gained great importance in the world from its applications in multiple scenarios, especially those applications aimed at border security, access control and forensic. Iris recognition is one of the most booming biometric modalities. It has been reached in the last 20 years due to its unique character as a biometric feature, which makes iris identification and verification systems one of the most accurate biometric modality. This report provides a comprehensive overview of the state of the art of the iris recognition systems. The report is structured in a way that is logically possible to traverse the elements of a system based on iris recognition, processes, constraints and challenges that users, researchers and application developers face.

Keywords: iris recognition systems, iris segmentation, iris feature extraction, performance metrics for biometric systems, a survey on iris.

Resumen. En los últimos años la identifcación biométrica de personas ha ido cobrando gran importancia en el mundo a partir de sus aplicaciones en multiples escenarios, sobre todo especial interés han despertado aquellas las aplicaciones encaminadas a la seguridad de fronteras, controles de acceso y forenses. El reconicmiento del Iris es una de las modalidades biométricas que más auge ha venido alcanzando en los últimos 20 años debido a su carácter único como característica biométrica, lo que hace que los sistemas de identificación y verificación basados en iris sean de los mas exactos. En este reporte se realiza un amplio resumen del estado del arte de los sistemas de reconocimiento de personas por el iris. El reporte esta estructurado de forma tal que es posible recorrer de forma lógica los elementos que conforman un sistema de reconocimiento basado en iris, los procesos que lo integran, las limitaciones y retos a que se enfrentan los usuarios, investigadores y desarrolladores de aplicaciones.

Palabras clave: reconocimiento de iris, segmentación de iris, extracción de rasgos del iris, métricas de rendimiento para sistemas biométricos, estado de arte sobre iris.

1 Introduction

Biometrics is typically defined as the study of methods for measurements of physical, biological or behavioral attributes that can be used to identify a person. Within the field of biometrics, fingerprint, face and Iris are often thought of as the current major general-purpose methods.

Iris recognition is a biometrics modality and the term biometrics refers to "automated recognition of individuals based on their biological characteristics" [ISO/IEC, 2005]. The iris recognition is the process of recognizing a person by analyzing the random pattern of the iris. The automated method of iris recognition is relatively young, existing in patent since 1994 [Daugman, 1994], that is to say 19 years.

The iris texture is a physical characteristic of human physiology which can be used for biometric authentication and identification of persons. Iris biometric modality for use in a specific application involves a set of seven factors identified by Jain et al., [2002, 2004, 2007] and they are present in a person identification system based on the iris biometric modality:

- *Universality* (everyone possesses the characteristic), means that every person possess the iris texture features in an iris system.
- *Uniqueness* (the characteristic is different for everyone) means that the iris texture features are sufficiently different for individuals such that they can be distinguished from one another. The iris pattern is epigenetic (not genetically determined).
- *Distinctiveness* (high discriminative power due to its entropy). The randomness of iris patterns has very high dimensionality which is superior of 266 degrees of freedom [Daugman, 1998].
- *Permanence* (the characteristic remains invariant over life time, except for pigmentation change over time) means that the iris texture remain invariant over the time. Then, a 'good' permanence will be reasonably over time with respect to the specific matching algorithm.
- *Measurability* (the characteristic is easy to capture) relates to the ease of acquisition of iris texture. The image acquired should be in a form that permits subsequent processing and extraction of the relevant iris feature sets.
- *Performance* relates to the accuracy, speed, and robustness of the Iris technology used.
- *Acceptability* (the characteristic is not invasive) relates to how well individuals accept the iris technology. The iris image capture is non-invasive. Furthermore, Iris biometrics has received remarkable attention in the biometric community due to its unrivaled properties.
- *Circumvention* (imitability of the characteristic) relates to the ease or not, the human iris might be imitated using an artifact or substitute.

An iris recognition system can operate in two modes.[1] In *Authentication-verification mode* the system performs a one-to-one comparison of a captured iris feature set with a specific IrisCode[1] stored in an iris database in order to verify the individual is the person they claim to be. In *Identification mode* the system performs a one-to-many comparison against an iris database in attempt to establish the identity of an unknown individual. The system will succeed in identifying the individual if the comparison of the iris sample to an iris template in the iris database falls within a previously set threshold. Identification mode can be used either for 'positive recognition' (so that the user does not have to provide any information about the template to be used) or for 'negative recognition' of the person "where the system establishes whether the person is who she (implicitly or explicitly) denies to be".[1]

Iris recognition is nowadays considered as one of the most accurate biometric recognition techniques. However, the overall performances of such systems can be reduced in non-ideal conditions, such as non-voluntary on-the-move, or non-collaborative setups [Labati et al., 2012].

With the development of the current networked society, personal identification based on biometrics has received more and more attention. Iris recognition has a satisfying performance due to its high reliability and non-invasion. In an iris recognition system, preprocessing, especially iris localization plays a very important role. The speed and performance of an iris recognition system is crucial and it is limited by the results of iris localization to a great extent. Iris localization includes finding the iris boundaries (inner and outer) and the eyelids (lower and upper) [Cui et al., 2004].

This report reviews current state-of-the-art in iris recognition systems taking into account all its fundamentals step in different applicative scenarios.

[1] IrisCode: The term, “iris code” was used by Daugman in his 1993 paper. Here, we use this term to refer to any binary representation of iris texture that is similar to Daugman’s representation.

2 History

In 1936, the ophthalmologist Frank Burch proposed the concept of using iris patterns as a method to recognize an individual [Daugman, 2001b]. In 1985, Leonard Flom and Aran Safir, ophthalmologists, proposed the concept that no two irises are alike and were awarded a patent for the iris identification concept in 1987. This moment was the origin of modern automated iris recognition, they proposed the idea but without any algorithm [Flom and Safir, 1987]. Among all biometric characteristics the pattern of an iris texture is believed to be the most distinguishable among different persons [Bowyer et al., 2008]. Dr. Flom approached Dr. John Daugman to develop an algorithm to automate identification of the human iris. In 1993, the Defense Nuclear Agency began work to test and deliver a prototype unit, which was successfully completed by 1995 due to the combined efforts of Flom, Safir, and Daugman [NTSC, 2006]. In 1994, Daugman was awarded a patent for his automated iris recognition algorithms and the first commercial products became available [Daugman, 1994]. It was based on doubly dimensionless coordinates for normalization, 2D Gabor filters as features, and Hamming Distance scores as comparator [Gil and Díaz, 2005], [Rathgeb et al., 2013]. In 2005, the broad patent of Flom covering the basic concept of iris recognition expired. Meantime, the patent on the IrisCode implementation developed by Daugman expired in 2011 providing marketing opportunities for other companies that have developed their own algorithms for iris recognition.

3 Biology of the Human Iris

The term Iris comes from the antiquity, from the Greek terminology "ipis", which literally means rainbow [Encarta, 2005]. The iris begins to form in the third month of gestation [Kronfeld, 1962] and the structures creating its pattern are largely complete by the eighth month, although pigment accretion can continue into the first postnatal years. Its complex pattern can contain many distinctive features such as arching ligaments, furrows, ridges, crypts, rings, corona, freckles, and a zigzag collarette [Daugman, 2001], some of which may be seen in Fig. 1. The Iris is the colored circular part of the exterior of the eye, which contains in its interior the pupil.

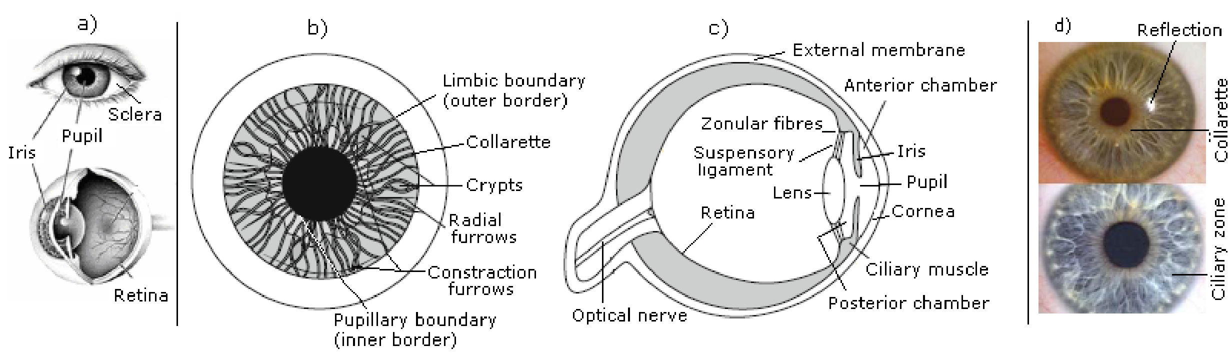

Fig. 1. a) Iris localization, b) and c) Generals biological structures in a frontal and lateral view [Rathgeb et al., 2013] and d) Iris texture detail [Daugman, 2004].

The human iris is an annular-shaped area between the pupil and the sclera, which is stable from the eighth month of gestation [Daugman, 2002]. A normal iris pattern shows hundreds of random texture features in its embeeding "trabecular meshwork" and pigmentation. These features are unique for each individual, also in the case of homozygote twins. Moreover, the iris is well protected by the cornea and it is not affected by external factors, differently from fingerprints, which are sensitive to skin conditions [Li and Savvides, 2009].

The high degree of randomness of the iris texture is the key feature exploited in the iris biometric systems to produce reliable and robust biometric templates that allow to obtain a very high accuracy of the recognition process [Donida et al., 2012].

3.1 Properties of the Iris

Morphogenesis, development and chromatic properties of the iris [Daugman, 2012]:

- The human iris begins to form during the third month of gestation. The structures creating its distinctive pattern are complete by the eighth month of gestation, but pigmentation continues into the first years.
- The layers of the iris have both ectodermal and mesodermal embryological origin, consisting of (from back to front):
  - a epithelium darkly pigmented;
  - two muscles: pupillary dilator muscle and sphincter muscle;
  - the vascularized stroma (connective tissue of interlacing ligaments);
  - an anterior layer of chromataphores and melanocytes with a genetically determined density of melanin pigment granules;
- Iris colour is determined mainly by the density of the stroma and its melanin content, with blue irises resulting from an absence of pigment: longer wavelengths differentially penetrate while shorter wavelengths are scattered, a phenomenon resembling that which makes the sky blue.

Main properties of the human iris as an identifier are the following ones [Daugman, 1998; 2012] [Muroò et al, 2000] [Dorizzi and Krichen, 2010].

- The iris is an internal organ highly protected (from natural environment) and externally visible from distance up to some meters. This is the only human body organ in this case. The fact that the iris is protected behind the eyelid, cornea and aqueous humors, means that, !different to other biometrics modality such as fingerprints, the probability of damage and/or abrasion is minimal! [Wildes, 1997].
- The iris is highly textured with random pattern of great complexity and unique. The keys to the uniqueness are randomness (high variability, high entropy) plus its combinatorial complexity.
- Iris patterns are epigenetic (not genetically determined). Then, the twins have not the same iris texture, neither left and right eye irises are equals, because the iris formation has not genetic influence, therefore is not hereditary. In essence, the iris is unique for each individual.
- Iris patterns are persistent. Presumedly is stable through the life, apart from pigmentation changes. There is not evidence of any visible pattern changes, although there is some evidence that computed IrisCode templates may "age".

Other characteristics which researchers and developers must take into account [Daugman, 1998; 2012] [Dorizzi and Krichen, 2010] [Daugman and Downing, 2001]:

- The iris is small and moving target to acquire from at a distance.
- The iris is usually occluded by eyelids, eyelashes, lenses, eyeglasses and light reflections. For some ethnic groups, the iris texture is poor and partly occluded.
- Iris texture deforms non-elastically when the pupil changes size.

In the visible band of light (400nm –700nm), the iris reveals a very rich, random, interwoven texture due to the "trabecular meshwork" (Fig. 1c). But even in "dark brown" eyes show rich texture when images are captured in infrared illumination. All pigmentation variations are due to melanin density. This can sometimes change (e.g. growth of freckles, or pigment blotches); but these are invisible in the

NIR band of light (Near InfraRed: 700nm –900nm) used in all publicly deployed iris cameras, because melanin is almost completely non-absorbing beyond 700nm (Fig. 2). However, in the visible band of light in unconstrained environments (e.g. outdoors), ambient corneal reflections are common, because the cornea is a specular surface [Daugman, 2012].

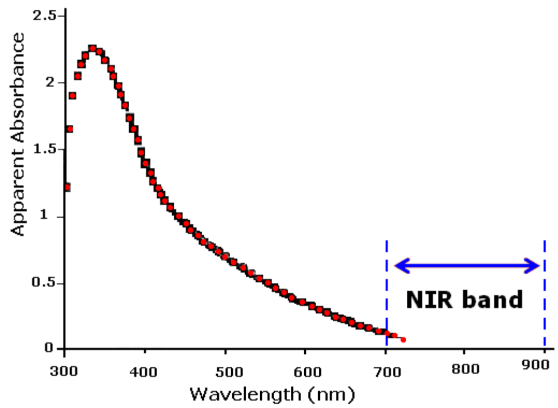

Fig. 2. Absorption spectrum of the iris melanin. Reported by Daugman.

In contrast to other biometric characteristics, such as fingerprints, the iris is a protected internal organ whose random texture is complex, unique, and believed to be very stable throughout life. Recently, it was found that iris patterns do slightly alter over time, i.e. aging does affect recognition accuracy in a way that dissimilarities between iris pattern of a single subject increase [Fenker, 2011]. However, compared to faces or other physiological biometric characteristics changing more drastically, the iris remains relatively stable and is rarely affected by external elements. As an internal organ the iris is well protected and cannot easily be altered [Roos, 2010]. The structure of the iris is substantially different between different persons, even in case of monozygotic twins [Daugman and Downing, 2001] [Daugman, 2012].

3.2 Iris Texture Entropy

The property entropy measures the amount of random variation in a population, for example:

1. The entropy determines the number of different states or patterns that are possible; and
2. It determines the probability distribution across those possible states.

In these sense, the entropy give the discriminating power of a biometric modality and it is the key to the biometric collision avoidance. The Entropy H (measured in bits) corresponds to 2^H discriminable states or patterns. Then, the survival of a large database requires a large biometric entropy [Daugman, 2012].

The Iris patterns are epigenetic features (not genetically determined) and this fact makes of them better biometrics features because produce high degree of entropy and therefore, a high degree of randomness. The mesures data on iris patterns referred to their variability and entropy was published by Daugman (http://www.cl.cam.ac.uk/~jgd1000/addisadvans.html):

- Variability = 244 degrees-of-freedom,
- Entropy H = 3.2 bits per square-millimeter,
- Uniqueness: set by combinatorial complexity.

The high degree of randomness of the iris texture is the key feature exploited in the iris biometric systems to produce reliable and robust biometric templates that allow to obtain a very high accuracy of the recognition process [Donida et al., 2012]. Like the iris texture features are an epigenetic biometric feature, they give a warranty to obtain a de-duplication in a large national database. These is the case of the UIDA programme in India [Aadhaar, 2011] actually in development, which will be include a quantity near to the 1200 millions of peoples.

Even when the high combinatorial complexity is big, the encoding and decision-making are tractable (see http://www.cl.cam.ac.uk/~jgd1000/addisadvans.html).

- Image analysis and encoding time: 30 milliseconds,
- Decidability index (d-prime): d' = 6 to 8 typically,
- Search speed: 1 million IrisCodes per second, with a 3 GHz CPU.

In UIDA programme, in two months of work, were enrolled 150 million of citizens. The amount of enrolled persons in database is 1 million per day. Each enrolled person is compared against all of those enrolled so far, to detect duplicates (“de-duplication”). Such verification process requires (1 million x 150 million) = 150 million-millon iris cross-comparisons daily: 1.5 x 10^{14} per day. Daugman concludes that: “the avoidance of biometric collisions among comparisons on this scale requires high biometric entropy, as possessed by IrisCode phase bits, ensuring very rapidly attenuating tails of the distribution obtained when comparing different eyes”. The iris texture entropy gives resistance against false matches. The probability of two different people colliding by chance, in so many bits (e.g. disagreeing in only one-third of their IrisCode bits) is infinitesimal. Thus, the False Match Rate is easily made minuscule.

This set of positive properties of the iris enhance its suitability for irris recognition systems because offer a fast and secure method for the recognition of individuals, with the ability to perform accurate identification even with databases composed by several millions of enrolled IrisCode [Donida et al., 2012].

4 An iris Recognition System

Considering other biometric modality, the mentioned set of properties associated to the Iris, enhance its suitability for use in automatic identification. A complete relation of a typical biometric system based on the iris trait is depicted in Fig. 3. The processes are Iris image acquisition, Iris pre-processing, Iris segmentation, Iris texture normalization, Iris feature extraction, Iris feature codification and Iris matching.

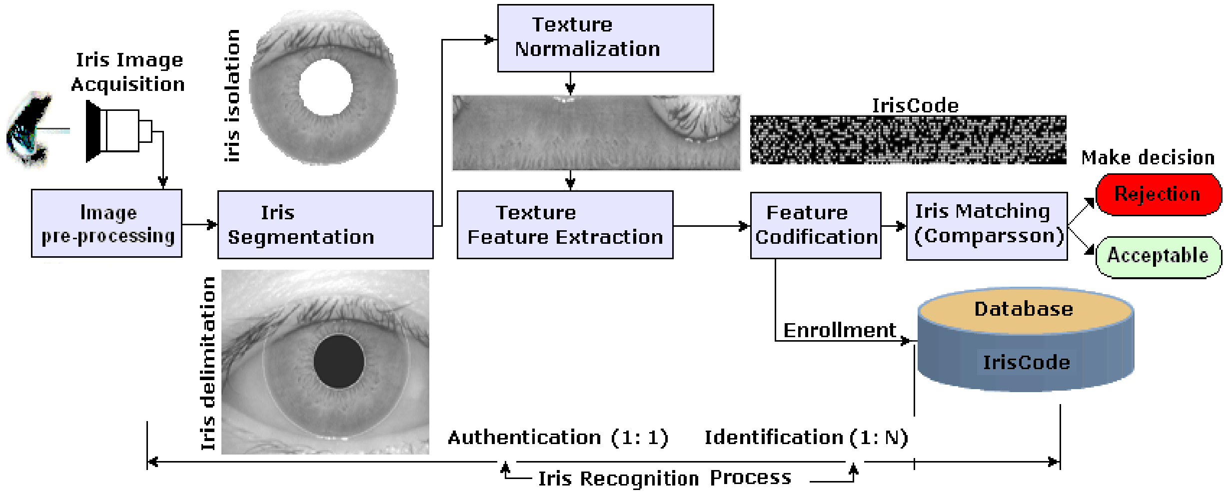

Fig. 3. Block diagram of an iris recognition system.

The processes that compose an iris recognition system have the following tasks:

1. The image acquisition task is usually composed by cameras that capture images in the near-infrared range (700 − 900nm). The ISO Iris Image Standard requires that the length of the iris diameter is at least 200 pixels [ISO/IEC, 2005]. The user cooperation is usually required in order to properly capture the iris image.
2. The image pre-processing and segmentation processes. An iris image, contains not only the region of interest (iris) but also some irrelevant parts (e.g. eyelid, pupil etc.). A change in the camera-to-eye distance may also result in variations in the size of the same iris. Furthermore, the brightness is not uniformly distributed because of non-uniform illumination. Therefore, before feature extraction, the original image needs to be preprocessed to localize iris, normalize iris, and reduce the influence of the factors mentioned above. The process performs the localization of the iris in the image and removes the areas corresponding to eyelids, eyelashes, reflections, and shadows [He et al., 2009]. Typically, the iris segmentation is the most time-consuming step [Daugman and Malhas, 2004] and its effectiveness is relevant because the obtained accuracy strongly influences the results of the biometric system [Ma et al., 2004]. An incorrectly segmented iris, in fact, can result in errors of the matching module.
   Since the iris region of the eye is a relatively small area, wet, and constantly moving due to involuntary eye movements, a robust segmentation is needed in order to correctly identify the region of the captured image that should be considered during the subsequent steps of the biometric recognition process [Donidas et al., 2012]. The iris segmentation is usually performed in two steps: first, the inner and outer boundaries of the iris region are estimated (well-known as iris delimitation and also iris isolation), then occlusions and reflections are detected and removed.
3. The process of feature extraction is based on algorithms that analyze the segmented iris image and extract the distinctive features from the iris texture pattern.
4. The feature codification process use the extracted features in order to compute an abstract representation, called template. One of the most commonly used templates is the IrisCode [Daugman, 2002].
5. The last process computes a matching distance between two or more templates, in order to determine if they belong the same person. In most of the cases, the matching value is computed as the Hamming Distance between shifted templates [Daugman, 2002],[Li and Savvides, 2009]. Other distances like

Levenshtein distance [Shirke et al., 2012] and Euclidean distance [Ma et al., 2002] had been used by researchers.

The Iris database is an IrisCode repository belonging to the population that will receive the iris recognition service. During enrollment, the system places encoded features into an Iris database. During authentication, the system compares the IrisCode presented against an IrisCode belonging to especific person to verify the claimed identity. During identification, the system compares the presented IrisCode against the entire IrisCode database to identify an individual.

Closely related with a person's recognition system is the evaluation of quality in order to know the efficacy and the efficiency of the implemented methods in each module of the system. In the following topics we will describe the more recognized methods related with each iris recognition process.

Iris verification: Recognizes a person by comparing the captured IrisCode with her own own IrisCode template pre-stored in the system (1-to-1 comparison).

Iris identification: Recognizes a person by searching the entire IrisCode database for a match (1-to-many comparisons).

5 Iris Image Acquisition

The image acquisition is done by a monochrome CCD[2]-camera covering the iris radius with at least 70 pixels. The camera is situated normally between half a meter to one meter from the subject. The CCD-camera job is to take the image from the optical system and convert it into electronic data.

Once the camera has located the eye, the iris recognition system then identifies the image that has the best focus and clarity of the iris. The image is then analyzed to identify the outer boundary of the iris, where it meets the white sclera of the eye. The pupillary boundary and the centre of the pupil also should be located. This results in the precise location of the circular iris. The iris recognition system then identifies the areas of the iris image that are suitable for feature extraction and analysis. This involves removing areas that are covered by the eyelids, any deep shadows and reflective areas [Shirke et al., 2012].

Table 1 show the parameters of iris image acquisition cameras used in the approaches of [Daugma, 1993] and [Wildes, 1997], and synthesized by [Dorizzi and Krichen, 2010]..

Table 1. Parameters of Iris image acquisition cameras.

Parameters	**Daugman (1993)**	**Wildes (1997)**	**NLPR** (2002)
Type	Monochrome camera	Monochrome camera	Monochrome camera
Resolution	640 x 480	Without indication	High resolution
Light	NIR[3]: 1 source of base	NIR: 2 sources of base	NIR: 2 sources of base
Objective	330 mm	80 mm	Without indication
Acquisition distance	20 to 45 cm	20 cm environ (circular)	Without indication
Size of Iris	140 pixels	256 pixels of diameter	Without indication

A sample of Iris images taken from public and available open Iris databases using this kind of cameras is shown in Fig. 4.

Examples of real iris images acquired using cameras used at the present time are the following ones (see Fig. 3): a) ISG LW-1.3S-1394; b) CASIA-Cam; c) CASIA-CamV2; d) CASIA.v3-Interval; e) CASIA.v3-Cam; f) OKI Irispass-H; g) CASIA-LR-Cam; h) Irisking IKEMB-100; i) N/A (Synthetic); j)

[2] CCD: Charge Coupled Device
[3] NIR: Near Infra Red

LG 2200; k) LG 2200; l) JIRIS JPC1000; m) MBGC-Portal; n) LG 2200; o) Panas BM-ET100; p) + LG 4000; q) LG 2200; r) Nikon E5700; s) Canon 5D; t) TOPCON TRC50IA; u) OKI Irispass-H; v) OKI Irispass-H and w) Sony DSC-F717.

These cameras capture the image which constitutes the primary data. From this image the ring of iris texture is isolated; its quantitative iris features are extracted and used then in the following steps with the purpose of the person authentication or identification, automatically.

In the past several years there has been a proliferation of companies selling iris capture devices. Today, these cameras are considered commodity items. With India's UID program as a primary catalyst, the cost of iris cameras has dropped to the same cost as a standard digital camera and in some cases, much less. The challenging environments and tremendous number of irises captured from people ranging in age from small children to elderly people in India and Indonesia has also been a factor in improving the usability of iris cameras.

They are available in a variety of form factors, one and two-eye capture models, and at prices that depend upon their sophistication. There are several multi-biometric capture devices on the market today. Other devices are simple, lightweight and meant only for iris capture. Cutting-edge devices automatically acquire irises at distances of 10 feet or more, while subjects are moving.

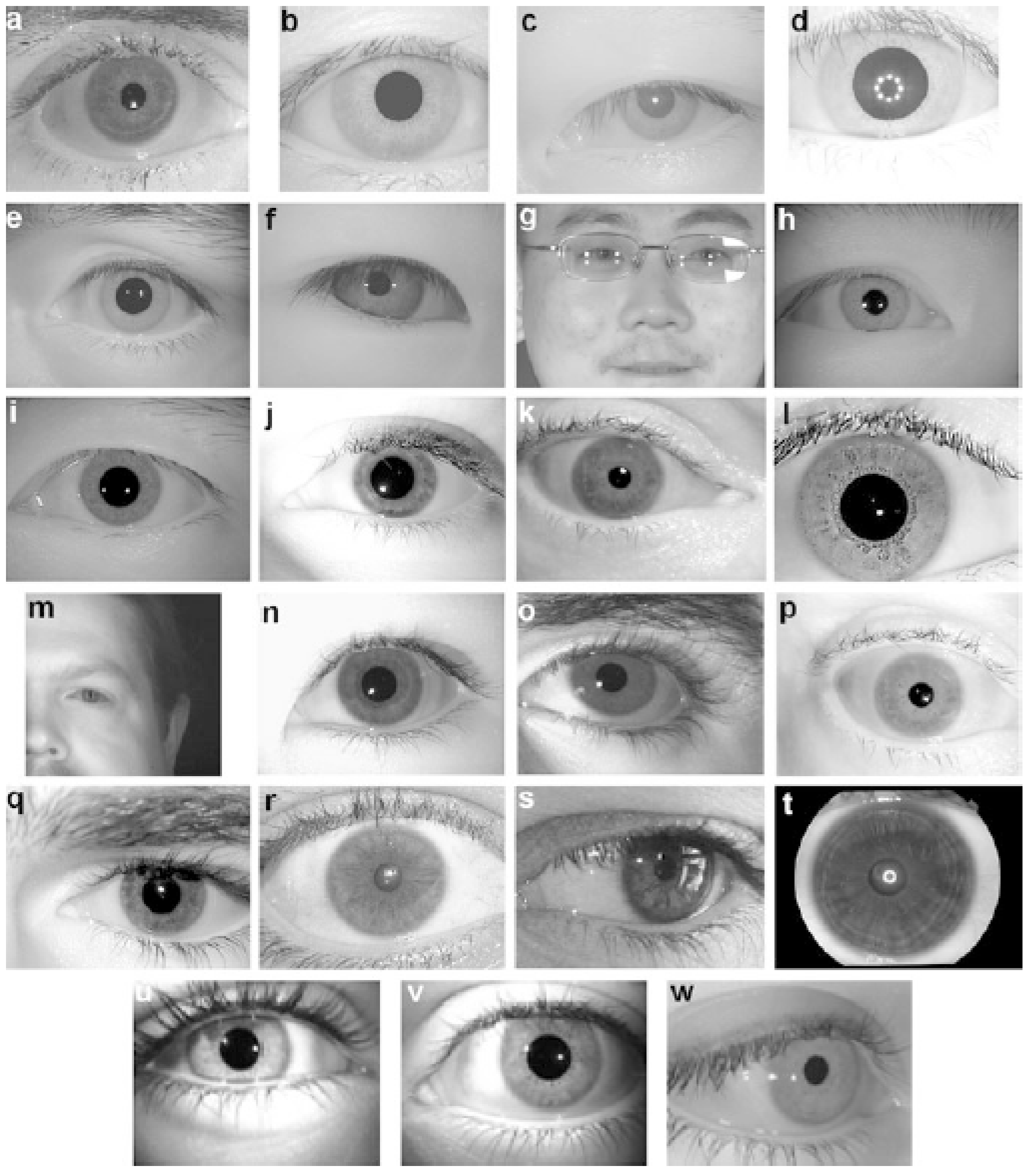

Fig. 4. Examples of real iris images acquired using cameras from the state of the art.

5.1 Iris Features

The iris has many features that can be used to distinguish one iris from another. One of the primary visible characteristic is the trabecular meshwork. It is a tissue that gives the appearance of dividing the iris in a radial form. The trabecular meshwork is permanently formed by the eighth month of gestation. During the development of the iris, there is not genetic influence on it, a process known as “chaotic morphogenesis that occurs during the seventh month of gestation, which means that even identical twins have differing irises”.

The textural details are uncorrelated and independent even in genetically identical pairs [Daugman, 1998]. The Iris has in excess of 266 degrees of freedom, and that means, the number of variations in the iris that allow one iris to be distinguished from another [Daugman, 1993], [Wildes, 1997].

The extensive trabecular meshwork develop the number of variations in the iris texture, and this characteristic is the key to differentiate an eye of the other one, in oneself person and also between differents peoples. That characteristic texture should be described quantitatively by means of some mathematical method that captures the texture variations among iris regions, and it is well-known as Iris features.

6 Iris Preprocessing Methods

A captured iris image contains not only the region of interest (iris) but also some 'unuseful' parts (e.g. eyelid, eyelashes, sclera, pupil, noises, etc.). So, the image cannot be used directly in an automatic iris recognition system of persons. In addition, a change in the camera-to-face distance may result in the possible variation in the size of the same iris. Furthermore, the brightness may be not uniformly distributed caused by a non-uniform illumination [Ma et al., 2002].

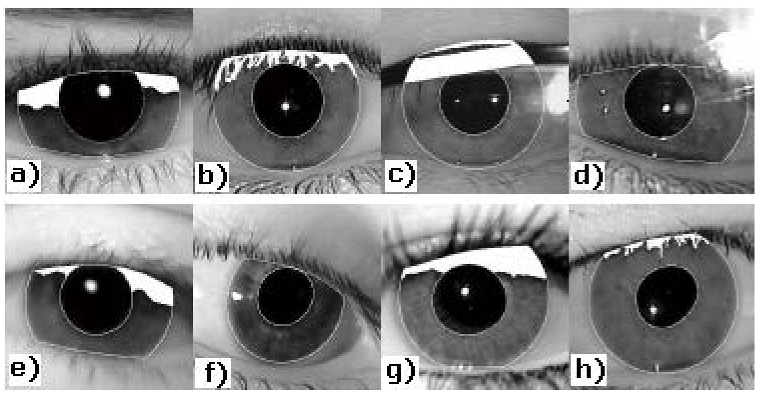

Fig. 5. a) Iris images with severe eyelid occlusion; b) Eyelash occlusion; c) Glass frame occlusion; d) Specular reflections; e) Defocusing; f) Off-axis view angle; g) Motion ghost and; h) Pupil deformation. [He et al., 2009].

Problems related to reflections and occlusions are particularly relevant (see Fig. 5). In many situations, in fact, the iris texture is not completely visible because the eyelids cover a portion of the region of interest (a). Eyelids and eyelashes are often present in the input image and can occlude big regions the iris (b). The presence of glass frame produce a severe occlusion on the iris texture (c). Moreover, since the eye is a wet convex surface, reflections can occur due to the presence of environmental light sources (d). Other important problems are related to the size variability of the same iris in different images like defocusing (e), the off-axis gaze situations with respect to the view angle of camera (f), motion ghost due to the natural movement of the eye (g) and pupil deformation due to any other cause (h). The examples were taken from paper of [He et al., 2009]. A probable situation is that several of these interferences be presented at the same time.

For the recognition purpose, the original image needs to be preprocessed to localize iris, normalize iris, and reduce the influence of the factors mentioned above (see Fig 6.).

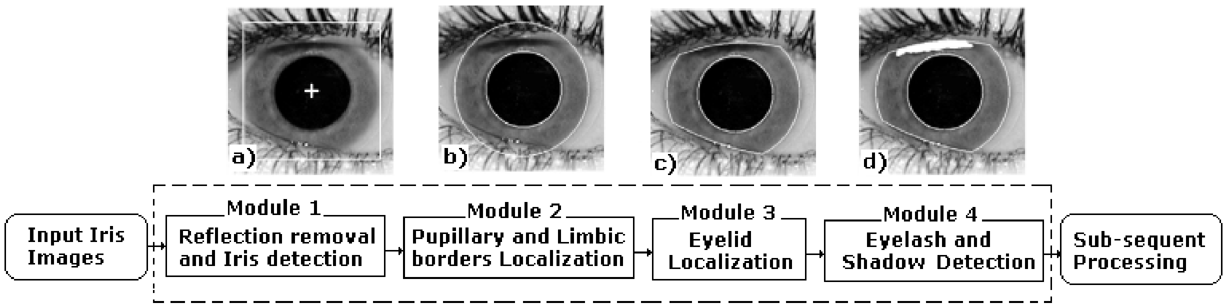

Fig. 6. The flowchart of the proposed iris preprocessing algorithm to iris image denoising and segmentation [He et al., 2009]. Four modules are namely, 1) Reflection removal and iris detection, 2) Pupillary and limbic boundary localization, 2) Eyelid localization, and 4) Eyelash and shadow detection. The images a), b), c) and d) are their results respectively.

Traditional iris segmentation methods often involve an exhaustive search of a large parameter space, which is time consuming and sensitive to noise. To address these problems, this paper presents a novel algorithm for accurate and fast iris segmentation. After reflection removal, an Adaboost-cascade iris detector is first built to extract a rough position of the iris center. Edge points of iris boundaries are then detected, and an elastic model named pulling and pushing is established. Under this model, the center and radius of the circular iris boundaries are iteratively refined in a way driven by the restoring forces of Hooke's law. Furthermore, a smoothing spline-based edge fitting scheme is presented to deal with noncircular iris boundaries. After that, eyelids are localized via edge detection followed by curve fitting. The novelty here is the adoption of a rank filter for noise elimination and a histogram filter for tackling the shape irregularity of eyelids. Finally, eyelashes and shadows are detected via a learned prediction model. This model provides an adaptive threshold for eyelash and shadow detection by analyzing the intensity distributions of different iris regions. He et al., [2009]

7 Iris Segmentation Methods

The iris segmentation methods are oriented toward isolation of the iris from an image. The Iris localization is related with finding the iris inner border and iris outer border with high precision because, both border determine the correct texture iris extension. Both, the inner boundary and the outer boundary of a typical iris can approximately be taken as circles. However, the two circles are usually not co-centric [Ma et al., 2002] [Cui et al., 2004]. Their correct delimitation is an important necessity.

A critical step of the recognition process is the segmentation of the iris texture in the input face/eye image. This process has to deal with the fact that the iris region of the eye is a relatively small area, wet and constantly in motion due to involuntary eye movements. Besides, eyelids, eyelashes and reflections are occlusions of the iris texture that can cause errors in the segmentation process. As a result, an incorrect segmentation can produce erroneous biometric recognitions and seriously reduce the final accuracy of the system [Donida et al., 2012].

To the problems related with the relatively small area of iris, the presence of wet, the motion constant of eyes due to involuntary movements, the eyelid occlusion, eyelash occlusion, glass frame occlusion and the pupil deformation; now is presented the necessity of extending the conditions of the iris recognition systems to: at distance and also in unconstrained conditions using natural light in outdoor ambient. The captured iris image may be have the presence of specular light reflections, defocusing, off-axis view angle in the iris image, and motion ghost on the eyes (Fig. 7).

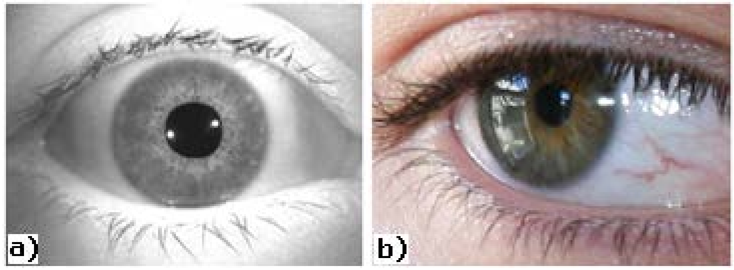

Fig. 7. Comparison between iris images captured in constrained and unconstrained conditions. a) An image captured in constrained conditions using infrared light; b) An image captured in unconstrained conditions using natural light. The image b) present problems related to reflections, occlusions and off-axis gaze at the same time. Taken from [Donidas et al., 2012].

In a recent published technical report by us [Sanchez-Gonzalez et al ,2014] we review the main research developed for iris texture segmentation and its progress in the last years, we also discuss the most recent results as well as the challenges associated with the iris segmentation process. Furthermore, we analyze methods used to refine and eliminate noise (reflections, occlusions, etc.), causing difficulties in the segmentation process. In general, the aim of this report was to provide an overview of the progress made in iris segmentation

A series of iris segmentation algorithms were discussed in this report. From this discussion, it is clear that (a) iris segmentation is a major problem in the process of iris recognition, (b) a substantial effort has been invested by researchers in solving the problem of iris segmentation under different scenarios: indoor and outdoor: from controlled to uncontrolled conditions; different kind of illumination: from NIR to visible lighting appearing news negative effects; in static and movement conditions, (c) the development of an iris segmentation algorithm depends on a number of image characteristics, such as intrinsic image resolution, degree of iris occlusion, (d) computational demands of different iris segmentation algorithms can vary considerably from one to other real application, and (e) evaluation of the output of an iris segmentation routine and combining the outputs of multiple methods of iris segmentation are ongoing activities in the field of iris biometrics.

8 Iris Normalization Methods

Once isolated the iris region, the next step is to describe the features of the iris in a way that facilitates comparison of irises. The first difficulty lies in the fact that not all images of an iris are the same size. The distance from the camera affects the size of the iris in the image. Also, changes in illumination can cause the iris to dilate or contract. This problem was addressed by mapping the extracted iris region into a normalized coordinate system. To accomplish this normalization, every location on the iris image was defined by two coordinates, (i) an angle between 0 and 360 degrees, and (ii) a radial coordinate that ranges between 0 and 1 regardless of the overall size of the image. This normalization assumes that the iris stretches linearly when the pupil dilates and contracts. A paper by [Wyatt, 2000] explains that this assumption is a good approximation, but it does not perfectly match the actual deformation of an iris.

A taxonomy of iris normalization methods is shown in Table 2.

Table 2. Iris normalization methods more widely used.

Methods	***References***
1. Pseudo-Polar coordinates	[Daugman, 1992]
2. Wildes iris normalization method	[Wildes, 1997]
3. Iris five parameter deformable model.	[Ivins et al, 1997]
4. Wyatt;s Meshwork for the Iris	[Wyatt, 2000]
5. Non-linear Normalization Model	[Yuan and Shi, 2005]

8.1 Pseudo-polar Coordinates

In Daugman's normalization method, the deforming of the meshwork of the iris is modeled as the linear stretching of a homogenous 'rubber sheet'. Thus, each point in the iris is remapped in a 'double dimensionless projected polar coordinate system' [Daugman, 1992] [Daugman, 2004] with:

$$I\big(x(r,\Theta), y(r,\Theta)\big) \rightarrow I(r,\Theta) \ . \qquad (1)$$

By this means, the annular iris region is unwrapped to a fix-sized rectangle block (shown in Fig. 8) regardless of pupillary change and overall iris image size. This iris normalization model is most frequently used by various researchers.

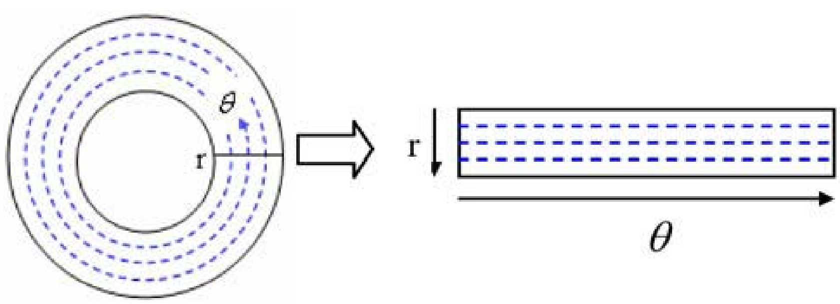

Fig. 8. Daugman's 'rubber-sheet' normalization method. The annular iris zone is 'stretched' to a rectangle block. The dashed lines are sampling circles.

Formally, the rubber sheet is a linear model that assigns to each pixel of the iris, regardless its size and pupillary dilate on, a pair of real coordinates (r, θ), where r is on the unit interval [0, 1] and θ is an angle in range [0, 2π]. The remapping of the iris image I(x, y) from raw Cartesian coordinates (x, y) to the dimensionless non concentric polar coordinate system (r, θ).

8.2 Wildes Iris Normalization Method

[Wildes,1997] applies an image-registration technique to geometrically warp a new iris image into alignment with a selected image in database. Thus, the iris scaling and rotation are compensated. The iris texture deformation caused by pupillary variation is also processed linearly in his method.

8.3 Other Methods

In order to analysis the binocular torsion, [Ivins et al,1997] introduces a five parameter deformable model that can translate (horizontal and vertical eye motion), rotate (torsion), and scale both uniformly and radially (pupil size changes). To normalize the iris pattern for iris-based recognition, this five-parameter deformable model is simplified in [Xing and Zheng, 2004].

[Wyatt, 2000], focuses on construction of a meshwork 'skeleton' that can minimize 'wear-and-tear' of iris when pupil size changes. His basic 'skeleton' is a double mesh of collagen 'fibers', which refer to the arcs inside the iris region of Fig. 2. It is a computational model that used to determine the optimal properties of such a mesh. The form of the fiber arcs was optimized across a set of pupil sizes by minimizing strain of the fibers, and constraining each point on a fiber to move only in the radial direction. A logarithmic spiral was used as an initial solution for optimization, and a twenty term polynomial was added to it.

In the viewpoint of physiology, pupil diameter may range from a minimum of about 1.5 mm to a maximum of over 7 mm due to the external variation, such as illumination. The iris is anchored to the globe at its 'root' (the outer circle of the iris), with an outer diameter of about 12 mm. In consequence, iris tissue may vary more than 5 times in circumferential extent (for tissue near the pupil).

Xiaoyan Yuan's work [Yuan and Shi, 2005] combines the linear and non-linear method to unwrap the iris region. First, non-linearly transform all iris image to a reference annular zone with a predefined λ, which is the ratio of the radii of inner and outer boundaries of the iris. Then linearly unwrap this reference annular zone to a fix-sized rectangle block for subsequence processing. This model still simplifies the real physiological mechanism of iris deformation for efficiency purpose in practical application and some assumptions and approximations are still needed to be made to support this model.

9 Iris Feature Extraction. A Taxonomy

In 1986 M. Alphonse Bertillon, a French anthropologist, proposed the use of iris patterns, particularly the color and shape, for the recognition persons [Yuan and Shi, 2005] In those remote times the discriminating iris features were extracted through the specialists observation, did not yet exist automatic methods. It was not until 1987 when the first patent [Flom and Safir, 1987] on the general concept of iris-based recognition appear and years later, in 1993, Daugman develop the most popular and commercial method [Daugman, 1993] in the early history of iris biometrics. Since then, growing interest has been shown in iris recognition and in recent years has been significantly increased, it has also achieved great progress in terms of effectiveness and efficiency of the methods. However, there is still much done to improvements performance and further the practical implementation of iris recognition systems under a variety of uncontrolled conditions.

In a recent published by us technical report [Chacon-Cabrera et al, 2014]. we review the main research developed for iris feature extraction. In this report we perform a critical analysis of current approaches involving this hot topic, both with their advantages and problems. We analize the main proposed features extraction methods and presented a taxonomic classification of these methods.

From this analysis we conluded that researches in feature extraction methods for Iris Recognition have been widely addressed to obtain techniques and algorithms for robust Iris Recognition over the last few years. However key and still open issue in Iris Recognition is how best to represent the iris texture information using a compact set of iris texture features. We reviewed many approaches regarding Iris Features Extraction Methods from the pioneering in Iris Recognition, Daugman's 2D Gabor and Wildes's Laplacian of Gaussian, up to algorithms for feature extraction in non-cooperative environment. We have identified two major approaches and new emerging trend: (1) Daugman's method, which is the most important work in the early history of iris biometrics. It is fair to say that iris biometrics as a field has been developed under the concepts of Daugman's approach which become a standard reference model. (2) The Ordinal Measures for Iris Recognition proposed by [Sun and Tan, 2009], not only because this novel method is more effective than existing algorithms, the results obtained from it provide a better explanation of how the best state of the art Iris recognition algorithms work effectively. An emerging and challenging area is Non-cooperative Iris Recognition, that can make Iris Recognition more friendly and flexible to use, this also we will allow its further use in video surveillance and multi-biometric systems.

10 Iris Matching Methods

Matching IrisCode is the used procedure to compare two irises. If the matching result is positive, means that the two IrisCodes satisfy an established threshold of differences between then, and therefore both irises belong to the "same" person. If the matching result operation is negative, means that both IrisCodes are very different between then, and therefore they belong to "different" individuals.

The central issue in texture iris recognition is the relation between "within-class variability" and "between-class variability". These are determined by the number of degrees-of-freedom (forms of variation) covered by the pattern classes. Ideally, the within-class variability should be small, and the between-class variability large, so that decisions about "same" versus "different" can easily and reliably be made. In the case of Iris biometric identification of persons, this basic principle implies that an optimal biometric measurement should have "maximal variation across individuals", but "minimal variation for any given person across time or conditions" [Daugman, 1998].

10.1 Independence of Bits Across IrisCodes

Theoretically is important to establish and to measure the amount of independent variation both within an iris and between different irises. There are correlations within an iris because local structure is self-predicting; for example, furrows tend to propagate themselves radially. Such self correlations limit the number of degrees of freedom within irises. But, even more important is the question of whether systematic correlations exist between different irises. This probability distribution (Fig. 9) suggests that they do not [Daugman, 1993].

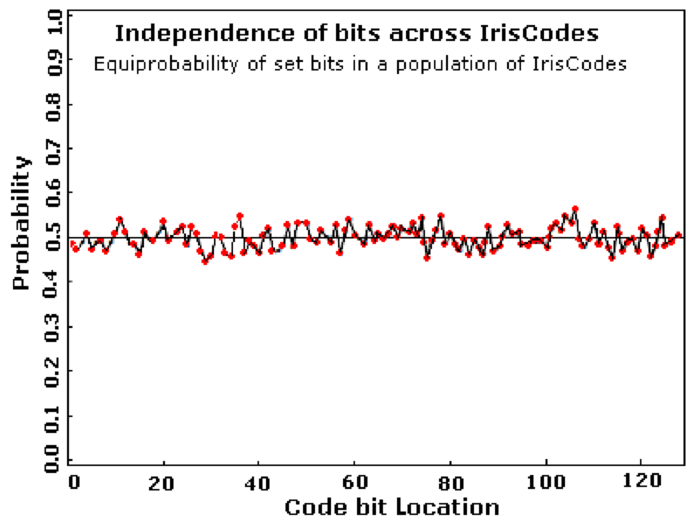

Fig. 9. The independence of bits across IrisCodes shown the equiprobability of set bit in a population of IrisCodes.

The curve plots the probability that bits in different positions within the IrisCode are set to 1, for a randomly sampled population of different IrisCodes. The fact that this distribution oscille near 0.5 indicates that all IrisCode bits are equally likely to be 0 or 1. This property makes that the IrisCodes codes the “maximum entropy” at a level of simple bits instead of wider unit of it dates (in to bitwise sense). The fact that this distribution is uniform indicates that different irises do not systematically share any common structure.

The recognition of persons by their IrisCodes is based at the failure of a test of statistical independence. Then, the independence of bits across IrisCodes, shown in Fig. 7, “illustrates why any given IrisCode is "statistically guaranteed" to pass a test of independence against any IrisCode computed from a different eye” [Daugman, 1993].

10.2 Measuring the Amount of Difference Between Two Codes

The comparison process of the extracted codes from the iris texture is the procedure to determine if two codes correspond to the same class or not, and it is the essence of people's recognition using iris modality.

The methodology to compares biometric codes imply the use of disimilarities measures and a decision threshold in order to determine if two codes are instances of the same class, which means that they also belong to the same biometric source [Daugman, 2001]. In iris recognition several distance measures have been used to identify similar patterns.

***Definition**: Two patterns are similar, if an appropriately defined distance measure between their feature vectors is small [Bolle et al., 2004]. In this sense, the following metrics (Table 3) have been designed for measuring the amount of difference between two IrisCode vectors in iris matching tamplate.*

Table 3. Measures more widely used for measuring the amount of difference between two IrisCode vectors.

Measures	**Description**	**Reference**
1. Hamming Distance	Measures the number of bits for which two iris codes disagree.	[Daugman, 1993]
2. Eucledean Distance	Metric for measuring the minimum distance between two IrisCode vectors and is therefore very fast.	[Ma et al., 2002]
3. Levenshtein Distance	Metric for measuring the minimum number of edits needed to transform one string into the other. Is an edit distance and use operations of insertion, deletions and substitutions of a single character.	[Shirke et al., 2012]
4. Series of comparison scores	New strategy for comparing IrisCode. Instead of optimally aligning two IrisCodes by maximizing the comparison score for several bit shifts, utilizes the total series of comparison scores, avoiding any information loss.	[Rathgeb et al., 2011a] [Rathgeb et al., 2011b]
5. Multimodal fusion of matching scores	Method for visible light iris image matching by using multiple characteristics of iris and eye images considering multibiometric combination of iris and periocular data based on global color-based features and local ordinal measures.	[Tan et al., 2011]

10.2.1 Hamming Distance

Hamming Distance (HD) as method to compare IrisCodes. The HD measures the fraction of bits for which two iris codes disagree. A low normalized HD implies strong similarity of the iris codes. If parts of the irises are occluded, the normalized HD is the fraction of bits that disagree in the areas that are not occluded on either image [Bowyer et al., 2008].

$$\mathrm{HD} = \frac{\|(\mathrm{codeA} \otimes \mathrm{codeB}) \cap \mathrm{maskA} \cap \mathrm{maskB}\|}{\|\mathrm{maskA} \cap \mathrm{maskB}\|} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{CodeA_i} \otimes \mathrm{CodeB_i} \,. \tag{2}$$

Where: $\otimes$, is the XOR operation.

codeA and codeB, are the input IrisCode and template IrisCode in database, respectively.

maskA and maskB, are the input mask and template mask, respectively.

In the case of rotation, the comparison between a pair of iris images involves computing the normalized HD for several different orientations that correspond to circular permutations of the code in the angular coordinate. The minimum computed normalized HD is assumed to correspond to the correct alignment of the two images [Bowyer et al., 2008].

The HD is employed for classification of iris templates and two templates is found to match if a test of statistical independence was failed.

10.2.2Levenshtein Distance

Levenshtein Distance (LD) as method to compare irisCodes. The LD is a measure of the variation between the IrisCode record for the current iris and the IrisCode records stored in the database. Each of the 2048 bits is compared against each other, i.e. bit 1 from the current IrisCode and bit 1 from the stored IrisCode record are compared, then bit 2 and so on. Any bits that don’t match are assigned a value of “1” and bits that do match a value of “0” [Shirke et al., 2012].

In information theory and computer science, the Levenshtein distance [Black, 2008] is a metric for measuring the amount of difference between two sequences (i.e. an edit distance). The term edit distance is often used to refer specifically to Levenshtein distance.

The Levenshtein distance between two strings is defined as the minimum number of edits needed to transform one string into the other, with the allowable edit operations being insertion, deletion, or substitution of a single character. It is named after Vladimir Levenshtein, who considered this distance in 1965.

For example, the Levenshtein distance between "kitten" and "sitting" is 3, since the following three edits change, one into the other, and there is no way to do it with fewer than three edits:

1. kitten → sitten (substitution of 's' for 'k')
2. sitten → sittin (substitution of 'i' for 'e')
3. sittin → sitting (insertion of 'g' at the end).

10.2.3Euclidean Distance

In mathematics, the Euclidean distance or Euclidean metric is the "ordinary" distance between two points that one would measure with a ruler, and is given by the Pythagorean formula. By using this formula as distance, Euclidean space (or even any inner product space) becomes a metric space. The associated norm is called the Euclidean norm. Older literature refers to the metric as Pythagorean metric [Black, 2004]

The Euclidean distance between points p and q is the length of the line segment connecting them (pq).

In Cartesian coordinates, if p=(p1, p2,...,pn) and q = (q1, q2,..., qn) are two points in Euclidean n-space, then the distance from p to q, or from q to p is given by:

$$d(p,q) = d(q,p) = \sqrt{(q1-p1)^2 + (q2-p2)^2} + \cdots + (qn-pn)^2 = \sqrt{\textstyle\sum_{i=1}^{n}(qi-pi)^2}\ . \qquad (3)$$

10.2.4Series of Comparison Scores

In [Rathgeb et al., 2011a] and [Rathgeb et al., 2011b] a new strategy for comparing binary biometric templates, in particular iris-codes, is presented. Instead of optimally aligning two iris-codes by maximizing the comparison score for several bit shifts utilizes the total series of comparison scores, avoiding any information loss. The soundness of the approach, which requires marginal additional computational effort, is confirmed by experiments applying two different iris-biometric feature extraction algorithms.

The presented comparison technique utilizes the total series comparison scores which are estimated at the time of template alignment, i.e. information loss is avoided.

At the time of authentication the deviation of comparison scores to the corresponding Gaussian (estimated at training stage) is measured at different shifting positions. For this purpose the function GaussFit is defined, which calculates the quadratic error of the comparison score between two iris

codes codeA and codeB at a distinct shifting position k to a Gaussian G.

The proposed comparator additionally tracks improvements of comparison scores towards the estimation of an optimal alignment, which is likely for genuine comparisons. On the other hand. The presented approach is expected to increase dissimilar- ity between pairs of iris-codes extracted from different subject where Gaussian progressions in comparison scores are rather unlikely.

The problem is that the proposed technique requires additional computational effort over others state of the art comparators.

10.2.5Multimodal Fusion of Matching Scores

Tan et al [Tan et al., 2011] proposed an effective method for visible light iris image matching by using multiple characteristics of iris and eye images. The method consists of image preprocessing, iris data matching, eye data matching, and multimodal fusion. Ordinal measures and color analysis are adopted for iris data matching, and texton representation and semantic information are used for eye data matching. After they obtain the four matching scores, a robust score level fusion strategy is applied to generate the dissimilarity measure of the two images under consideration.

They described four types of feature extraction and matching strategies respectively. These features can be seen as four biometric patterns. They play different roles in classification and have different performances. They employed an improved score level fusion strategy to combine the four matching scores. Score normalization was necessary before score level fusion, because the individual matching scores may not be homogeneous. The first step of the score level fusion is to normalize different matching scores into the same order of magnitude. They normalized the four matching scores achieved by different features into [0, 1], where ‘‘1’’ means totally different and ‘‘0’’ exactly the same. The min–max method was adopted as the normalization rule due to its easy implementation and satisfactory performance. In this work the maximum and minimum values used for each modality were experimentally determined. The matching score can indicate the degree of confidence about two irises belonging to the same class. These four matching scores generated from ordinal measures, color analysis, texton representation and semantic information are denoted by *So, Sc, St, Ss* respectively,

where *So, Sc, St* are normalized into [0,1] and *Ss* is 0 or 1.

Without changing the distribution of matching scores, they select the weighted sum rule to fuse the four matching scores. The weights are learned from the training dataset via a simple exhaustive search method. The fused matching score is defined as follows:

$$S = \omega 1 So + \omega 2 St + \omega 3 St\ . \tag{4}$$

where ωi, i = 1, 2, 3 are the weights of the three matching scores.

10.3 Statistical Decision Criteria Based Threshold

The statistical decision theory is the baseline to determine the threshold criterion between authentics and impostors users in biometric technologies. The definition of the threshold criterion determines the accuracy of the comparison module in any biometric system.

In the context of the biometric decision can happen four different answers denominated False Acceptance (FA), Correct Acceptance (CA), False Rejection (FR) and Correct Rejection (CR). The first one and the third are considered errors of the system.

The manipulation of the decision rule allows the relative probabilities of the answers to be adjusted. It’s selection depends on the interests of the situation: in the case of product users it is pretend that the probability of false rejection will be less than the false acceptance, when in the case of security otherwise is pretended

The analysis of the decision environment (Decision Landscape) are responsible for assessing the degree of change that the improvement in the likelihood of a response may produces the worsening in the other.

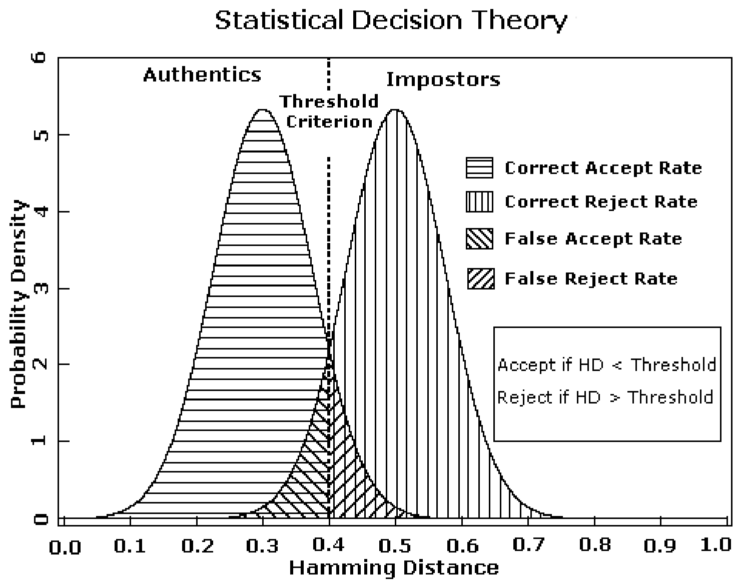

Fig. 10. Desicion criteria selection used in biometrics. [Daugman, 2001].

In Figure 10 is observed as the decision environment analysis presented two distributions associated with the states of the universe of decision that are not well separated. The abscissa of the graph is any dissimilarity measure, in this case the Hamming distance is illustrated. The decision criterion is determined by the vertical dashed line. In this case codes dissimilarities less than 0.4 are considered to belong to the same class and and those over 0.4 belong to different classes..

11 Performance Evaluation Measures for Biometric Systems

Decision errors in biometric verification or identification are due to various types of errors occurred in each process of a biometric system: sample acquisition, feature extraction, and comparison. How these fundamental errors combine to form decision errors depends upon various factors such as the number of comparisons required, either positive or negative claim of identity, and the decision policy, for example, whether the system allows multiple attempts (comparison).

Biometric performance testing focuses on the evaluation of technical performance considering these various types of errors rates of biometric algorithms or systems. The expression “performance evaluation measures” is sinonyn of “performance metrics”.

***Definition**: Performance evaluation assesses accuracy and usability of biometric algorithms or systems. Performance measures are computed for verification, identification, and other list tasks, in order to either; a) discover the state-of-the-art of biometric technologies, or b) quantify how well a biometric system execute the requirements of specific applications. Evaluation protocols and biometric databases for testing should be carefully designed to avoid influenced results or conclusions [Shan et al., 2009].*

Performance estimation is a key issue in the comparison of biometrics system for usage in large scale secure access technology. The challenge consist in to develop and to apply indices that can provide measures for security, reliability, confidentiality in relation to the biometric information content [Bolle et al., 2004], [Wayman et al., 2005].

Performance measures in biometrics define quantifiable assessments of the processing speed, recognition accuracy, and other functional characteristics of a biometric algorithm or system [Jang and Kim, 2009]:

1. System processing speed: The system processing speed is evaluated by performance rate which represents the number of users that can be processed per unit time.
2. System recognition accuracy: The typical metrics for system recognition accuracy are the rates of failure-to-enroll, failure-to-acquire, false match, false nonmatch, false reject, and false accept.
3. Other system functional characteristics: In addition to obove fundamental performance measures, there are other measures which are specifically dependent on applications (verification, open-set identification, or closed-set identification), such as false-negative and false-positive identification error rates. Also, graphic measures such as DET curve (detection error trade-off), ROC curve (receiver operating characteristic), and CMC curve (cumulative match characteristic) are very efficient tools to present overall matching performance of biometric algorithms or systems.

Performance in biometric identification is determined by two kinds of variability among the acquired biometric templates: 1) within-Subject variability, which sets a minimum False Reject Rate; and 2) between-Subject variability, whose lower limit sets a minimum False Match or False Accept Rate. Clearly, it is desirable for a biometric to have maximal between-Subject variability but minimal within-Subject variability [Daugman, 1998].

A taxonomy of performance metrics for biometrics systems is shown in Table 4. The error rates include both false-positive and false-negative decisions as well as failure-to-enroll and failure-to-acquire rates across the test population. Performance rates refer to the number of users processed per unit time, based on both computational speed and human–machine interaction. These measures are defined to be applicable to all biometric systems and devices, of course including iris recognition.

Table 4. Performance measures to all biometrics systems and worldwide accepted.

Measures	Abbreviation	Reference
I. Fundamental performance measures		
1. Failure To Enroll rate	FTE	[ISO/IEC 19795-1]; http://biometrics.derawi.com/?page_id=51
2. Failure To Acquire rate	FTA	[ISO/IEC 19795-1]; http://biometrics.derawi.com/?page_id=51,
3. False Match Rate or False Accept Rate	FMR, FAR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
3. False NonMatch Rate or False Reject Rate	FNMR, FRR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
II. Performance measures for verification system		
1. False Accept Rate	FAR	http://www.javvin.com/networksecurity/FAR.html
2. False Reject Rate	FRR	http://www.javvin.com/networksecurity/FRR.html
3. Generalized False Accept Rate	GFRR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
4. Generalized False Reject Rate	GFAR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
5. Template Capacity	TC	http://en.wikipedia.org/wiki/Biometrics
6. System Error	SE	http://nice1.di.ubi.pt/
7. Success Rate	SR	[Werner, 2013]
8. Decidability Index	d′	http://nice2.di.ubi.pt/
III. Performance measures for identification system		
1. Correct Identification Rate	CIR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
2. False Negative Identification-error Rate	FNIR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
3. False Positive Identification-error Rate	FPIR	[ISO/IEC 19795-1]; [Jang and Kim, 2009]
IV. Graphic performance measures		
1. Receiver Operating Characteristic	ROC curve	http://en.wikipedia.org/wiki/Biometrics, [Jang and Kim, 2009]
2. Detection Error Trade-off	DET curve	[Jang and Kim, 2009]
3. Cumulative Match Characteristic	CMC curve	[Jang and Kim, 2009]
V. Other performance measures [Jang and Kim, 2009]		
1. Genuine Score Distribution and Impostor score distribution are computed and graphically reported to show how the algorithm ‘‘separates’’ the two clases.		
2. EER: equal error rate (see ROC curve).		
3. EER^* is a particular case of EER (see ROC curve).		
4. FMR100 is the lowest FNMR for FMR $\leq 1\%$.		
5. FMR1000 is the lowest FNMR for FMR $\leq 0.1\%$.		
6. ZeroFMR is the lowest FNMR at which no False Matches occur.		
7. ZeroFNMR is the lowest FMR at which no False NonMatches occur.		
8. Average Enroll Time (AET) is the average CPU time for a single enrollment operation.		
9. Average Match Time (AMT) is the average CPU time for a single match operation between a template and a test sample.		

11.1 Fundamental Performance Measures

The following measures are considered to be fundamental because they can be employed independently of the types of applications of biometric systems. The failure-to-enroll and failure-to-acquire rates measure the performance of the feature extracting component, while the false match and false nonmatch rates measure that of the matching component [Jang and Kim, 2009].

11.1.1Failure to Enroll Rate

***Definition**: Failure to enroll rate (FTE) is the proportion of the population for whom the system fails to complete the enrolment process [Jang and Kim, 2009].*

Expressed with other words, FTE is the rate at which attempts to create and store an enrollment iris data record (template) from an input is unsuccessful [http://biometrics.derawi.com/?page_id=51].

FTE is the proportion (rate) of biometric enrollment transactions considering only fail caused for biometric reasons. The FTE measures the percentage of data input which is considered invalid and fails to input into the system, in accordance with an enrolment procedure (policy).

$$\mathrm{FTE} = \mathrm{NEP}/\mathrm{TNEP}\,. \tag{5}$$

Where:

NEP, is the number of persons wich fails to complete enrollment by the system.

TNEP, is the total number of persons to be enrolled by the system.

Failure to enroll happens when the data obtained by the sensor are considered invalid or of poor quality [Balakrishnan, 2011]. By this rason FTE is most commonly caused by low quality inputs. Particularly, FTE increases when the biometric features on the person are not good enough to be extracted and create a biometric feature.

The failure-to-enroll also occurs when the user cannot present the required biometric characteristic, or when the submitted biometric sample is of unacceptably bad quality. In the latter case, stricter requirements on sample quality at enrollment will increase the failure-to-enroll rate, but improve matching performance because the failure-to-enroll cases do not contribute to the failure-to-acquire rate, or matching error rates [Jang and Kim, 2009].

11.1.2Failure to Acquire Rate

***Definition**: Failure To Acquire rate (FTA) is the proportion of verification or identification comparison for which the system fails to capture, or locate biometric samples of sufficient quality [Jang and Kim, 2009].*

$$\mathrm{FTA} = \mathrm{NCF}/\mathrm{TNC}\,. \tag{6}$$

Where:

NCF, is the number of comparison failed to complete verification or identification by the system.

TNC, is the total number of comparison (or attempts) to be verified or identified by the system.

The FTA case occurs when the required biometric characteristic (iris pattern) cannot be presented due to temporary illness or lesion (hurt) during the acquired sample, or the extracted features do not satisfy the quality requirements for the recognition. In the latter case, stricter requirements on sample quality at acquisition will increase the failure-to-acquire rate but improve matching performance, because the failure-to-acquire cases are not included in calculating the false match and nonmatch rates.

The FTA is related to the probability that the device capturing biometric data is not able to capture the required information, or due to the failure of any biometric process (segmentation, feature extraction, encoding) to produce a biometric description acceptable for recognition.

11.1.3 False Match Rate, or False Accept Rate

***Definition**: False Match Rate (FMR) is the proportion of zero-effort impostor attempt samples falsely declared to match the compared nonself template [Jang and Kim, 2009].*

***Definition**: False Accept Rate (FAR) is the proportion that the system incorrectly matches the input pattern (IrisCode) and a non-matching pattern in the database. It measures the percent of inputs which are incorrectly accepted.*

The FAR is the measure of the likelihood that the biometric security system will incorrectly accept an access attempt by an unauthorized user [Chang et al, 2011]. A system's FAR typically is defined as the ratio of the number of false acceptances divided by the number of identification attempts.

$$\mathrm{FMR} = \mathrm{FAR} = \frac{\mathrm{NIA}}{\mathrm{TNI}}. \tag{7}$$

Where:

NIA, is the number of impostors accepted by the system, or number of unauthorized persons being identified as an authorized persons.

TNI, is the total number of impostors attempting to breach the system contained in the database.

For example, if the $\mathrm{FAR} = 0.1\%$, it means that on the average, one out of every 1000 impostors attempting to breach the system will be successful. Said otherwise, it means that the probability of an unauthorized person being identified as an authorized person is 0.1%.

The false match and false nonmatch rates are determined by the same decision threshold value on similarity scores. By adjusting the decision threshold, there will be a trade-off between false match and false nonmatch errors. They are calculated with the number of comparisons (or attempts) and useful for evaluating the performance of a component algorithm [Jang and Kim, 2009].

Likewise, the measure Correct Reject Rate, $\mathrm{CRR} = 1 - \mathrm{FAR} = 1 - \mathrm{FMR}$ is the probability that the system correctly non-matches the input pattern (IrisCode) to a non-matching template in the database. It measures the percent of non-valid inputs which are correctly rejected.

For example, if the $\mathrm{CAR} = 99.25\%$, it means that on the average, 1985 out of every 2000 nonauthorized persons attempting to access the system will be not recognized by that system.

11.1.4 False Non-match Rate, or False Reject Rate

***Definition:** False Non-Match Rate (FNMR) is the proportion of genuine samples falsely declared not to match the template of the same characteristic from the same user submitting the sample [Jang and Kim, 2009].*

***Definition**: False Reject Rate (FRR) is the proportion that the system fails to detect a match between the input pattern (IrisCode) and a matching pattern in the database. It measures the percent of valid inputs which are incorrectly rejected.*

The probability that the system incorrectly declares failure of match between the input pattern and the matching template in the database is measured by the percent of valid inputs being rejected. This happens in some of the biometric authentication technique as it will give a negative result when the log is generated as the image it has authenticated is different which will be considered as a negative parameter [Balakrishnan ,2011].

$$\mathrm{FNMR} = \mathrm{FRR} = \frac{\mathrm{NAP}}{\mathrm{TNAP}}. \tag{8}$$

Where:

NAP, is the number of authorized persons identified by the system.
TNAP, is the total number of authorized persons contained in the data base.

False rejection, also called a type I error, is a mistake occasionally made by biometric security systems. In an instance of false rejection, the system fails to recognize an authorized person and rejects that person as an impostor [Yoshimura, 2011].

For example, if the $\mathrm{FRR} = 0.05\%$, it means that on the average, one out of every 2000 authorized persons attempting to access the system will not be recognized by that system.

The false-match and false-nonmatch rates are determined by the same decision threshold value on similarity scores. By adjusting the decision threshold, there will be a trade-off between false-match and false-nonmatch errors. They are calculated with the number of comparisons (or attempts) and useful for evaluating the performance of a component algorithm [Jang and Kim, 2009].

11.2 Performance Measures for Verification System

Verification is one of the two major applications of biometrics, where the user makes a positive claim to an identity, features extracted from the submitted biometric sample are compared with the enrolled templates for the claimed identity, and an accept- or reject decision regarding the identity claim is returned. In evaluating the performance of biometric systems, the unit operation is a transaction, which can be a single attempt but mostly consists of multiple attempts. In this aspect, the fundamental measures, FMR and FNMR, cannot be directly applied to the overall performance evaluation of a biometric system, and the following metrics are designed for more general measures.

11.2.1 False Reject Rate

Definition*: False Reject Rate (FRR) is the proportion of verification transactions with truthful claims of identity that are incorrectly denied. When a transaction consists of a single attempt, a false rejection includes a failure-to-acquire or a false nonmatch, and the false reject rate is given by [Jang and Kim, 2009]:*

$$\mathrm{FRR} = \mathrm{FTA} + \mathrm{FNMR} * (1 - \mathrm{FTA})\ . \tag{9}$$

Where:

FNMR, is the false nonmatch rate.
FTA, is the failure-to-acquire rate.

11.2.2 False Accept Rate

Definition*: False Accept Rate (FAR) is the proportion of verification transactions with zero-effort wrongful claims of identity that are incorrectly confirmed. When a transaction consists of a single attempt, a false acceptance requires a false match with no failure-to-acquire, and the false accept rate is given by [Jang and Kim, 2009]:*

$$\mathrm{FAR} = \mathrm{FMR} * (1 - \mathrm{FTA})\ . \tag{10}$$

Where:

FMR, is the false match rate.
FTA, is the failure-to-acquire rate.

A first order estimation of FRR and FAR for transactions of multiple attempts can be derived from the detection error trade-off curve. However, such estimates cannot take into account correlations in sequential attempts and in the comparisons involving the same user, and consequently can be quite inaccurate.

Therefore, ISO/IEC 19795 recommends that these performance metrics shall be derived directly, using test transactions with multiple attempts as specified by the decision policy.

FRR and FAR do not include the failures occurred in enrollment. As mentioned earlier, increasing the FTE rate generally improves matching performance. For comparing the performance of biometric systems having different failure-to-enroll rates, both FRR and FAR need to be generalized so that they can take enrollment errors into account.

11.2.3 Generalized False Reject Rate

***Definition**: Generalized False Reject Rate (GFRR) is the proportion of genuine users who cannot be enrolled, whose sample is submitted but cannot be acquired, or who are enrolled, samples acquired, but are falsely rejected [Jang and Kim, 2009]:*

$$\mathrm{GFRR} = \mathrm{FTE} + (1 - \mathrm{FTE}) * \mathrm{FRR}\,, \tag{11}$$

$$\mathrm{GFRR} = \mathrm{FTE} + (1 - \mathrm{FTE}) * \mathrm{FTA} + (1 - \mathrm{FTE}) * (1 - \mathrm{FTA}) * \mathrm{FMR}\,.$$

Where:

FTE, is the failure to enroll rate.	FRR, is the false reject rate.
FTA, is the failure-to-acquire rate.	FMR, is the false match rate.

11.2.4 Generalized False Accept Rate

***Definition**: Generalized False Accept Rate (GFAR) is the proportion of impostors who are enrolled, samples acquired, and falsely matched. [Jang and Kim, 2009]:*

$$\mathrm{GFAR} = (1 - \mathrm{FTE}) * \mathrm{FAR}, \tag{12}$$

$$\mathrm{GFAR} = (1 - \mathrm{FTE}) * (1 - \mathrm{FTA}) * \mathrm{FMR}\,.$$

Where:

FTE, is the failure to enroll rate.	FAR, is the false Accept rate.
FTA, is the failure-to-acquire rate.	FMR, is the false match rate.

11.2.5 Template Capacity

***Definition** : Template Capacity (TC) is the maximum number of sets of iris data which can be stored in the system [Balakrishnan, 2011].*

$$\mathrm{TC} = \max_{\mathrm{capacity}_{\mathrm{in}_{\mathrm{database}}}(|\text{sets of iris data strored}|)}\,. \tag{13}$$

11.2.6System Error

***Definition**: System Error (SE) is the error of an iris segmentation system, considering simultaneously the False Accept Rate, and the False Reject Rate (http://nice1.di.ubi.pt/).*

$$\mathrm{SE} = 0.5 * \mathrm{FAR} + 0.5 * \mathrm{FRR}\ . \tag{14}$$

In the extreme cases, when FAR = FRR = 0 =0 (there is not false accept rate, and also there is not false reject rate) then SE = 0 and the system will be ideal.This SE measure was used in the competition NICE.II and with the lowest SE values were ranking the participant iris segmentation algorithms.

11.2.7Success Rate

***Definition**: Success Rate (SR) is the value of an iris segmentation system, considering simultaneously the False Accept Rate and the False Reject Rate using the following relation [Werner, 2013].*

$$\mathrm{SR} = 1 - (\mathrm{FAR} + \mathrm{FRR})\ . \tag{15}$$

The success rate describes how good a biometric system makes their work considering simultaneously the FAR and the FRR which are the two more important errors of the system. In the extreme cases, when FAR = FRR = 0 (there is not false accept, and also there is not false reject) then SR = 1 and the iris recognition system will be ideal.

11.2.8Decidability Index

Discernability, decidability index, *d*-prime is widely known in the biometrics literature [Bolle et al., 2004], [Wayman et al., 2005].

***Definition**: The decidability index d' of the task of recognizing persons by their iris pattern is revelead by comparing the Hamming Distance (HD) distributions for "same irises" versus "different irises". The Decidability d' measures how well separated the two distribution are. The separation of the two distribution is very important because the recognition error are caused by their overlap. Then the Decidability d' is defined as [Daugman, 1999]:*

$$d' = \frac{|\mu_1 - \mu_2|}{\sqrt{(\sigma_1 + \sigma_2)/2}}\ . \tag{16}$$

Where:

μ_1 and μ_2: means values of the irises distributions 1 and 2.
σ_1 and σ_2: standard deviation values of the irises distributions 1 and 2.

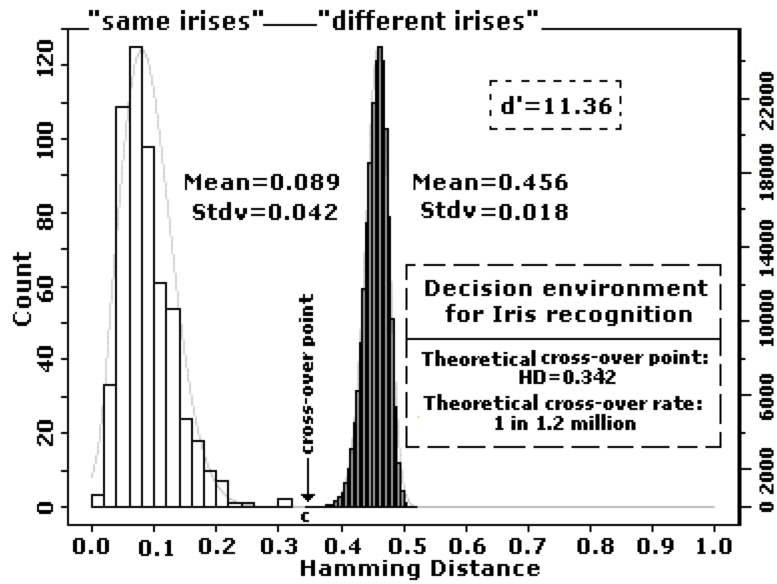

Fig. 11. Decision environment for personal identification based on iris pattern. Daugman reported his experiments (in 1999) with 340 comparisons of same iris pairs and 222,743 comparisons of different iris pairs.

The measure of decidability or detectability of the system is independent of the acceptance threshold used. The decidability reflects the degree to which any improvement in the False Accept Rate (FAR) must be paid for by worsening of the False Reject Rate (FRR). With his experiments, [Daugman, 1999] obtained for the measure $d' = 11.36$ for iris recognition, which is much higher than that reported for any other biometric modality from their corresponding dual histogram plots showing "sames versus differents" template comparison as in Fig. 11.

By calculating the areas under the curves fitted to the observed distributions of Hamming Distances, Daugman could compute the theoretical error rate as a function of the decision criterion employed. He used various HD as the acceptance threshold, and for each one, he calculated the "Probability of FAR" (false acceptance rate) and the "Probability of FRR" (false rejection rate) obtaining a count of irises in each case (Table 5). He found that, when $HD = 0.342$ the "Count of irisis" that generate the same probability for FAR and FRR is of 1 in 1.2 million for the fitted pair of distributions in Fig. 10. These value of HD is the theoretical cross-over rate for the iris system.

Table 5. Errors probabilities obtained for various Hamming Distance used as acceptance thresholds.

HD Decision Criterion	Probability of False Accepts	Probability of False Rejets
0.32	1 in 81 million	1 in 201 000
0.33	1 in 11.1 million	1 in 433 000
0.34	1 in 1.7 million	1 in 950 000
0.342 Cross-over point	**1 in 1.2 million**	**1 in 1.2 million**
0.35	1 in 295 000	1 in 2.12 million
0.36	1 in 57 000	1 in 4.84 million
0.37	1 in 12 300	1 in 11.3 million

Because the probabilities of False Accepts are so low even at rather high HD, as shown in the table above [Daugman, 1999], it is possible with this approach to perform exhaustive searches through very large databases for identification of a presenting iris pattern, rather than only a one-to-one comparison for verification. Additionally, to the degree that one can confidently decide whether an observed iris pattern belongs to the left or right distribution in Fig. 11, the iris recognition task can be successfully performed.

Nowadays, in the NICE.II web page (http://nice2.di.ubi.pt/) is possible to see the Decidability $\mathrm{d}' = 2{,}57;\ 1{,}82;\ 1{,}77;\ 1{,}63;\ 1{,}47;\ 1{,}25;\ 1{,}18;\ 1{,}09$ for the best eight iris matching algoritms at the 2010 international competition . These values of d' were obtained in a noise detection contest that operates on noisy data, resultant from less constrained image capturing conditions than Daugman images. The best decidability index obtained in NICE.II ($\mathrm{d}' = 2.57$) is faraway from that one $\mathrm{d}' = 11.36$ obtained by Daugman. This means that should even be made more work to improve the measure d' under the new less constrained image capturing conditions.

11.3 Performance Measures for Identification System

In the identification process, compared with the verification process, the user presents a biometric sample (iris pattern) without any claim of identity, and a candidate list of identifiers are returned as a result of matching the user's iris pattern features with all the enrolled templates in a database. Identification has two cases: a) while the closed-set identification always returns a nonempty candidate list, assuming that all the users are enrolled in the database, and b) the open-set identification may return an empty candidate list because some potential users are not enrolled.

11.3.1 Correct Identification Rate

Definition*: Correct Identification Rate (CIR) is the probability that the system correctly matches the input pattern (IrisCode) to a pattern (template) in the database. It measures the percent of valid inputs which are correctly accepted.*

CIR is an other important specification in any biometric system. The CIR is defined as the percentage of identification instances in which true admision occurs. This can be expressed as a probability.

$$\mathrm{CIR} = 1 - \mathrm{FRR}\,. \tag{17}$$

Where:

FRR, is the false reject rate.

For example, if the $\mathrm{CIR} = 0.99\%$, it means that on the average, 99 out of every 100 authorized persons attempting to access the system will be recognized by that system.

The identification rate at rank r is the probability that a transaction by a user enrolled in the system includes that user's true identifier within the top r matches returned. When a single point identification rank is reported, it should be referenced directly to the database size [Jang and Kim, 2009].

11.3.2 False Negative Identification-Error Rate

Definition*: False Negative Identification-error Rate (FNIR) is the proportion of identification transactions by users enrolled in the system, in which the user's correct identifier is not among those returned [Jang and Kim, 2009].*

$$\mathrm{FNIR} = \mathrm{FTA} + (1 - \mathrm{FTA}) * \mathrm{FNMR}\,. \tag{18}$$

Where:

FTA, is the failure to acquire rate. FNMR, is the false non-match rate.

11.3.3False PositiveIidentification-Error Rate

***Definition**: False Positive Identification-error Rate (FPIR) is the proportion of identification transactions by users not enrolled in the system, where a nonempty list of identifiers is returned. For a template database of the size N, FPIR is given as [Jang and Kim, 2009]:*

$$FPIR = (1 - FTA) * \{1 - (1 - FMR)^N\}. \tag{19}$$

Where:

FTA, is the failure to acquire rate. FMR, is the false match rate.

11.4 Graphic Performance Measures

11.4.1ROC Curve

***Definition**: The Receiver Operating Characteristic (ROC) curve, or Relative Operating Characteristic curve is a visual characterization of the trade-off (results) between the FAR and the FRR (Fig. 12). ROC or DET curves is used because how FAR and FRR measures can be changed, such change is shown clearly.*

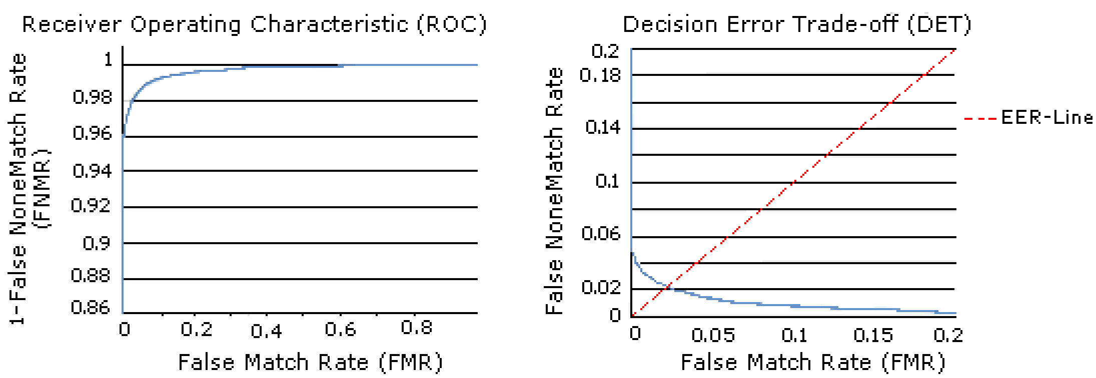

Fig. 12. The ROC and DET curves (http://biometrics.derawi.com/?page_id=51).

ROC curves are a traditional method for summarizing the performance of imperfect diagnostic, detection, and pattern-matching systems. ROC curves are threshold independent, allowing performance comparison of different systems under similar conditions, or of a single system under differing conditions. ROC curves may be used to plot matching algorithm performance (1-FNMR against FMR), end-to-end verification system performance (1-FRR against FAR), as well as open-set identification system performance (CIR against FPIR) [Jang and Kim, 2009].

In general, the matching algorithm performs a decision based on a threshold which determines how close to a template (authentic IrisCode) the input needs to be, for it to be considered a match. If the threshold is reduced, there will be less false non-matches but more false accepts. Correspondingly, a higher threshold will reduce the FAR but increase the FRR. A common variation is the Detection Error Trade-off (DET) (Fig. 12, right), which is obtained using normal deviate scales on both axes. This more linear graph clarify the differences for higher performances (rarer errors).

There is a small difference between DET curve and ROC curve. If assuming that the false accept rate (FAR) = False Match Rate (FMR) and False Reject Rate (FRR) = False None Match Rate (FNMR), then the only difference is a change in the y-axis that applies (1 – FNMR) instead of FNMR (for DET curve).

The next is to decide which threshold one should use. This depends heavily on the application. For Example, if one wants a high security application, then one should use as low FMR (or FAR) value as possible in order to reject impostors accessing the system. As well, there are forensic application which works with negative recognition (FAR = FNMR and FRR = FMR), where it is acceptable to have a higher FMR in order to catch the criminal. But most civilian applications are in somewhere in between the two mentioned.

The next definition looks toward the so called Equal Error Rate (EER) point. This rate is a very common used rate, which is being used to compare different systems against each other, and briefly it gives an idea of how good a system it is. In DET curve (Fig. 13, right), one can observe how it is possible to read the EER. Simply draw an angle of 45 degree line from the (x,y) = (0,0).

Definition*: The Equal Error Rate (EER) is the location on ROC curve, where the false reject rate (FRR) and false accept rate (FAR) are the same (Fig. 13), or is computed as the point where FNMR=FMR. In practice, the matching score distributions are not continuous and a crossover point might not exist.*

The EER is a quick way to compare the precision (truthfulness) of two systems which have differents ROC curves. In general, the system with the lowest EER is the most precise (truthful) [Balakrishnan, 2011].

- EER^{*} is the value that EER would take if the matching failures were excluded from the computation of FMR and FNMR [Jang and Kim, 2009].

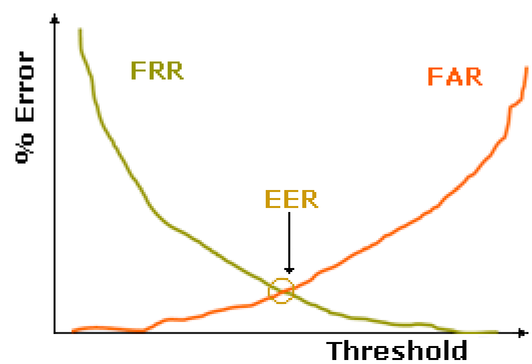

Fig. 13. The ROC curve is a characterization of the trade-off between the FAR and the FRR. [Sánchez-Ávila, 2013].

It is observed that, most operational systems are not set to operate at the "equal error rate", so the true usefulness of ROC curve is limited to comparing biometric system performance. When a quick comparison of two systems is required, the ERR is commonly used.

11.4.2 DET Curve

Definition*: Detection Error Trade-off or DET curve are used to plot matching error rates (FNMR against FMR), decision error rates (FRR against FAR), and open-set identification error rates (FNIR against FPIR) [Jang and Kim, 2009].*

The DET curve is a modified ROC curve which plots error rates on both axes (false positives on the x-axis and false negatives on the y-axis). For example, in Fig. 14 each DET curve is generated by varying the value of the decision threshold. If the threshold is set to a higher value in order to decrease the false acceptances, the false rejections will increase. On the contrary, if the threshold is set to a lower value, the false rejections will decrease with the increase in false acceptance [Jang and Kim, 2009].

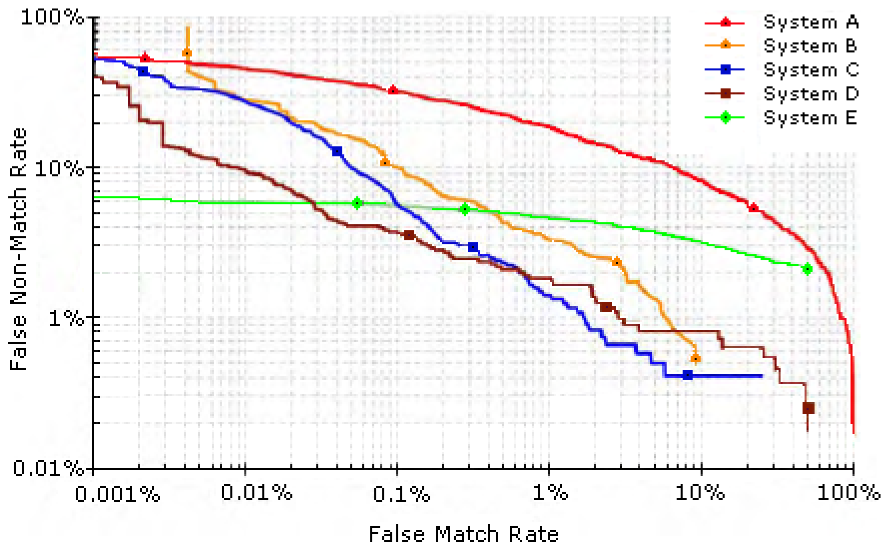

Fig. 14. Performance measures. Example set of DET curves [ISO/IEC JTC1/SC37 IS19795-1].

11.4.3 CMC Curve

Definition*: Cumulative Match Characteristic or CMC curve provide a graphical representation of identification test results and plots rank values on the x-axis with the corresponding probability of correct identification rate on the y-axis. The CMC curves are used for comparing the performance of a set of biometric identification systems [Jang and Kim, 2009]. Performance results of closed-set identification applications are often illustrated using CMC curves (Fig. 15).*

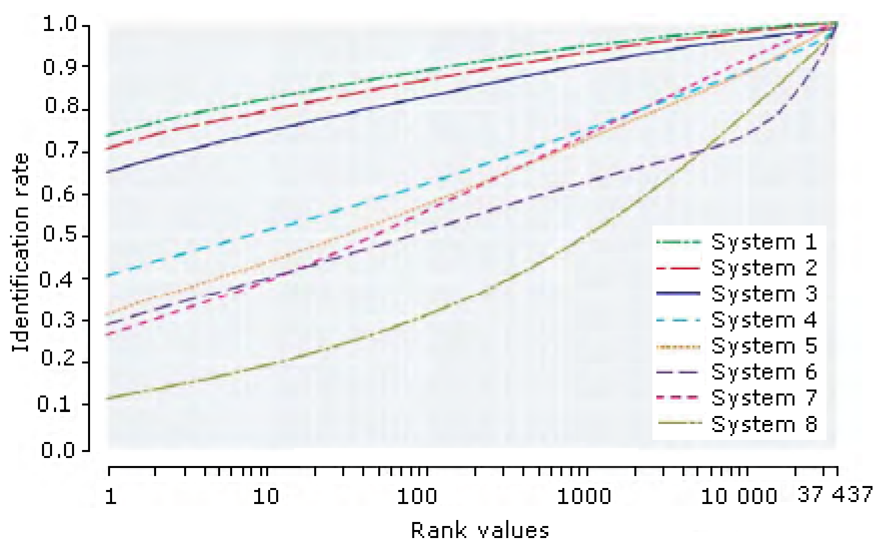

Fig. 15. Performance measures. Example set of CMC curves [Jang and Kim, 2009].

12 Iris Recognition Evualuation

In all biometric system is essential to make the process of evaluate its performance. This process of experimentation uses benchmark databases that allow comparison of their performance with other satate of the art systems. Another way to do this system evaluation once validated in the laboratory is the participation in international competitions convened by international organizations. There are competitions free of charge, usually held on benchmark databases containing different degrees of complexity allowing the evaluation of systems with different challenges involved.

In the case of iris recognition, several competitions have been developed [Krichen et al., 2009a]. One of the first was the Iris Challenge Evaluation (ICE) organized by NIST. The goal of this challenge was to promote the state-of-artof iris biometrics and to promote the use of this modality by the USA government: 12 algorithms of 9 submitters were evaluated between August 2005 and March 2006.

The second ICE, the (ICE,2006) was combined with the Face Recognition Vendor Test (2006). The goal of this second challenge was an independent evaluation with closed data instead of a technology evaluation and to alleviate comparison between face and iris biometrics by employing a common testing protocol. Experiments involved verification mode tests with an upper limit given on processing time (three weeks for all tests on a 3.6 GHz CPU). Algorithms from 3 groups were evaluated: Sagem–Iridian (SG-2), (Irtch-2), and Cambridge (Cam-2)

Based on these two last challenges, from 2007 to 2009 led the NIST Multiple Biometrics Grand Challenge (MBGC). It consists of several sub-challenges (still face, video and portal), the main objective of this project was to evaluate the face and iris recognition technology on both still images and video over the more real world scenarios: exploring more realistic resolutions (90-120 pixels) around the eye; evaluation of capturing conditions; development of multimodal algorithms; comparing video with still iris images, evaluating controlled versus uncontrolled capture; and (6) evaluate through sensors (NIR vs HD) comparing different types of data.

For iris, the portal challenge is of special interest as it has pushed development towards ocular biometrics.As sensor for high-quality iris images, an LG 2200 camera was employed. All contestants had to locate irides, segment and normalize iris texture, generate an iris template and combine results.

The Noisy Iris Challenge Evaluation (NICE) organized by the University of Beira Interior in 2007-2009 was the first initiative towards iris recognition data from unrestricted data. This evaluation was developed in two different parts (NICE.I and NICE.II) and used VW instead of NIR iris images (different from e.g. ICE). The experiments were conducted on the UBIRIS.v2 dataset of largely Latin Caucasian irides (90%) with 15 eye per session.

NICE.I, was aimed at improving the state of the art in the field of iris segmentation and noise detection and was oriented only to evaluation on segmentation focusing on less-constrained image acquisition conditions and robustness to noise. Given an iris image, the challenge was to create a mask of the iris to allow for decisions on the membership of each pixel. All participants were informed of the misclassification rate (proportion of pixels in disagreement with ground truth based on 500 manually constructed binary segmentation masks) and error rates of type I and type II (average rate of false positives and false negatives). The best participants were invited to publish their results. From the 97 petitioners, the algorithm by [Tan et al, 2010] with an error of 0.0131% was selected as the winner among the six best algorithms showing errors below 0.03%.

The competition that followed in time (2009-2011), the NICE.II, attracted 67 participants. The second phase of NICE was focused on the coding and comparison techniques. Given two iris images with corresponding binary segmentation masks, the challenge consisted of generating a dissimilarity scores (ie, remove the template and make comparison) following the conditions of a metric. Based on decidability index the best algorithm by [Tan et al, 2011] considers multibiometric combination (sum rule) of iris and periocular data based on global color-based features and local ordinal measures.

12.1 Iris image evaluation databases

Definition*: Iris-image databases are crucial to the development and advancement of iris-based biometrics. These databases along with prescribed evaluation methodologies allows for direct* *comparison of iris segmentation or recognition algorithm performance. The databases will increase in size and complexity of iris-image until all algorithmic problems, inefficiencies, and shortcomings have been fully addressed [Woodard and Ricanek, 2009].*

Advances in the state-of-the-art on iris recognition have led to the emergence of a lot of databases, either as part of challenges or published for public use. The closed or proprietary databases, are difficult to acquire for the study of biometric systems with the aim of demonstrating their performance, public or free datasets are a valuable means to compare existing approaches.

The perfect iris-image database should be sufficiently large, consist of images collected from a large and heterogeneous group of subjects, and contain images that depict noise factors typically encountered in real world applications [Woodard and Ricanek, 2009].

According to [Jain et al, 2007], the biometric databases should have the following properties:

- Relevant (large number of samples within the class, i.e. the same person, in the identification mode).
- Large (size should exceed the lower limit needed to support the required accuracy).
- Representative (vary in gender, age and other demographic characteristics).
- Targeted (with respect to the specific types of sensors, models, etc.).
- Tagged (provide meta information).
- Time-variant (characteristics are captured during large time periods).
- Un-edited (without postprocessing).

With this properties, several biometric databases are available for iris recognition. The Table 6 shows a list of the most used iris database with detailed specifications. Different iris images examples belonging to they can be seen in Fig 3. These iris databases are available and free for research purposes.

Table 6. Overview of common open iris databases free for research purposes. Take it from [Rathgeb et al., 2013].

Dataset	Type	Size	Format	Images	Classes	Sensor
[DB-Bath]	NIR	1280 × 960	J2K	1600	800	ISG LW-1.3S-1394
[DB-CASIA.v1]	NIR	320 × 280	BMP	756	108	CASIA-Cam
[DB-CASIA.v2]	NIR	640 × 480	BMP	2 × 1,200	2 × 60	OKI Irispass-H CASIA-CamV2
[DB-CASIA.v3-Interval] [DB-CASIA.v4-Interval]	NIR	320 × 280	JPG	2,639	395	CASIA-Cam
[DB-CASIA.v3-Lamp] [DB-CASIA.v4-Lamp]	NIR	640 × 480	JPG	16,212	819	OKI Irispass-H
[DB-CASIA.v3-Twins] [DB-CASIA.v4-Twins]	NIR	640 × 480	JPG	3,183	400	OKI Irispass-H
[DB-CASIA.v4-Distance]	NIR	2,352 × 1,728	JPG	2,639	395	CASIA-LR-Cam
[DB-CASIA.v4-Thousand]	NIR	640 × 480	JPG	20,000	2,000	Irisking IKEMB-100
[DB-CASIA.v4-Syn]	NIR	640 × 480	JPG	10,000	1,000	N/A (Synthetic)
[DB-ICE.2005]	NIR	640 × 480	TIFF	2,953	132	LG 2200
[DB-ICE.2006]	NIR	640 × 480	TIFF	59,558	480	LG 2200
[DB-IITD.v1]	NIR	320 × 240	BMP	1,120	224	JIRIS JPC1000
[DB-MBGC-NIR Video]	NIR	2,000 × 2,000	Video	571	–	MBGC-Portal
[DB-MMU.1]	NIR	320 × 240	BMP	450	92	LG 2200
[DB-MMU.2]	NIR	320 × 238	BMP	995	200	Panas BM-ET100
[DB-ND-Cross Sensor]	NIR	640 × 480	TIFF	264,945	1,352	LG 2200 + LG 4000
[DB-ND-Iris-0405]	NIR	640 × 480	TIFF	64,980	712	LG 2200
[DB-UBIRIS.v1]	VW	200 × 150	JPEG	1,877	246	Nikon E5700
[DB-UBIRIS.v2]	VW	400 × 300	TIFF	11,102	522	Canon 5D
[DB-UPOL]	VW	576 × 768	PNG	384	128	TOPCON TRC50IA + Sony DXC-950P
[DB-WVU-Biomdata.v1]	NIR	640 × 480	BMP	3,043	462	OKI Irispass-H
[DB-WVU-Biomdata.v2]	NIR	640 × 480	BMP	763	144	OKI Irispass-H
[DB-WVU-OffAxis]	NIR	720 × 480	JPG, TIF, BMP	268 597	38 146	Sony DSC-F717 Ever Focus EQ100A

- DB-Bath: The BATH iris database [Daugman, 1993] was designed to obtain very high quality iris images. The initial objective was to capture 20 images from each eye of 800 subjects. The commercially available database is now twice this size. A majority of the database is comprised of students from 100 different countries and staff from the University of Bath. The images are of a very high quality taken with a professional Machine Vision Camera with infrared illumination and a consistent image capture setup.

- DB-CASIA.v1: [DB-CASIA]. It is an iris database provided by National Laboratory of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences freely for iris recognition researchers. Iris images of CASIA-IrisV1) were captured with a homemade iris camera. Eight 850nm NIR illuminators are circularly arranged around the sensor to make sure that iris is uniformly and adequately illuminated. In order to protect our IPR in the design of iris camera (especially the NIR illumination scheme) before appropriate patents were granted, the pupil regions of all iris images in CASIA-IrisV1 were automatically detected and replaced with a circular region of constant intensity to mask out the specular reflections from the NIR illuminators before public release. Clearly, such processing may affect pupil detection but has no effects on other components of an iris recognition system such as iris feature extraction since iris feature extraction only uses the image data in the region between the pupil and the sclera, i.e. the ring-shaped iris region.
  The database includes 756 iris images from 108 eyes. For each eye, 7 images are captured in two sessions with our self-developed device CASIA close-up iris camera (Fig.1), where three samples are collected in the first session (Fig.2(a)) and four in the second session (Fig.2(b)). All images are stored as BMP format with resolution 320*280.

- DB-CASIA.v2: [DB-CASIA]. It was used for the First Biometrics Verification Competition (BVC) on face, iris, and fingerprint recognition in the 5th Chinese Conference on Biometrics Recognition (Sinobiometrics 2004), held in GuangZhou, China in 2004. CASIA-IrisV2 includes two subsets captured with two different devices: Irispass-h developed by OKI and they self-developed device CASIA-IrisCamV2. Each subset includes 1200 images from 60 classes.

- DB-CASIA.v3-Interval: Contains images captured in two sessions, separated by an interval of at least one month. This database contains images of resolution 320 × 280 pixels captured from 249 subjects. In most cases, both the left and right eye images of a subject are present in the database. However all users do not have the same number of image samples per eye [buscar].
  The CASIA Iris Image Database V3.0 was used in the experimental evaluation of the iris indexing techniques proposed by [Mukherjee and Ross, 2008]. This database is divided into three parts: the CASIA-IrisV3-Interval dataset, the CASIA-IrisV3-Lamp dataset and the CASIA-IrisV3-Twins dataset.

- DB-CASIA.v3: : [DB-CASIA]. It was used in the experimental evaluation of the iris indexing techniques proposed by [Mukherjee and Ross, 2008]. This database is divided into three parts: the CASIA-IrisV3-Interval dataset, the CASIA-IrisV3-Lamp dataset and the CASIA-IrisV3-Twins dataset.
  Contains images captured in two sessions, separated by an interval of at least one month. This database contains images of resolution 320 × 280 pixels captured from 249 subjects. In most cases, both the left and right eye images of a subject are present in the database. However all users do not have the same number of image samples per eye.
  CASIA-IrisV3 includes three subsets which are labeled as CASIA-Iris-Interval, CASIA-Iris-Lamp and CASIA-Iris-Twins. CASIA-IrisV3 contains a total of 22,034 iris images from more than 700 subjects. All iris images are 8 bit gray-level JPEG files, collected under near infrared illumination. Almost all subjects are Chinese except a few in CASIA-Iris-Interval. Because the three data sets were

collected in different times, only CASIA-Iris-Interval and CASIA-Iris-Lamp have a small overlap in subjects.

- ➢ DB-CASIA.v3-Interval: Iris images of CASIA-Iris-Interval were captured with a self-developed close-up iris camera. The most compelling feature of this iris camera is that it have designed a circular NIR LED array, with suitable luminous flux for iris imaging. Because of this novel design, this iris camera can capture very clear iris images. CASIA-Iris-Interval is well-suited to study the detailed texture features of iris images.
- ➢ DB-CASIA.v3-Lamp: CASIA-Iris-Lamp was collected using a hand-held iris sensor produced by OKI. A lamp was turned on/off close to the subject to introduce more intra-class variations when we collected CASIA-Iris-Lamp. Elastic deformation of iris texture due to pupil expansion and contraction under different illumination conditions is one of the most common and challenging issues in iris recognition. So CASIA-Iris-Lamp is good for studying problems of non-linear iris normalization and robust iris feature representation.
- ➢ DB-CASIA.v3-Twins: CASIA-Iris-Twins contains iris images of 100 pairs of twins, which were collected during Annual Twins Festival in Beijing using OKI's IRISPASS-h camera. Although iris is usually regarded as a kind of phenotypic biometric characteristics and even twins have their unique iris patterns, it is interesting to study the dissimilarity and similarity between iris images of twins.

- DB-CASIA.v4 [DB-CASIA]. It is an extension of CASIA-IrisV3 and contains six subsets. The three subsets from CASIA-IrisV3 are CASIA.v3-Iris-Interval, CASIA.v3-Iris-Lamp and CASIA.v3-Iris-Twins respectively. The three new subsets are CASIA.v4-Iris-Distance, CASIA.v4-Iris-Thousand, and CASIA.v4-Iris-Syn.

  CASIA-IrisV4 contains a total of 54,601 iris images from more than 1,800 genuine subjects and 1,000 virtual subjects. All iris images are 8 bit gray-level JPEG files, collected under near infrared illumination or synthesized. The six data sets were collected or synthesized at different times and CASIA.v3-Iris-Interval, CASIA.v3-Iris-Lamp, CASIA.v3-Iris-Distance and CASIA.v4-Iris-Thousand may have a small inter-subset overlap in subjects.

  - ➢ DB-CASIA.v4-Distance: CASIA-Iris-Distance contains iris images captured using a self-developed Long-range Multi-modal Biometric image acquisition and recognition System (LMBS). The advanced biometric sensor can recognize users from 3 meters away by actively searching iris, face or palmprint patterns in the visual field via an intelligent multi-camera imaging system. The LMBS is human-oriented by fusing computer vision, human computer interaction and multi-camera coordination technologies and improves greatly the usability of current biometric systems. The iris images of CASIA-Iris-Distance were captured by a high resolution camera so both dual-eye iris and face patterns are included in the image region of interest. And detailed facial features such as skin pattern are also visible for multi-modal biometric information fusion.
  - ➢ DB-CASIA.v4-Thousand: CASIA-Iris-Thousand contains 20,000 iris images from 1,000 subjects, which were collected using IKEMB-100 camera produced by IrisKing (http://www.irisking.com). IKEMB-100 is a dual-eye iris camera with friendly visual feedback, realizing the effect of “What You See Is What You Get”. The bounding boxes shown in the frontal LCD help users adjust their pose for high-quality iris image acquisition. The main sources of intra-class variations in CASIA-Iris-Thousand are eyeglasses and specular reflections. Since CASIA-Iris-Thousand is the first publicly available iris dataset with one thousand subjects, it is well-suited for studying the uniqueness of iris features and develop novel iris classification and indexing methods.
  - ➢ DB-CASIA.v4-Syn: CASIA-Iris-Syn contains 10,000 synthesized iris images of 1,000 classes. The iris textures of these images are synthesized automatically from a subset of CASIA-IrisV1 with the approach described in [Tan, et al., 2010]. Then the iris ring regions were embedded

into the real iris images, which makes the artificial iris images more realistic. The intra-class variations introduced into the synthesized iris dataset include deformation, blurring, and rotation, which raise a challenge problem for iris feature representation and matching. In [Tan, et al 2010]was demonstrated that the synthesized iris images are visually realistic and most subjects can not distinguish genuine and artificial iris images. More importantly, the performance results tested on the synthesized iris image database have similar statistical characteristics to genuine iris database. So users of CASIA-IrisV4 are encouraged to use CASIA-Iris-Syn for iris recognition research.

- DB-ICE.2005: ICE mean Iris Challenge Evaluations. The National Institute of Standards and Technology (NIST) has provided researchers the database ICE.2005 [http ://iris.nist.gov/ice/] [Phan Viet Anh et al., 2009]. This database consists of 2953 grayscale eye images of 132 people. They are acquired with a dedicated LG2200 camera. Each image captures one eye and has a size of 640x480 pixels. This database has been divided into two sub-databases : one for images of the right iris (1425 iris images from 124 persons) and another one for images of the left iris (1528 iris image of 120 persons). In most cases, images of the right and left irises are acquired at the same time. This database contains images with a wide range of visual quality; some images seem near perfect while others are very blurry, have iris that extend off the periphery of the image, contain significantly occluded irises, and/or have video interlace artifacts.

- DB-ICE.2006: The database of iris images ICE.2006 is an extention of the ICE.2005 database . The images in the ICE.2006 intentionally represent a broader range of quality than the ICE 2006 sensor would normally acquire. This includes images that did not pass the quality control software embedded in the sensor. The database is composed by 59 558 images collected from 480 subjects. The images are all VGA resolution, 480 rows by 640 columns, with 8-bit grayscale resolution.

- DB-IITD.v1: [DB-IITD v1]. The IITDelhi Iris Database mainly consists of the iris images collected from the students and staff at IIT Delhi, New Delhi, India. This database has been acquired in Biometrics Research Laboratory during Jan - July 2007 using JIRIS, JPC1000, digital CMOS camera. The image acquisition program was written to acquire and save these images in bitmap format and is also freely available on request. The currently available database is from 224 users, all the images are in bitmap (*.bmp) format. All the subjects in the database are in the age group 14-55 years comprising of 176 males and 48 females. The database of 1120 images is organized into 224 different folders each associated with the integer identification/number. The resolution of these images is 320 x 240 pixels and all these images were acquired in the indoor environment.

- DB-MBGC-NIR Video [DB-MBGC NIR-Video]: The NIR face videos of the Multi Biometric Grand Challenge (MBGC) database (http://face.nist.gov/mbgc/). The database was constructed by capturing the facial videos of subjects walking through a portal. The videos have a spatial resolution of 2048 x 2048 pixels recorded in the AVI format with a frame rate of 15 frames per second (fps). Even though the extracted frames are of a very high resolution, the average usable spatial extent of the iris is about 120 pixels. The database contains 149 videos collected from 114 distinct subjects.

- DB-MMU.1: [DB-MMU (v1)]. The Multimedia University has developed MMU1 iris database contributes a total number of 450 iris images which were taken using LG IrisAccess 2200. This camera is semi-automated and it operates at the range of 7-25 cm.

- DB-MMU.2: [DB-MMU (v2)]. The MMU2 iris database consists of 995 iris images. The iris images are collected using Panasonic BM-ET100US Authenticam and its operating range is even farther with a distance of 47-53 cm away from the user.

These iris images are contributed by 100 volunteers with different age and nationality. They come from Asia, Middle East, Africa and Europe. Each of them contributes 5 iris images for each eye. There are 5 left eye iris images which are excluded from the database due to cataract disease. Obviously, the images are highly homogeneous and their noise factors are exclusively related with small iris obstructions by eyelids and eyelashes

- DB-ND-Cross Sensor: The Notre Dame University ND-CrossSensor-Iris-2012 Dataset. This dataset was initially released for the Cross Sensor Iris Recognition Challenge associated with the BTAS 2012 conference [DB-ND(v-CrossSensor, v-Iris-0405)]. This dataset occupies about 104 GBytes, and consists of 27 sessions of data with 676 unique subjects. An average session contains 160 unique subjects which have multiple images from both the LG2200 and LG4000 iris sensors. There are 29939 images from the LG4000 and 117503 images from the LG2200. Every subject occurs in at least two sessions across the entire data set. This data set spans three years, 2008 to 2010. The initial images are taken from both sensors and are 640 by 480. There are additional images included in this data set, known as the modified LG2200 images. The original images have been stretched vertically by 5% to compensate for the non-unit aspect ratio of the digitizer used in the LG2200 computer-hosted runtime acquisition system (this elongation was suggested by Imad Malhas of IrisGuard Inc. in 2009). Hence these additional images are of size 640 by 504.

- DB-ND-Iris-0405: The Notre Dame University ND-IRIS-0405 Iris Image Dataset [Bowyer and Flynn, 2005]. The data set contains 64,980 iris images obtained from 356 subjects (712 unique irises) between January 2004 and May 2005.
  The age range of the subjects is 18 to 75 years old. 158 of the subjects are female, and 198 are male. 250 of the subjects are Caucasian, 82 are Asian, and 24 are other ethnicities. None of the images correspond to subjects wearing glasses during image acquisition. However, a significant fraction of the subjects wore contact lenses.Image artifacts arising from contact lenses are discussed in a later section. All images were acquired using the same LG 2200 iris biometrics system. The LG 2200 uses near-infrared illumination of the eye, and provides audible prompts to help the subject position their head appropriately for image acquisition.

- DB-UBIRIS.v1: UBIRIS database [DB-UBIRIS v1] created by the SOCIA Lab. (Soft Computing and Image Analysis Group) of the Department of Computer Science, University of Beira Interior, Portugal [Proenca and Alexandre, 2005]. This dabase was presented in 2 versions.
  - UBIRIS.v1 database is comprised of 1877 images collected from 241 persons in two distinct sessions. This database incorporates images with several noise factors, simulating less constrained image acquisition environments. Since September 2005, this database has been freely downloaded by more than 500 individuals and institutions from over 70 different countries and its data constituted the basis for a large number of works with academic, research and commercial purposes.
    UBIRIS.v1: Its most fundamental characteristic is the high levels of noise that images contain, to simulate less constrained image capturing conditions. Since September 2005, this database has been freely downloaded by more than 500 individuals and institutions from over 70 different countries and its data constituted the basis for a large number of works with academic, research and commercial purposes.

  - UBIRIS.v2 database[DB-UBIRIS v2] is the second version of the UBIRIS database. This database has significantly more images and with new and more realistic noise factors, when compared to its predecessor. Both databases contain visible wavelength iris images captured in heterogeneous lighting conditions, with strong appearance of highly degraded images [Proenca et al., 2010].

DB-UPOL: [DB-UPOL] [Machala and Machala, 2004]. The UPOL iris image database was built within the Palacký University of Olomouc, Czech Republic. Its images have the singularity of being captured through an optometric framework (TOPCON TRC50IA) and, due to this, are of extremely high quality and suitable for the evaluation of iris recognition in completely noise-free environments. The database contains 384 images extracted from both eyes of 64 subjects (three images per eye). Its images have maximum homogeneity and inclusively the iris segmentation is facilitated by the dark circle that surrounds the region corresponding to the iris. Obviously, these characteristics make this database the less appropriate for the non-cooperative iris recognition research.

- DB-WVU-Biomdata.v1[DB-WVU (Biomdata v1, Biomdata v2, OffAxis]. The West Virginia University multimodal biometric dataset collection (BIOMDATA), collects iris, fingerprint, palm-print, voice and face data from over 200 people [Ross et al., 2006]; [Crihalmeanu et al., 2007]. The data was collected using standard enrolment devices, where possible, such as the SecuGen optical ngerprint biometric scanner, the OKI IRISPASS-h handheld device for the iris, and the IR Recognition Systems HandKey II for hand geometry with image and sound recordings for face and voice, respectively. The dataset also includes soft biometrics such as height and weight, for subjects of diferent age groups, ethnicity and gender with variable number of sessions/subject.
  First release of the biometric dataset collection contains image and sound files for six biometric modalities: Iris, face, voice, fingerprint, hand geometry and palm print.
  OKI IRISPASS-h handheld device is used to capture the image of the iris. The user is asked to hold the device away from one eye (at a distance eyeglasses would be away from the face) while covering the other eye with the hand; the covered eye must remain open, so that the pictured eye does not squint. The user should be able to see all sides of the green box displayed on the screen of the biometric device. The software used is provided by the constructor of the biometric scanner. The size of the iris picture is 302 KB, 480×640 and 2 KB for the .log file that contains the setup parameters of the biometric scanner. Four images of each eye are taken during one session. At the discretion of the volunteer more data samples were acquired when subjectively was determined that the quality of the image was poor. First release of the iris biometric dataset contains 3043 bmp iris images.

- DB-WVU-Biomdata.v2[DB-WVU (Biomdata v1, Biomdata v2, OffAxis)]: Second release of the biometric dataset collection contains image and video files for the following modalities: Iris; Face; Face video and voice; Fingerprint; Hand geometry; Palmprint. The dataset also includes soft biometrics such as height and weight, for subjects of different age, ethnicity and gender with variable number of sessions/subject. The size of the iris picture is 302 KB, 480×640 and 2 KB for the .log file that contains the setup parameters of the biometric scanner. Second release of the iris biometric dataset contains 763 bmp iris images.

- DB-WVU-OffAxis: [DB-WVU (Biomdata v1, Biomdata v2, OffAxis)]. Offaxis/angle iris dataset contains images collected with two cameras, a Sony Cyber Shot DSC F717 and a black and white, monochrome camera (Table 7). The angles are as accurate as the subject can hold their eye in position. The Sony camera was used in infrared mode, called night vision. However, while the camera was still in night vision mode, it still used all three RGB sensor data hence the green hue to the images.

Table 7. Characteristics of WVU-OffAxis database.

Devise	**Sony Cyber Shot DSC F717**	**Monochrome Camera**
Number of Sessions	1	1
Number of Subjects	19	73
Eye	Left & Right	Left & Right
Gaze direction (angle in degrees)	0,15,30	0,15,30,0
Number of files	268	597
Image Type	JPG, TIF	BMP
Spectrum	Infrared mode (night vision)	Visible mode
Distance Eye-camera	~4 inches	~4 inches
Illumination	Ceiling, ambient office lighting	Ceiling, ambient office lighting
Location	Indoor	Indoor

12.2 Open Source Iris Software

Until the expiry of the famous patent on iris recognition by [Flom and Safir, 1986] in 2005, access to market for manufacturers and algorithm proprietaries for iris recognition has been limited. Besides, the expiration of Daugman patent in 2011 [Daugman, 1994] that protected the IrisCode approach opens up new opportunities for competition in the market for iris recognition. However, today there are not many software and open source algorithms for iris recognition available. The computacional implementation on iris softwares which have been released and published and also more knowned are Masek system, OSIRIS vers. 2.01; PT-UBIID vers. 2; VASIR software and USIT vers. 1.0.1. All systems are accompanied with a benchmarking database, assessment protocol and benchmarking results to the evaluation framework [Mayoue and Petrovska-Delacrétaz, 2007].

- Masek System

[Masek, 2003] and [Masek and Kovesi, 2003] from The University of Western Australia has developed a modular and open-source iris recognition system (first version) running in Matlab [Mayoue, 2003]. The system has three modules corresponding to the three stages of any iris recognition process, namely: segmentation, normalisation and classification. The classification process relies on the use of Log-Gabor filters and four quadrant phase encoder on 1D signal, corresponding to one orientation on the iris rim. This system, mostly related to Daugman's work, offers a good benchmarking system for the community. The U.S. NIST has re-written the Masek System in C language with the name OSIRIS and used it as benchmarking algorithm for the Iris Challenge Evaluation (ICE).

- OSIRIS System version 2.01 - 05/03/2010 [Phan Viet Anh et al., 2009]

The OSIRIS (Open Source for IRIS) reference system based on iris modality is an open source iris recognition system developed in the framework of the BioSecure project [Krichen, 2007]. This system is deeply inspired by the [Daugman, 1993] works and the database used for the benchmarking experiments was CASIA iris image database [DB-CASIA].

OSIRIS is an iris recognition system available that is probably more widespread and was developed by [Masek and Kovesi, 2003], obtained in the framework of the Libor Masek's thesis [Masek, 2003]. It is an open source re-written in C language from the MATLAB source code first version and it is provided for research and testing. OSIRIS includes functions for segmentation, feature extraction, and comparison.

The segmentation part uses the cicular Hough Transform and an Active Contour approach to detect the contours of iris and pupil. The classification part is based on Gabor phase demodulation and Hamming distance classification. For segmentation they used circular Hough Transform, restricted to a range of interest for the radii of the pupil and the iris using the gamma correction, the detection of the eyelids is also performed by Hough Transform and Canny edge detection, and removal of the eyelash by thresholding. The feature extraction is based on the convolution of each row of an image with 1D Log-Gabor filters using iris polar representation with masks noise generating iris template according to the bitmask. Finally, provided comparison functions take two biometric templates and bit masks as input to generate the fractional Hamming Distance as output.

The OSIRIS reference system is currently available on the Telecom & Management Sud Paris subversion server at the following address: http://share.int-evry.fr/svnview-eph/. The full system has been tested under Linux (Fedora 8.0).

The OSIRIS version 2.01 has been used and tested on the ICE.2005 database. This reference system is made of several modules but it is not completely modular. Indeed, the two modules feature extraction and matching can currently not be dissociated. The segmentation module has been modified and improved in order to better adapt to degraded data such as the presented in ICE.2005.

The performance of the new version of the OSIRIS reference system was experiemented [Phan Viet Anh et al., 2009], they used the rights iris in the database ICE 2005. There were totally 7704 intra-class comparisons. For the inter-class, they selected randomly 219231 comparisons. They get an EER equal to 5.14% and the FRR at FAR of 0.1% was equal to 16.03%. The new version allows a big amelioration compared to version 1 which gave an EER of 26.86% and the FRR at FAR of 0.1 % of 90.37% on the same database with the same protocol.

- PT-UBIID version 2 [Popescu, 2010] (http://fmi.spiruharet.ro/bodorin/pt-ubiid/)

PT-UBIID is the first publicly available set of processing tools for the University of Bath Iris Image Database (UBIID - the free version containing 1000 eye images), tools that can be used to generate test data sets (IrisCode databases), without wasting precious time. The toolbox is written in Matlab & ANSI C. The main components of the package are:

- Fully automatic unsupervised heuristic iris segmentation procedure derived from Circular Fuzzy Iris Segmentation [Popescu, 2009a]., [Popescu, 2009b].
- A binary encoder based on Hilbert Transform and derived from Gabor analytic iris texture binary encoder.
- A statistical occlusion detection procedure based on standard deviation of the chromatic values.
- A single / multienrollment iris recognition simulator.
- Graphical display functions for generating Encapsulated PostScript files.

- IrisBEE Algorithm [Lee et al., 2011]

IrisBEE is based on Masek’s algorithm [Masek, 2003] and was originally developed at NIST to be used as a reference implementation for such a classical-still-based iris recognition. IrisBEE algorithm [Lee et al., 2011] is comprised of five distinct steps for iris recognition. In the first step, an image of the subject’s eye region is taken through classical image acquisition system (e.g., LG2200) – such an image is captured with careful image quality controls. The segmentation in the second step isolates the iris region from the rest of the acquired image. The isolated iris region is then normalized for comparison to another. Next, the features of the iris pattern are extracted from the normalized image and encoded to generate the iris template. Finally, the created iris template is compared with a template generated from an enrolled iris image.

- VASIR Software [Rathgeb et al., 2013]

The Video-based Automatic System for Iris Recognition (VASIR) [Lee et al., 2011] is an iris recognition algorithm implemented by NIST for less constrained distant video captures. It has been employed as a baseline reference for the Multiple Biometric Grand Challenge (MBGC) and consists of several components for image acquisition, eye region detection and extraction, quality-based selection, segmentation, feature extraction, normalization and comparison. Segmentation employs fast morphological-based preselection on the Gaussian blurred binarized input. Classical circular Hough Transform (HT) is used for boundary fitting and line HT for eyelid detection. The normalization and feature extraction stages are based on Masek's algorithm. VASIR supports cross-scenario comparison (e.g., distant-video to classical still) and utilizes OpenCV library.

The "Grand Challenge" in iris recognition is to have an effective algorithm for subject verification or identification under a broad range of image and environmental conditions. The VASIR team has developed a new version for both baseline performance and the new VASIR procedure have superiority over the IrisBEE algorithm [Lee et al., 2011].

- USIT Software version 1.0.1 [Rathgeb et al., 2013]

The USIT (University of Salzburg Iris Toolkit) is a Windows/Linux software package for iris recognition, made publicly available together with the book of [Rathgeb et al., 2013]. The software package includes algorithms for iris preprocessing (iris segmentation + iris texture normalization), feature extraction and comparisons. Input and output relies on files. Open source iris recognition software is made available under http://www.wavelab.at/sources/

12.3 Benchmark for Iris Recognition

A benchmark is an obligatory reference because it is a software that has been rigorously evaluated using datasets and protocols that also fulfill requirements of high quality. The benchmarks for iris recognition are based on principles that have proven their efficiency, and their purpose is to serve as comparison point to measure the real progress achieved with new research methods.

The benchmarks for iris recognition normaly are accompanied with open-source reference systems, publicly available databases for purpose of research, provide benchmarking assessment protocols which define the blocks of the evaluation framework, and also reports benchmarking results. For example, results obtained by applying the reference system on the benchmarking database according to the benchmarking protocol. The following benchmark are availables in internet to evaluate iris recognition solutions in progress.

- Biometrics Ideal Test (BIT)

CASIA Iris Recognition Group (bitadmin@nlpr.ia.ac.cn) have developed a website (http://biometrics.idealtest.org) namely Biometrics Ideal Test (BIT) for biometric database sharing and algorithm evaluation. The mission of BIT is to facilitate biometrics research and development by providing quality public services to biometric researchers. The iris researchers and developers of iris systems are welcome to register an account in BIT, so that they can download publicly available iris, face, fingerprint, palmprint, multi-spectral palm and handwriting databases and submit their algorithms online for testing and certification free of charge.

- The BioSecure Reference and Evaluation Framework
(http://biosecure.itsudparis.eu/AB/index.php?option=com_content&view=article&id=12&Itemid=15)

The BioSecure Network of Excellence has taken in charge the development or improvement of existing open-source identity verification systems for the most widely used biometric modalities (iris, face, fingerprint, and others). OSIRIS is the benchmarks reference for iris recognition developed in the framework of the BioSecure project and their baseline is deeply inspired by Daugman works. The evaluation tool is currently available at the address: http://share.int-evry.fr/svnview-eph/ref_syst/.

12.4 Benchmarking Framework on Iris Technology

A benchmarking is a reference point, like a standard through which something can be measured or evaluated as a product. A benchmarking is a rigorous evaluation. During the last decade various benchmarking on iris technology were carried out with different objectives.

The performance of an iris recognition system clearly depends on the quality of the iris images. However, if image quality is sufficient good, the performance of an iris recognition system might be high because the iris is known as one of the biometric characteristic that performs better results. This fact has been verified by a range of studies [Rathgeb et al., 2013].

The researchers have evaluated the following aspects: 1) performance in a large-scale independent iris recognition using thousand and thousand iris samples (2005); 2) large-scale studies related with million-million of iris comparisons in a border control programme (2006); 3) a study targets especially trade-offs between speed, image quality, capture volume and system accuracy (2006); 4) a study to evaluates the effect of compression on iris matching performance of commercial algorithms (IREX-2009); 5) a study targets large-scale iris quality calibration and evaluation (IREX-2009) ; and 6) a large-scale performance evaluation of iris identification algorithms with millions of images (IREX-2013). Next, a summary of the main results.

- The Independent Testing of Iris Recognition Technology (ITIRT): This study was performed by the International Biometric Group in 2005 [Ross, 2010] and was the first large-scale independent iris recognition evaluation with more than 100 thousand samples. ITIRT was organized by the U.S. Department of Homeland Security and Intelligence Technology Innovation Center. The aim of this test was oriented to estimate state-of-the-art of match, enrollment and acquisition rates, as well as level of effort (like transaction duration or FTA rates), in both intra-device and cross-device constellation. The study has been conducted using commercial hardware (LG IrisAccess 3000, OKI IRISPASS-WG, Panasonic BM-ET300) with a gallery of 24,627 and probe set of 87,004 iris-codes.

- Jonh Daugman performed one of the first large-scalle studies. He analized 200 billion of iris comparisons from the United Arab Emirates' border control programme in 2006 (http://www.sipri.org/research/disarmament/eu-consortium/publications/dunne_eunpc12). The study included 632,500 iris images, the FMR was lower than 1 in 200 billion. Theoretical calculations gave the result that the HD thresholds were to be set in 0.25 to achieve less than 1 false match in 1015 comparisons. This exceptional property of iris recognition makes it an ideal candidate for large-scale identification systems.

- AuthentiCorp's Iris Recognition Study 2006 (IRIS06) (http://www.authenti-corp.com/iris06/report/). This study targets especially trade-offs between speed, image quality, capture volume, and accuracy. Again very low failure rates (three attempts per eye) could be verified: 0.35–3.39% failure to enroll (FTE) and 1.5–6.9% failure to acquire (FTA). Reported transaction duration is 7.9–21.4 second (including failures) and the total accuracy is 0.0–1.8% FNMR using camera-specific algorithms (at HD threshold t = 0.32). Further findings comprise a flat ROC curve, similar performance for left and right eyes, and that a recording timespan of several minutes until weeks does not degrade performance.

- The Iris Exchange (IREX) [Grother et al., 2009] evaluates the effect of compression on iris matching performance of commercial algorithms (among them: Cambridge University, Cogent Systems, Crossmatch Technologies, Honeywell, Iritech, L1 Identity Solutions, LG, Neurotechnology, Retica Systems, Sagem); and also the interoperability of formats (ROI encoded, polar).
  IREX I suggests:
  - Use of cropped images and storage reduced to 50–80 KB in lossless mode;

  - Use of cropped and masked images as the primary exchange format (also for smart card storage);
  - Discourages the unsegmented polar format. JPEG and JPEG2000 negatively affected FNMRs and, for some algorithms, also FMRs.

  IREX I reports:
  - High variation with respect to computational efficiency of commercial algorithms.
  - The fastest implementations are more than twice as fast, thant the slowest implementation.

- The IREX-II [Tabassi et al, 2011] targets the large-scale iris quality calibration and evaluation.
  IREX II concludes that:
  - The differences in FNMRs between high and low-quality input images are as large as two orders of magnitude. Therefore, it it is necessary to obtain high quality input images.
  - The rejection of the 10% of lowest quality images reduces FNMR from 0.1% to 0.07%.
  - Greatest impact on recognition accuracy has the following effects: usable iris area, iris pupil contrast, pupil shape, iris-sclera contrast, gaze angle, and sharpness. While results on motion blur and signal-to-nose-ratio were inconclusive.

- The IREX-III [Grother et al, 2013] evaluates the large-scale performance evaluation of iris identification algorithms (used 6.1 million images).
  IREX III reports that:
  - Template generation time: 0.02–0.8 seconds.
  - IrisCode comparisons: 10^5 - 10^7 per second per core.
  - High variation in processing time (factor = 400 between slowest and faster algorithm of same accuracy.
  - The most accurate quality measure failed to provide low scores for 76.4% of the poorest 2% of false negative outcomes.
  - Verification mode yield FRRs of 1.5% (single eye) and 0.7% (both eyes) and 98.5% SR in identification mode.
  - FRR and FAR are found to be related to pupil and iris radii proportions (e.g., different dilations, large dilations).
  - FAR can be arbitrarily low with reported 2.5% FRR at 25 false matches in 1013 comparisons.
  - Failures of left eye comparison are found to be correlated with right eyes (simultaneous off-gaze, occlusion by long eyelashes, etc.).
  - Some algorithms exhibit false positive rates independent of population size at a fixed operating threshold.
  - Compared to face, iris exhibits 105 times fewer false positives than face (assuming equal false negative identification rate).

12.5 Methodology for Iris Performance Evaluation

Measuring real progress achieved with new research methods and pinpointing the unsolved problems is only possible within a well defined evaluation methodology. This point is even more crucial in the field of biometrics, where development and evaluation of new biometric techniques are challenging research areas. Such an evaluation methodology is developed and put in practice, for example, in the European Network of Excellence (NoE) BioSecure [Petrovska-Delacretaz et al., 2009]. The key elements of this methodology are the following elements: existence of open-source software, publicly available biometric databases, well defined evaluation protocols, and additional information (such as how-to documents) that allow the reproducibility of the proposed benchmarking experiments.

Jang and Kim [2009] presented a classification of the biometric evaluation processes. They identified 3 kind of processes: technology evaluation, scenario evaluation and operational evaluation.

1. **Process of Technology Evaluation:** is an offline process for testing biometric components using a precollected corpus of samples. Its goal is to compare the performance of biometric algorithms for the same biometric modality. Only algorithms compliant with a given input/output protocol are tested. Although sample data may be distributed for developmental or tuning purposes prior to the test, the actual testing must be done on data that have not been previously seen by algorithm developers. The test results are repeatable because the test corpus is fixed, and provide most of the performance metrics.
2. **Process of Scenario Evaluation:** is an online process for determining the overall system performance in a prototype or simulated application. Testing is performed on a complete system in an environment that models a real-world target application. Each tested system has its own acquisition devices, while data collection has to be carried out across all tested systems with the same population in the same environment. Test results are repeatable only to the extent to which the test scenario and population can be carefully controlled, and provide only predicted end-to-end throughput rates and error rates.
3. **Process of Operational Evaluation:** is also an online process whose goal is to determine the performance of a complete biometric system in a specific application environment with a specific target population. In general, its test results are not repeatable because of uncontrolled operational environments and population. This evaluation provides only end-to-end efficiency rates, false accept, and false reject rates.

In the case of iris recognition some examples of benchmark iris test evaluations were described in topics 14.3 and 14.4. Not only the performance metrics but also the test protocols introduced by these technology evaluations and others biometrics evaluations have become the basis of the ISO/IEC standards on biometric performance testing and reporting.

The international standards for testing and reporting the performance of biometric systems [Jang and Kim, 2009] have been studied and developed by the Working Group 5 of ISO/IEC JTC 1's Subcommittee 37 on Biometrics, one of which is ISO/IEC IS 19795 consisting of the following multiparts described in Table 8, under the general title Information technology.

Table 8. Biometric performance testing and reporting standards by ISO/IEC JTC 1/SC 37

Estándar No.	Subtitle
19795-1	Principles and framework
19795-2	Testing methodologies for technology and scenario evaluation
19795-3	Modality-specific testing
19795-4	Performance and interoperability testing of data interchange formats
19795-5	Performance of biometric access control systems
19795-6	Testing methodologies for operational evaluation

Biometric performance testing and reporting. ISO/IEC 9795 is concerned solely with the scientific ‘‘technical performance testing’’ of biometric systems and devices. Especially, ISO/IEC 19795-1 presents the requirements and best scientific practices for conducting technical performance testing. It presents testing methodologies for technology evaluation, scenario evaluation and describes testing methodologies for operational evaluation.

12.6 Remote Evaluation of Biometric Algorithms

Fallowing the idea of appliying the international standards for testing and reporting the performance of biometric systems [Sanchez-Reillo et al, 2012] presented the "Automatic Remote Evaluation System" (ARES) an automatic performance evaluation and remote framework for biometric evaluations. It has been developed using current standards developed within ISO/IEC JTC1/SC37 for Data Formats, Application Program Interfaces (APIs) and evaluation methodology. Standardised technology is able to provide developers in biometrics and third parties with away to perform comprehensive evaluations remotely without compromising the privacy of the individuals included in the test crew.

The solution described offers to the developers the ability to evaluate large databases that are stored in a secured centralised server. As this system is modality-independent, researchers can use the same protocol to perform different evaluations, and therefore lower the costs for testing purposes. Additionally, such protocols can be plugged directly into end-user applications, minimising technology transfer costs.

The framework can be accessed remotely by developers and evaluators and it is fully automatic, so it is accessible 24 hours a day, 7 days a week. All development has been done using current international standards. For example, the evaluation protocol is based on ISO/IEC 19784–1, also known as BioAPI [ISO, 2005]. Developers will feed their compiled algorithms as a Biometric Service Provider (BSP), which is also the way of integrating the algorithm in a future identification or authentication solution. Therefore, as developers do not have to make any further adaptation for going through the evaluation, to the product that will be integrated in the future solution. This means a sensible reduction in time to market. Finally, the evaluation framework is modality independent, so algorithms and databases for different modalities are accepted. This provides developers of different modalities with a common framework, also reducing time and cost.

The ISO/IEC 19784–1: BioAPI is the Standard API for Biometric Applications. The use of standardised APIs is demanded for allowing interoperability among developers and removing the cost for adapting the biometric solution to the evaluation protocol. In Biometrics, ISO/IEC JTC1/SC37 has developed the 19784–1 standard [ISO/IEC, 2005], most commonly known as BioAPI 2.0. This standard comes from the input of the BioAPI Consortium (http://www.bioapi.org .), which previously developed the high level biometric API that was called BioAPI-1.1. The basic idea of BioAPI is based on a Framework that serves as an interface between the application and those biometric units available. A biometric unit can be understood as any element that can provide biometric related services, such as capture devices, algorithms, or storage units.

13 Applications of the Iris Biometric Recognition

Biometric recognition offers a promising approach for security applications, with some advantages over the classical methods, which depend on something you have (key, card, etc.), or something you know (password, PIN, etc). The use of biometrics within Physical Access Control (PAC) systems is one of the most broadly commercialized sectors of biometrics, outside of forensic applications. The requirements for the use of biometrics within a larger physical access control system are dependent on the interaction with existing access control infrastructures. For this reason, the biometric system must be designed to interface appropriately with a wide range of access control systems. The most significantly deployed biometric types for access control are: fingerprint; hand geometry; face and iris [Li and Jain, 2009].

Iris recognition is a proven, accurate means to identify people [Chaudhari, 2012]. Since the randomness of iris patterns has very high dimensionality (more than 266 degree of fredom), recognition decisions are made with confidence high levels, high enough to support rapid and reliable exhaustive searches through national-sized databases [Rathgeb et al., 2013]. In the last decade, research on the automated recognition of humans has evolved to cover a large number of applications.

Applications such as immigration control, aviation security, bank and other financial transactions, access to defense organization requires a more reliable and authentic identification system. Iris is now considered to be one of the most time invariable biometric features of a person for recognition [Pushpalatha et al., 2012]. Examples of applications include the passenger identification in major city airports or border controls, where accuracy and speed are of uttermost importance [Jain et al., 2004]; [Li and Savvides, 2009]; [Daugman, 2009]; [Daugman and Malhas, 2004]. Moreover, biometric technologies based on the iris recognition are becoming more and more affordable and widespread due to the integration of iris scanners in mobile phones [Cho et al., 2005]; [Cho et al., 2006] and embedded systems.

13.1 Iris Applications in National Borders Control

The iris as a living passport. The applications are designed for the security control in frontier. This task is related with the entrances and exits to the country of nationals and not national's peoples as part of the daily exchange with other countries of the world. Normally the places are airports, ports, marine and industrial areas linked to the marine fishing and the external commerce of merchandise . The major task is the identification of travelers, immigrants, employees, temporal workers, etc.

- Major deployments of iris recognition around the world [Daugman, 2012]
  - Border & Inmigration Agency in UK. Here "IRIS" means "Iris Recognition Immigration Security". IRIS gates (entry, entrance, way in; admittance) at 10 UK airport terminals for registered frequent travelers in lieu of passport presentation (Fig. 16a).
  - USA-Canadian border crossing in lieu of passports (Fig. 16b).
  - The United Arab Emirates iris - based border security system (Fig. 16c). Deployed at all 32 air, land, and sea-ports. Approximately, 1 190 000 IrisCodes registered in a watch-list created and on a typical day 12 000 irises are compared to all on the watch-list, this means 14 billion comparisons/day. Each exhaustive search takes less than 2 seconds. About 30 trillion (30 million of million) comparisons of irises have been done since 2001. After an amnesty for violators of work permit laws or other offences in 2001, expellees' iris patterns were encoded and about 150 000 persons have since been caught trying to re-enter illegally to the country.
  - Schiphol Airpol (Netherland): Iris recognition in lieu of passport presentation (Fig. 16d).
  - Residency permit Applications (Fig. 16e).
  - Frontier control in Narita airport, Japan (Fig. 16f).
  - Voluntary Repatriation Centre, Pakistan-Afghan border (Fig. 16g).
  - Military control into war regions Fig. 16h).

Fig. 16. Examples of applications with an iris recognition system in statics services (a-g) and movil controls (h).

13.2 Iris Applications in Homeland Security

The iris as a secure way of people identification. The applications are designed for the internal security control and services in diverse human activities.

- Major deployments of iris recognition in homeland security.
  - Creation of a unique national identity system, which include digital IrisCode information. The bigger deployment of an iris recognition system for the citizens identification is developing currently in the Republic of India (Fig. 17a) [Daugman, 2012].
  - Activities of the routine police checkup (Fig. 17b) [Daugman, 2012].
  - Police Department - enrollment and release. Iris used for obtaining driving licenses and other personal certificates (Fig. 17c) [Daugman, 2012].
  - Access to condominium building and another programs by iris recognition (Fig. 17d).
  - Iris recognition to authenticate users in banking transactions (Fig. 17e). Secure access to bank accounts at cash machine. Iris access to: home, office, laboratory, hall inside a building and so on.

- Others possible applications are the followings:
  - Computer login (scanner, printers, computer networks): the iris as a living password.
  - Security alarm notification using iris detection systems. Its are adaptable for control alarms condition following: a presence of undesirable person, a predetermined blinking pattern by a user's eyelid, a predetermined movement pattern of a user's eyeball, etc.

13.3 Iris Applications in Forensics Science

The forensic science is the application of a wide range of sciences to solve issues of interest for the legal system (related with a crime, people's authentication, documents authentication, search and people's pursuit, and others.)

This kind of applications are designed for creating of criminalistic services using iris recognition:

- Authentication of persons, credit-card, governmental documents, official documents, etc.
- Iris for authentication of “rights to services”. An example is the “birth certificates”.
- Tracing missing or wanted people.
- Missing people's identification which don't remember their home address (kids, sick persons, etc). An example is IrisKids (USA) missing children and identification (Fig. 17f) [Daugman, 2012].
- Ethnic classification based on iris images. Iris texture not only have the capacity to be highly discriminative between eyes during all the individual lifetime, which makes iris particularly suitable for personal identification. But also, iris texture contains more information related to genes, which has been demonstrated by successful use of ethnic and gender classification based on iris [Zhang et al., 2011].

Fig. 17. The iris applications are designed for the internal security control and forensic services

13.4 Iris Recognition in Commercial Applications

The Iris applications give possibilities for to develop service, devices and apparatus related with iris person recognitions, the following are only some examples:

- Authentication using cell phone and other wireless devise (electronic commerce, telephony).
- Ticketless travel: iris recognition to omit the traditional ticket of travel.
- Automobile ignition and unlocking.
- Anti-theft devices.
- Iris recognition apparatus: Apparatus and method for determining where in a field of view, the eyes of a person to be recognized are located [Patent No. 5956122, 1999].
- Portable iris imaging apparatus: It can be used to capture high-quality iris images for identification of a person [Patent No. 6289113 B1, 2001].
- IrisCode generating device: This invention determines whether or not the image of an eye is a living thing. It is capable of sensing when a third party is pretending to be another person [Patent No. 6542624, 2003].

- Iris identification apparatus [Patent No. 0012413 A1, 2003] [Patent No. 6526160 B1] [Patent No. 6546121 B1].
- Pupil detection device and iris authentication apparatus: [Patent 2006/0291702 A1, 2006] [Patent No. 2007/0036396 A1, 2007] [Patent No. 7347547 B2, 2008].
- Photographic apparatus [Patent No. 2009/0161965 A1, 2009].
- Vision recovery training apparatus [Patent No. 2009/0225275 A1, 2009].
- Method and apparatus for iris recognition [Patent No. 7693307 B2, 2010].
- Method and apparatus for providing image capture [Patent No. 7657127 B2, 2010].
- Iris recognition method and apparatus: The invention is relates to an iris recognition method for effectively and accurately detecting iris from captured eye image although the eye is covered by an eyebrow or an eyelid in the capture image, and an apparatus to iris recgnition [Patent No. 7869626 B2, 2011].
- Method of authentication using pupil border and apparatus: The invention is relates to a method of recognizing unique information from a shape of a pupil of border and an apparatus using the method. Such method includes: a) acquiring an image of a pupil and an iris; b) extracting a pupil region from the image; and c) generating unique information by extracting a specific pattern of the pupil from the pupil region. The method performs biometric authentication by combining unique information obtained from a pupil region with unique information obtained from an iris region [Patent No. 2012/0308089 A1, 2012].
- Others development that could be dependent of the human creation.

14 Iris Multi-Modality

With the wide application, the performance of unimodal biometrics systems has to contend with a variety of problems such as background noise, signal noise and distortion, and environment or device variations. Therefore, multimodal biometric systems are proposed to solve the above mentioned problems [Wang et al., 2011]. The combination of iris biometrics with other biometrics modalities began in 2003 [Wang et al., 2003].

Table 9. Main iris multimodal biometric systems

Iris Multimodality	**Reference**
1. Iris and Periocular	[Woodard et al., 2010]; [Tan et al., 2011] , [Xiao et al., 2012]
2. Iris and Face	[Wang et al., 2003]; [Son and Lee, 2005], [Rattani and Tistarelli, 2009]; [Zhang et al., 2010]; [Wang et al., 2011]; [Eskandari and Toygar, 2012]; [Connaughton et al, 2013]
3. Iris and Fingerpring	[Lumini and Nanni., 2007]; [Besbes et al, 2008]; [Conti et al , 2010]; [Lahane and Ganorkar, 2012] ; [Abdolahi et al,2013]

14.1 Iris+Periocular Biometric Multimodality

A fixed region surrounding the iris of an individual is referred to as the periocular region [Woodard et al., 2010]. Depending on the size of the image used, this region usually encompasses the eyelids, eyelashes, eyebrows, and the neighboring skin area. Using the periocular region has the following advantages: (a) the information regarding the shape of the eye and texture of the skin around it can vary across individuals; which can be used as a soft biometric trait, and (b) no additional sensors, besides the iris camera, are required to acquire the periocular data.

From 2009 some authors are reported that the periocular data, namely the skin pattern around the eye, can also be used for biometric identification. [Park et al., 2009], [Xu et al., 2010], [Xu and Savvides, 2011], [Fazendeiro et al, 2012]. In (http://socia-lab.di.ubi.pt/~ubipr/paper_list.html) a periocular recognition paper list can be consulted.

In [Woodard et al., 2010] the autors discussed the use of the periocular region surrounding the iris, along with the iris texture patterns in order to improve the overall recognition performance in such images. Periocular texture is extracted from a small, fixed region of the skin surrounding the eye The periocular skin texture representation is inspired by the idea of local appearance features. To this effect, the periocular images are tessellated into blocks for which the texture features are computed locally. The entire image is then represented by a feature set computed by concatenating the vectors corresponding to each block. Such a representation preserves the spatial relationship of the features, and leads to a fixed length feature vector for each image that can be used directly for matching without any further normalization of the set.

The combination of iris and periocular region demonstrated it effectiveness in the second phase of the Noisy Iris Challenge Evaluation (NICE II). The winner approach [Tan et al., 2011], presented an effective method for visible light iris image matching by using multiple characteristics of iris and eye images considering multibiometric combination (sum rule) of iris and periocular data based on global color-based features and local ordinal measures.

They took the whole eye region as a biometric pattern including the iris data and the periocular data. In addition, the structure of eye region provides some important semantic information, such as double/single eyelid, and left/right eye, which can be taken as auxiliary traits for noisy iris image matching.

More recently [Xiao et al., 2012] focused on the problem of iris sensor interoperability, they demonstrated the fusion of iris and periocular biometrics for cross-sensor human identification. An improved feature extraction method (Multi-OM) is applied to representing the discriminative features. Features of iris and periocular images are extracted and encoded by Multi-OM and different encoding strategies. Iris and periocular biometrics are fused for cross-sensor comparisons.

14.2 Iris+Face Biometric Multimodality

Face and iris identification have been employed in various biometric applications. Besides improving the verification performance, the fusion of both of the biometrics has several other advantages such as enlarging user population coverage and reducing enrollment failure [Wang et al., 2003].

The fusion of face and iris modalities is a biometric approach that has gained increasing attention over the past decade, likely due to the popularity of the individual modalities as well as the natural connection between them. Despite this recent trend, very few studies have been done on fusion of face and iris biometrics from a single sensor [Connaughton et al, 2013].

[Wang et al., 2003], presented a first attempt to combine face and iris biometrics. They used two different strategies for fusing iris and face classifiers. The first strategy was to compute either an unweighted or weighted sum of the two matching distances and compare the distances to a threshold. The second strategy was to treat the matching distances of face and iris classifiers as a two-dimensional feature vector and use a classifier such as the Fisher's discriminant analysis or a neural network with radial basis function (RBFNN) to classify the vector as being genuine or an impostor. Combined systems showed more robust performance than the iris verification system and the face verification system alone. Fusion based on the RBF neural network produced the highest verification accuracy. In general, the experimental results also showed that the learning based methods perform better when they are used to fuse a ‘strong’ classifier and a ‘weak’ classifier. Experimental results have further demonstrated that the enrollment failure rate of stand-alone systems can be decreased by fusion, while maintaining a high accuracy.

[Son and Lee, 2005] extract features for face and iris images based on a Daubechies wavelet transform. Concatenation is used to form a joint feature vector, and Euclidean distance between feature vectors is used to generate match scores.They specifically applied 2-D discrete wavelet transform to extract the feature sets of low dimensionality from iris and face. And then to obtain Reduced Joint Feature Vector (RJFV) from these feature sets, Direct Linear Discriminant Analysis (DLDA) is used in thier multimodal system. This system can operate in two modes: to identify a particular person or to verify a person's claimed identity. The results for both cases show that the proposed method leads to a reliable person authentication system.

[Rattani and Tistarelli, 2009] proposed an approach that computes the SIFT features from both biometric sources, either multi-modal or multi-unit. For each source, feature selection on the extracted SIFT features is performed via spatial sampling. Then these selected features are finally concatenated together into a single feature supervector using serial fusion. This concatenated super feature vector is used to perform classification.

The main advantages of the proposed fusion method are the ease of implementation and the robustness of the resulting representation. Due to the scale-space analysis, SIFT features proved to be very stable and almost insensitive to illumination variations while providing a scale and translation invariant representations. At the same time, the adoption of a common feature representation greatly simplifies the normalization, concatenation and matching processes in the feature level fusion, which is generally an issue related to fusion at this level. From the experiments performed on a mixed database obtained by combining face images from the Equinox database and iris images from the CASIA v.3 database the representation based on feature level fusion demonstrate superior matching performance with respect to unimodal systems and score level fusion.

One of the most common method of multi-biometric fusion is score-level fusion. sensor [Zhang et al., 2010], approach the problem of fusing face and iris biometrics under near-infrared lighting using a single image. Frontal face images are acquired using a 10-megapixel CCD camera. Eye detection and face alignment are performed using Local Binary Pattern histogram matching and the eigenface algorithm and Daugman's algorithm are used to perform face and iris recognition, respectively, and score-level fusion is accomplished via the sum and product rules after min–max normalization.

An score-level fusion approach was proposed by Chen and Te Chu [Chen and Te Chu, 2006] using an unweighted average of the outputs of matchers based on neural networks. Firstly, the features of face and iris are separately extracted, and feed into WPNN classifier to make the multimodal decision. They combined a face database ORL and iris database CASIA to construct a multimodal biometric experimental database with which they validated the proposed approach and evaluated the multimodal biometrics performance. The experimental results reveal the multimodal biometrics verification is much more reliable and precise than single biometric approach.

[Wang et al., 2011], proposed a multimodal biometric algorithm for iris and face. The algorithm first extract face feature based on eigenface method and iris feature using 2D even Gabor filter, and then adopts z-score normalization model to eliminate the difference of the order of magnitude and the distribution between iris features and face features. The normalized features are combined in series and take Euclidean distance as a classifier. They performed experiments on CASIA iris database and two face database (ORL database and Yale database). Experiments showed that the algorithm improves the performance of two unimodal biometrics and outperforms sum rule fusion and weighted sum rule fusion.

The Multiple Biometrics Grand Challenge (MBGC) provided a collection of face and iris data to researchers in order to provide a standard test bed for comparing matching and fusion techniques [Connaughton et al, 2013] . The MBGC data included a subset of the near-infrared videos used in the experiments, as well as face stills, high-quality color face video, iris stills, and iris video. In general, results showed that fusion of face and iris biometrics offered improved accuracy over either biometric alone. The near-infrared videos released as part of the MBGC are also used by [Yang et al., 2009]. They investigated the use of SIFT features to perform alignment between the partial faces present in the dataset in order to facilitate face matching, but do not incorporate these results into a multi-biometric experiment.

[Eskandari and Toygar, 2012] combined the strengths of face and iris modalities to obtain better recognition accuracy for person identification by using several feature extractors, score normalization and fusion techniques. Face and iris features are extracted separately using global and local feature extractors and then the fusion of these modalities is performed. They applied both local and global feature extraction methods to extract iris and face features. Subpattern-based Principal Component Analysis (spPCA), modular Principal Component Analysis (mPCA) and Local Binary Patterns (LBP) methods were used as local feature extractors and global feature extractors such as Principal Component Analysis (PCA), and subspace LDA (ssLDA) also used to compare the performance of global feature extractors with local feature extractors on face and iris images.

Fusion of face and iris biometrics systems starts by applying one of the five algorithms (PCA, ssLDA, spPCA, mPCA, LBP) to extract the features of face and iris biometrics. The same feature extractor is applied on both face and iris images. The fusion of face and iris matching scores is achieved using Sum Rule and Product Rule. ORL and CASIA datasets are used for the fusion of face and iris biometrics.Fusion of face and iris scores lead to a higher recognition accuracy compared to the unimodal biometric systems. The unimodal (face and iris) methods achieve the performance of 2% EER. The multimodal face and iris method achieves a performance of 0.525% EER.

[Connaughton et al, 2013] presented an approach that differs from previous work in the fusion of face and iris biometrics in several facets. First, this approach uses only genuine multimodal data, rather than chimeric data for experimentation. Additionally, the fusion is accomplished using a single sensor. The authors manually acquire each image to guarantee high-quality face and iris samples. In the experiments presented, an on-the-move and at-distance sensor is used to acquire data for a high-throughput scenario. The resulting dataset consists of a much wider range of sample quality with incomplete data for some subjects, making the dataset a practical but challenging test bed for fusion experiments. These experiments also differ from work presented on the MBGC data; the near-infrared videos used in the MBGC dataset were manually selected to guarantee the presence of a subject in the field of view, whereas in the experiments shown in this work, this process is done automatically. Finally, this work uses multi modal, multi-sample, and multi-instance approaches to improve system accuracy and robustness.

14.3 Iris+Fingerpring Biometric Multimodality

[Lumini and Nanni, 2007] Was one of the first efforts for integrate iris and fingerprint. They Investigated whether the integration of iris and fingerprint biometrics can achieve performance that may not be possible using a single biometric technology. Thet evaluated the correlation among the best state of art algorithms for fingerprint verification presented at FVC2004. They showed that the fusion among some competitors of FVC2004 permits a drastically reduction of the performance. Particularly interesting was the result obtained by combining the competitors of FVC2004 and an IRIS matcher in terms of EER (the most used parameter in the evaluation of real identification systems), significantly lower than for other approaches. This indicates that the intrinsic error of the system is very low and tends to 0 for some of the tests carried out. The results of this paper confirm that a multimodal biometric can overcome some of the limitations of a single biometric resulting in a substantial performance improvement.

The authors examined a scenario for integrating fingerprint and iris biometric by comparing different fusion strategies: the mean rule (MEAN) to combine similarity scores and three Machine Learning approaches: linear support vector machines (LSVM), radial-basis-function support vector machines (RSVM) and the Dempster-Shafer model (DS) [Xu et al., 1992] they compared. They selected this approach for their work. The Dempster-Shafer theory, also known as the theory of belief functions, is a generalization of the Bayesian theory of subjective probability. In the Dempster-Shafer frame, the best representation of support is a belief function rather than a Bayesian mass distribution. The theory embraces the familiar idea of assigning numbers between 0 and 1 to indicate the degree of support but, instead of focusing on how this numbers are determined, it concerns the combination of degrees of belief.

[Besbes et al, 2008] proposed a multimodal biometric system using fingerprint and iris features. They use a hybrid approach based on: 1) fingerprint minutiae extraction and 2) iris template encoding through a mathematical representation of the extracted iris region. This approach is based on two recognition modalities and every part provides its own decision. The final decision is taken by considering the unimodal decision through an “AND” operator. No experimental results have been reported for recognition performance.

[Conti et al , 2010] presented a template-level fusion algorithm working on a unified biometric descriptor. The result leads to a matching algorithm that is able to process fingerprint-codified templates, iris-codified templates, and iris and fingerprint-fused templates. In contrast to the classical minutiae-based approaches, the proposed system performs fingerprint matching using the segmented regions (ROIs) surrounding (pseudo) singularity points. This choice overcomes the drawbacks related to the fingerprint minutiae information: the frequency-based approach should consider a high number of ROIs, resulting in the whole fingerprint image coding, and consequently, in high-dimensional feature vector. At the same time, iris preprocessing aims to detect the circular region surrounding the feature, generating an iris ROI as well. For best results, they adopted a Log-Gabor-algorithm-based codifier to encode both fingerprint and iris features, thus obtaining a unified template. Successively, the HD on the fused template has been used for the similarity index computation. The multimodal biometric system has been tested on different congruent datasets obtained by the official FVC2002 DB2 fingerprint database [30] and the BATH iris database [31]. The first test conducted on ten users has resulted in an FAR = 0% and FRR = 5.71%, while the tests conducted on the FVC2002 DB2A and BATH databases resulted in an FAR = 0% and an FRR = 7.28% ÷ 9.7%.

In [Lahane and Ganorkar, 2012] a multimodal biometric system based on fingerprint and iris characteristic is proposed. The proposed multimodal biometric system consists of two main stages: the preprocessing stage and matching stage. Iris and fingerprint images are preprocessed to extract the ROIs (Regions of Interest). The fingerprint singularity regions based approach requires a low execution time, since image analysis is based on a few points (core and delta) rather than 30–50 minutiae. Iris image preprocessing is performed by segmenting the iris region from eye and deleting the eyelids and eyelashes. The extracted ROIs are used as input for the matching stage. They are normalized and then processed in order to generate a homogeneous template. A matching algorithm is base on the HD (Hamming Distance) to find the degree of similarity.

The region of interest (ROI) extracted from the original images are stored in different vectors. Successively, each vector is normalized in rectangular coordinates. The features are extracted using Gabor filter. Then fusion is performed by combining the biometric features extracted from pair of fingerprint and iris images. Finally HD is used for matching score computation.

The proposed system works fine as it’s FAR & FRR are 0% & 5.71% respectively. The accuracy of the multimodal system is 99.5% for threshold 1. So that multimodal biometric system has the potential to overcome the limitations of any individual biometric system.

[Abdolahi et al.,2013] presented a novel fusion strategy for personal identification using fingerprint and iris at the decision level fusion scheme. It is also shown that integration of fingerprint and iris biometrics can achieve higher performance than using each single biometric alone. A fuzzy logic method is used for fusion which is given better performance and accuracy. Hamming distance and fuzzy logic are used for comparing and deciding to verification.

Fuzzy logic is a kind of soft computing, which mimics human decision making. In this paper, fuzzy logic decision fusion is used and gives reasonable results. The general block diagram for FL is shown in figure X. Fuzzification is the process of each input convert to linguistic variable. One or more membership function with a degree of membership function is obtained from linguistic variables. The degrees of membership function based on predefined rules and rule weights are combined and the output is produced. Each rule can be given a weight to show the influence of the particular rule on the output.

In this paper, fuzzy logic is used for fusion at decision level. The fuzzy engine has two inputs, one of them named fig and the other iris. Fig considered as fingerprint results in identification and iris considered as iris result identification.

In the previous fusion methods, each single biometrics has same weight, but some biometrics have more features and more stability. It is better that biometric with more features will have more chance to participate. Iris has more features than fingerprint and also more stability. It is also more resistant against cheating and copying. So in this paper, iris has more weight in fusion with fingerprint.

In the experimental results they reported that the fuzzy inference system gives an output and accepts the main output. If they have two inputs, 1 for fingerprint and 5 for iris, system gives accuracy 99.4%., but do not mentioned which database were used

They compared two other multi- biometric systems (face & iris, 96,2%; fingerprint & face, 97,7%) and showed that with fusion two single biometrics iris and fingerprint could give "better result" with an aaccuracy 98,3 % but do not mentioned or refered any specific system eider any database.

15 International Activities on Iris Biometrics

Biometrics is becoming an area of increasing interest to the Pattern Recognition research community. Evidence of this interest is the large number of conferences and other events which are currently organized and sponsored by International Association on Pattern Recogniton (IAPR) or by its Technical Committee 4 on Biometrics (TC4). Moreover, there is a rapid growth in the number of organizations that are showing interest in deploying biometric technologies in different application scenarios. For this reason, IAPR TC4 has been very active in promoting biometrics in several scientific events and places.

15.1 Conferences, School, Group and Technical Committee on Biometrics

Biometric recognition has attracted much attention from academia, industries and government in recent years. Iris recognition is included. The purpose is to promote exchange of novel ideas on biometrics.

Main topic in discussion:

1. What are the most up-to-date core biometric technologies developed in the field?;
2. What is the potential impact of biometrics in forensic investigation and crime prevention?;
3. How can biometrics facilitate man-machine interaction?;
4. What are the most relevant issues in biometric standardization?;
5. What can we learn from human perception?;
6. What does it involve to integrate a biometric recognition system?;
7. How biometrics meets forensic, security and the e-society challenges of tomorrow.

Meetings:

1. Chinese Conference on Biometric Recognition. For eight times since 2000-2013.
2. International Summer School on Biometrics: For the last ten years, this school on Biometrics has been closely following the developments in science and technology to offer a cutting edge,

intensive training course, always in-line with the current state-of-the-art. For ten times since 2003-2013.

3. International Conference on Biometrics (ICB). For five time since 2006-2012.
   The ICB was established in 2006 as a biennial conference by merging AVBPA (Audio- and Video-based Person Authentication), ICBA (International Conference on Biometric Authentication) and other biometric workshops, and has established itself as a premier international conference in biometrics. The first edition of ICB was held in Hong Kong, China (2006), the second in Seoul, Korea (2007), and the third in Alghero, Italy (2009). The fourth edition was held in conjunction with the BTAS conference (Biometrics: Theory, Applications, Systems) in Washington, DC, USA (October 2011) and called the International Joint Conference on Biometrics (IJCB). ICB is an official conference of the IAPR Technical Committee on Biometrics (TC4).
   The 5th ICB (2012) had a broad scope and invites papers that advance biometric technologies, sensor design, feature extraction and matching algorithms, analysis of security and privacy, and evaluation of social impact of biometrics technology. The topics on biometric systems were based on fingerprint, iris, face, voice, gait and other modalities as well as biometric fusion and emerging biometrics based on novel sensing technologies (Source URL: http://icb12.iiitd.ac.in/).

The conferences and courses have the purpose of provide a clear and in-depth picture on the state-of-the-art in biometric verification - identification technology, both under the theoretical and scientific point of view as well as in diverse human’s application domains.

4. Technical Committee 4 on Biometrics (TC4)
   TC4 is the Technical Committee number 4 of IAPR for the thematics related with the biometrics technologies. IAPR TC4 is the organizer of ICB and have two biometric awards named a) IAPR JK Aggarwal award, and b) “IAPR Young Biometrics Investigator Award (YBIA) ”. The objectives and criteria of both awards are similar, except that YBIA award is given to outstanding scientists in the biometrics field.

5. International biometric group (IBG) [https://ibgweb.com/about]
   IBG is the biometric and identity management industries' leading independent. It is a consulting firm, providing a broad range of services to U.S. government and private sector clients. IBG is a completely vendor-independent and provides business and technical expertise in biometrics for large-scale identification, network security, transaction systems, and access control. IBG has extensive experience with a wide range of biometric hardware and software solutions, including fingerprint, AFIS, face recognition, hand geometry, iris recognition, multimodal systems, and emerging biometrics.

This whole international activity around the iris biometric usefulness demonstrates the institutional relevance of iris recognition for the human society.

15.2 Iris Biometric Standardization

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC have established a Joint Technical Committee, ISO/IEC JTC 1. The main task of the JTC is to prepare international standards. Preliminary sketch (draft) of an International Standards adopted by the JTC 1 are circulated to national bodies for voting. Publication as an International Standard requires approval by at least 75 % of the national bodies casting a vote [ISO/IEC, 2005].

ISO/IEC 19794-6 consist of the 8 part, under the general title "Information technology - Biometric data interchange formats; and the Part 6: "Iris image data" is to define a standard for exchange of iris image information. This part contains a specific definition of attributes, a data record format for storing and transmitting the iris image and certain attributes, a sample record and conformance criteria. The exchange of iris information between equipment from different vendors can only be done using a large-scale image of the entire eye. This is expensive in storage and bandwidth. To provide interoperability among vendors, it is necessary to define a standard, compact representation of a human iris [ISO/IEC, 2005].

The biometric data record specified in the Part 6 of ISO/IEC 19794 shall be embedded in a CBEFF-accommodating structure in the CBEFF Biometric Data Block (BDB). The most relevant issues in iris biometric standardization are related with the following topics: a) Iris format – rectilinear, b) Iris format – polar, c) Iris image – rectilinear, d) Iris image – polar, e) JPEG2000 image format, f) Microsoft Windows bitmap image, g) Portable Network Graphics (PNG) data, h) Biometric reference template certificate, i) Biometric fusion data format, j) Iris data compressibility, k) Iris image data interchange format standard, l) Electronic biometric transmission specification (EBTS).

The second ISO/IEC standard on BioAPI, incorporating Amendments 1, 2 and 3 to the first edition. The corrections and improvements are included in BioAPI specification with Amd.1, Amd.2, and change marked proposed Amd.3 [ISO/IEC, 2010].

The International Biometrics & Identification Association (IBIA) (http://www.ibia.org/id-solutions/) is an industry association (USA) that promote the use of identification technologies for managing human identity. With the global need for identification and authentication of individuals, IBIA association is looking for solutions for enhance security, privacy, productivity and convenience. In their website se encuentra una relacion of standar specification which shall be embedded in a CBEFF BDB format identifiers for biometric identification such as fingerpring recognition, face recognition, iris recognition, signature recognition, hand geometry recognition, vascular recognition and biometric fusion data format. The specifications related with an iris recognition system you can see in Table 10.

Table 10. CBEFF BDB format identifiers for iris systems **(**http://www.ibia.org/base/cbeff/_bdb.phpx **).**

Organization Name	Format Short Name	Specification Name
1. INCITS Technical Committee M1	Iris Format – rectilinear	ANSI/INCITS 379-2004
2. INCITS Technical Committee M1	Iris Format - polar	ANSI/INCITS 379-2004
3. ISO/IEC JTC 1 SC 37-Biometrics	Iris-image-rectilinear	ISO/IEC 19794-6 {iso registration-authority cbeff (19785) biometric-organization (0) 257 bdbs (0) iris-image-rectilinear (9)}
4. ISO/IEC JTC 1 SC 37-Biometrics	iris-image-polar	ISO/IEC 19794-6 {iso registration-authority cbeff (19785) biometric-organization (0) 257 bdbs (0) iris-image-polar (11)}
5. INCITS Technical Committee M1	JPEG2000 image format	ISO/IEC 15444 - Information Technology - JPEG 2000 Image Coding System
6. INCITS Technical Committee M1	Microsoft Windows bitmap image	Http://www.fileformat.info/format/bmp/egff.htm http://www.dcs.ed.ac.uk/home/mxr/gfx/2d/BMP.txt
7. INCITS Technical Committee M1	Portable Network Graphics (PNG) data	ISO/IEC 15948:2003 http://www.libpng.org/pub/png/
8. ISO/IEC JTC 1 SC 27 - IT Security techniques	biometric-reference-template-certificate	ISO/IEC 24761 {iso(1) standard(0) acbio(24761) contentType(2) brcContent(7)}
9. INCITS Technical Committee M1	Biometric Fusion Data Format	ANSI/INCITS 439-2008
10. INCITS Technical Committee M1	Electronic Biometric Transmission Specification (EBTS)	IAFIS-DOC-01078-8.00x, http://www.fbibiospecs.org/fbibiometric/biospecs.html
11. ----	Iris Image Data Interchange Format Standard	ISO/IEC 19794-6 (revision published in 2011)

The related specifications above should guarantee that an iris recognition system has the following properties:

- Iris Image Compression Format. For example, a NIST IREX study developed a new compact formats for iris image compression to as little as 2 KB using JP2K (not JPEG), with cropping and ROI masking; or lossless compression format using PNG container.
- Iris Image Data Interchange Format Standard. It is a requirement to use inter-operable image formats, not proprietary IrisCode templates (vendor neutral).

15.3 Iris Biometrics Competitions

Noisy Iris Challenge Evaluation (NICE): is an open competition on iris recognition organized by the University of Beira Interior, Portugal. The NICE competition is concerned with methods that use the texture pattern of the Iris as a means to recognize a person. Whereas, commercial iris biometrics technology such as that employed in India's Unique ID program, uses near-infrared illumination of the eye, the NICE competition looks at what level of performance can be obtained using color images taken under already-existing illumination [Bowyer, 2012].

NICE main purpose is the evaluation of the iris segmentation robustness to noise factors. It was open to individuals and institutions, either with academic, research or commercial purposes.The participants that obtain the lowest error rates on the NICE contest were invited to publish their approach in a special issue of Elsevier in Image and Vision Computing Journal.

- The NICE.I (September 2008) was a completely free-of-charge iris segmentation and noise detection contest that operates on noisy data, resultant from less constrained image capturing conditions. UBIRIS.v2 database was selected as data source for this contest.

It received over 90 participants from 20 different countries and the best 10 participations were invited to publish their approach. Also, all the remaining participants published their method in the Proceedings of the NICE.I contest. The first 8 winner of the contest is shown in Table 11.

Table 11. The NICE.I contest winners using UBIRIS.v2 (http://nice1.di.ubi.pt/)

Ranking	***Affiliation***	***Country***	***Error****=0.5*FRR + 0.5*FAR*
1	NLPR, Institute of Automation, Chinese Academy of Sciences	China	0,0131
2	Department of Microelectronics and Computer Science, Technical University of Lodz	Poland	0,0162
3	Department of Computer Science, University of Beira Interior	Portugal	0,0180
4	College of Computer Science and Technology, Heilongjiang University	China	0,0224
5	Dept. of Electronics Engineering, Dongguk University, Biometrics Engineering Research Center	Korea	0,0282
6	Department of Electrical and Computer Engineering, Florida International University	USA	0,0297
7	Biolab, Department of Information Technologies, University of Milan	Italy	0,0301
8	Department of Electronic Engineering, Universidad Politécnica de Madrid	España	0,0305

FPR and FNR respectively represent False Positive and False Negative Rate.

The main problem in the NICE.I contest was the segmentation of noisy iris images for non-cooperative iris recognition. To address this problema the winners used different strategies.

Approach of the winner in NICE.I contest: The winner approach was presented by the authors, Tieniu Tan, Zhaofeng He and Zhenan Sun [Tan et al., 2010] from NLPR, China. They presented a novel iris segmentation algorithm. After reflection removal, a clustering based coarse iris localization scheme is first performed to extract a rough position of the iris, as well as to identify non-iris regions such as eyelashes and eyebrows. A novel integro differential constellation is then constructed for the localization of pupillary and limbic boundaries, which not only accelerates the Daugman's traditional integro differential operator but also enhances its global convergence. After that, a curvature model and a prediction model are learned to deal with eyelids and eyelashes, respectively.

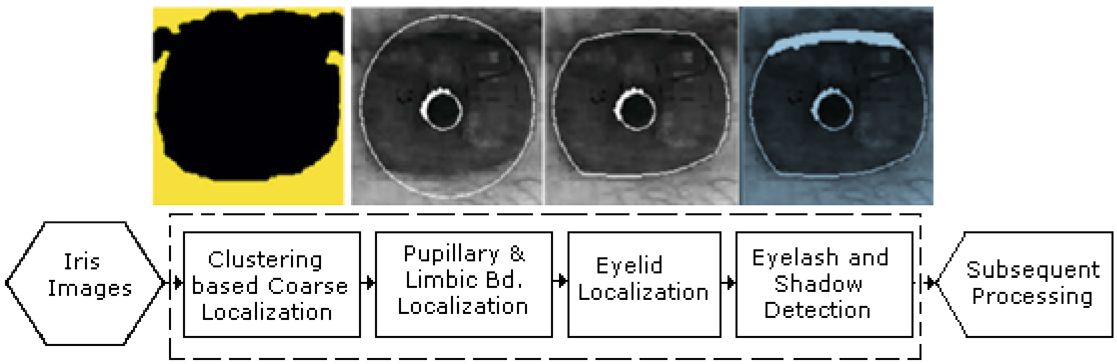

Fig. 18. The flowchart of the winner iris segmentation method at NICE.I contest [Tan et al., 2010].

As illustrated in Fig. 18, it incorporates four key modules, namely coarse iris localization based on clustering, localization of pupillary and limbic boundaries, eyelid localization and eyelash/shadow detection.

Extensive experiments on the challenging UBIRIS iris image databases showing a System Error = 0.0131% demonstrate that encouraging state of the art accuracy is achieved by the algorithm and therefore it can be well for non-cooperative iris recognition.

- The NICE.II (September 2010) was the second phase of the Noisy Iris Challenge Evaluation and attracted participation by 67 research groups from around the world. In contrast to all current commercial Iris biometrics technology, the NICE competitions focus on performing iris biometrics on visible-light images. Whereas NICE.I focused on segmentation, NICE.II focused on performance in feature extraction and matching [Bowyer, 2012].
  - It also operates on iris images similar to the ones of the UBIRIS.v2 composed by 1000 iris images.
  - It is exclusively focused in the *signatures encoding and matching* stages of degraded visible wavelength iris images previously segmented, according to the segmentation method executed in the segmentation contest (NICE.I).
  - An automatic JAVA Evaluation Framework was used.

The first 8 winner of the contest is shown in Table 12.

Table 12. The NICE.II contest winners using UBIRIS.v2 (http://nice2.di.ubi.pt/)

Ranking	*Affiliation*	*Country*	*Decidability d'*
1	NLPR, Institute of Automation, Chinese Academy of Sciences	China	2,5748
2	Techshino Biometrics Research Center,Depar. of Mathematics, Northeastern University	China	1,8213
3	University of Beira Interior, Portugal	Portugal	1,7786
4	Biometrics Engineering Research Center (BERC), Dongguk University	Rep. of Korea	1,6398
5	College of Computer Science and Technology, Heilongjiang University	China	1,4758
6	University of Salerno	Italy	1,2565
7	College of Computer Science and Technology, Heilongjiang University	China	1,1892
8	Technical University of Lodz	Poland	1,0931

Approach of the winner in NICE.II contest: The winner approach was presented by the authors, Tieniu Tan, Xiaobo Zhang, Zhenan Sun and Hui Zhang [Tan et al., 2011] from NLPR, China. They presented an effective method for visible light iris image matching by using multiple characteristics of iris and eye images considering multibiometric combination (sum rule) of iris and periocular data based on global color-based features and local ordinal measures.

The presented method (Fig. 19) consists of image preprocessing, feature extraction, matching, and multi-modal fusion. In image preprocessing, a decision level fusion method is proposed to localize limbic and pupillary boundaries using the original iris images and the corresponding mask images. For feature representation and matching, multiple sources, including ordinal measures, color histogram, texton representation and semantic information, are adopted for noisy iris image matching.

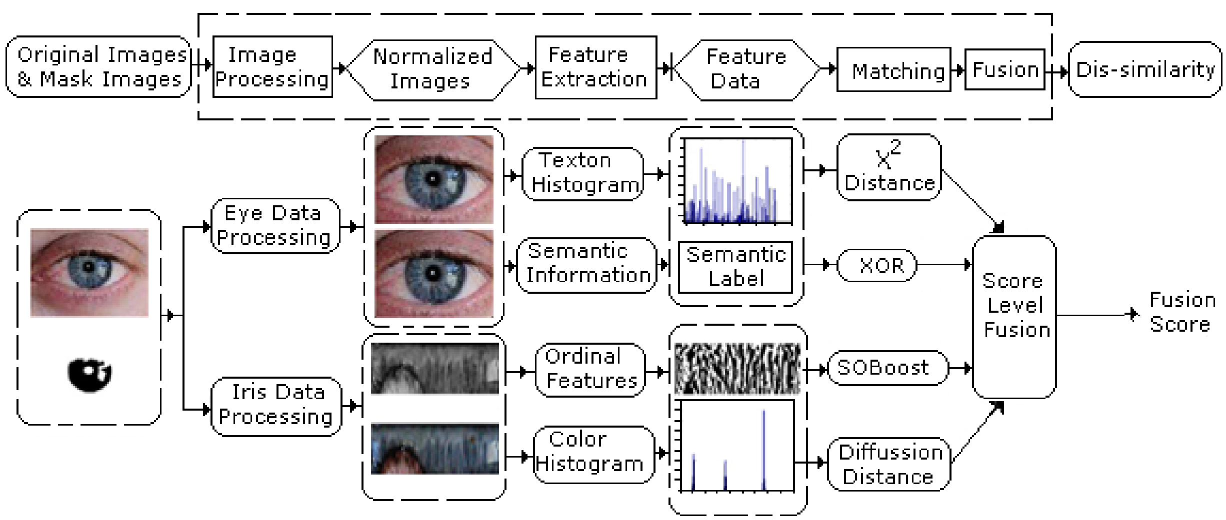

Fig. 19. The flowchart of the NICE.II winner method on performance in feature extraction and matching [Tan et al., 2011].

Their approach is distinguished from most of the approaches presented in the competition by being a strongly multi-biometric approach that exploits multiple sources of information available in both the iris region and the surrounding ocular region. They use two iris-based sources of information: Iris texture representation using ordinal measures as previously described by the CASIA research group, and iris color based matching. They also use two ocular-based sources of information: a texton-based matching of skin texture in the ocular region, and ‘‘semantic information’’ based on geometrical asymmetry of the eyelash distribution. Fusion of the four sources of matching information is done using a weighted sum of scores. The use of two sources of ocular information is an especially interesting aspect of this method, as ocular biometrics has recently become a hot topic. Even more interesting is the use of two different types of ocular information, including one based on the eyelashes [Bowyer, 2012].

Here researchers applied a multimodal fusion, designing a robust score level fusion strategy in order to combine the four matching scores used into the final dissimilarity measure. Extensive experiments on the UBIRIS.v2 database and the NICE.II training dataset have demonstrated the effectiveness and robustness of the proposed matching method with the best Decidability measure $d' = 2.57$.

15.4 Main Project in Iris Recognition

Currently a large number of projects are developing. These projects are aimed at the implementation of biometric solutions in various fields of human activity. Basically, many of these projects are aimed at strengthening internal security mechanisms of the states, the creation of national identification systems of persons, or the research of new and improved biometric identification algorithms. In the case of iris there is increased use in large-scale projects for the identification of people, it is combined with other biometric features such as fingerprint or face which considerably reduces errors. Other projects are directed towards obtaining algorithms for identifying people in an uncontrolled environment. Below is a summary of the major projects being developed.

- Project Unique Identification Authority of India (UIDAI) (in progress)
  Summary: The main objective of UIDAI Project (http://uidai.gov.in/about-uidai.html) is to acquire face, ten-print fingerprint and both irises for all of the approximately 1200 millions residents of India [Aadhaar, 2011]. The authority aims to provide a unique 12-digit ID number to all Indians in a Unique Identification Number database (on a voluntary basis), but not smart cards.
  The number will be stored in a centralized database and linked to the basic demographics and biometric information – photograph, ten fingerprints and iris – of each individual. It is easily verifiable in an online, cost-effective way. It is unique and robust enough to eliminate the large number of duplicate and fake identities in government and private databases. The random number generated will be devoid of any classification based on caste, creed, religion and geography. UIDAI Model, Aadhaar is dependent on biometrics, being reliable enough to guarantee that there is a one-to-one correspondence between real people and electronic identities on the Central ID repository.
  In December 2010, UIDAI's hierarchy published show error rate at 0.01% using finger print and iris only, this low rate combined with photograph match can achieve the desired unique identification. In December 2011, UIDAI conducted a study using the enrolment of 84 million residents and obtained statistical results to measure the efficacy of use of biometrics for de-duplication of Indian population. The accuracy of actual recorded biometric was found to be several order higher than the accuracy achieveable by the critics. This analysis has resulted in the UIDAI releasing the paper “The Role of Biometric Technology in Aadhaar Enrollment” [Aadhaar, 2011].
  Some of the key findings of this paper include:

  1. Since both fingerprints and irises are being captured using high quality sensors, as well as the use of 3 different biometric service providers at the Central ID Repository, high levels of accuracy are being achieved in enrolling residents.
  2. On the effectiveness of biometric technology in Indian context with large number of rural/agricultural workers, the analysis has shown that the ‘Failure to Enroll’ (FTE) rate of the UIDAI Biometric system is at: 0.14%. This implies that 99.86% of the population can be

uniquely identified by the biometric system. Even the exceptions (0.14%) are checked manually and processed. The False Negative Identification Rate (FNIR) of the UIDAI system is computed to be as low as 0.035%. This implies that 99.965% of all duplicates submitted to the biometric de-duplication system are correctly caught by the system as duplicates.

3. The amount of hardware processing power needed by the UIDAI system is well within the design and expectations and has not increased in a non-linear fashion.

- Project National ID program (Indonesia).
  Summary: The main objective of indonesian NID Project is to acquire fingerprint, iris and face, for all of the approximately 172 millions residents of Indonesia and provide a national identity card in 2014 (http://www.thirdfactor.com/2012/09/24/indonesia-close-to-rolling-out-ambitious-biometric-based-national-id-card-project#top). The project will emit each citizen an official document called e-KTP card — an electronic national ID card to be used for a number of purposes including identification for voter registration, passport issuance, tax and financial applications.
  Citizens enroll at registration centers where their fingerprint, iris and face are captured as images using biometric equipment and along with their personal data stored as a record and inserted into their electronic identity card.
  In development since 2010, the e-KTP Technical Team, estimates that the program is emitting 8,000 cards daily with 118 million e-KTP records already stored in the country's databases. Future plans include building a foundation for authenticating local transactions by financial institutions [Novel, 2013].
- Next Generation Identification (NGI) project (USA) (http://www.concurringopinions.com/archives/2012/09/biometric-databases-and-quantitative-privacy.html). March 2013.
  Summary: NGI is a joint project of federal, state, and local law enforcement in USA. It is a nationwide network of databases containing images of the body's characteristics, such as fingerprints, iris, retina, voice, and face. Elementary schools, airports, gas providers, grocery stores, health clubs, workplaces, and even Disney's theme parks collect iris scans and fingerprints to secure access to physical plants and/or accounts. NGI is a "state-of-the-art identification system that will be bigger, faster, and better than IAFIS (Integrated Automated Fingerprint Identification System)". It is "bigger" because it will increase the capacity of fingerprint storage plus multimodal biometrics records like palm prints and iris scan and in the future others biometric technologies (voice, gait, etc.) as they become available. It is "faster" because it will speed up response time for high priority from two hours to about 10 minutes on average. It is "better" because going beyond fingerprints as biometric identifiers will enhance the identification processes.

- Project Biometric Standards (http://www.nist.gov/itl/iad/ig/biometric_standards.cfm). March 2013.
  Summary: This project develops biometric data exchange formats, biometric sample quality, biometric acquisition and processing protocols, and conformance testing methodologies standards (e.g., WSQ) that reflect the operational needs of U.S. government, including open source reference implementations, standard reference datasets and technical reports/guidance. This project has relevance and interaction across the other projects in the biometric world.

- Project BioSecure (http://svnext.it-sudparis.eu/svnview2-eph/ref_syst/). March 2013.
  Summary: Biosecure is a project of the 6th Framework Programme of the European Union. In this proyect has been developed biometric references and evaluation framework concerning to eight biometric modalities. It is comprised of five publicly available databases and ten benchmarking open-source reference systems (iris, face, fingerpring, hand, signature, and speech).

- Project: Iris Recognition at a Distance based on Automatic Acquisition and Robust Algorithm [http://www.nlpr.ia.ac.cn/english/research.htm]. March 2013.

  Summary: Iris recognition has many biometric advantages: uniqueness, stableness, anti-spoof, noninvasiveness and efficiency, so it is widely applied in e-passport, banking, forensics, welfare, Internet and assess control. The main of this project is how to improve the convenience of iris image acquisition and robustness of iris recognition algorithm. These both issues, acquisition and robustness, are still the challenging and unsolved problems in this area. This project aims to research and develop advanced iris recognition system, being able to identify subjects at a distance (1~3m) with a user-friendly interface. In this proposal, iris images are captured with the cooperation of wide-angle and Pan/Tilt/Zoom cameras. Face region could be automatically detected by wide-angle camera, and then iris region could be located and acquired with PTZ camera. New iris recognition algorithms will be proposed to process and analyze low-quality and distorted iris images. In this project, researchers attempt to break the constraint that subjects must stop and stare at iris camera for iris recognition, by using a new manner that machine could be self-adaptive to the distance, height, pose and motion of users.

The research of last decade indicates that using a combination of biometric avenues for human identification is more effective, but more challenging. The main teaching is that the future of identification systems is currently progressing beyond the dependency of a unimodal biometric identifier, as fingerprint or iris, or face, towards multimodal biometrics (iris, periocular, facial, fingerprint, palmpring, voice, etc.).

16 Discussion

In this section, the results of the main described issues on iris recognition systems are reviewed and commented. Particularly, we discusses about; a) the iris like biological organ with exceptional properties to identify the humans; b) the fundamental theoretical aspects of iris and its advantages of the iris for identification; c) the disadvantages of the iris for identification; d) the evolution of the iris technology from the NIR illumination in restricted conditions and short distances, to the white light illumination with unconstrained conditions and long distances; e) the computacional evolution of the iris recognition from the simple algorithms to the constellation of algorithms, and finally; f) the development of compact devices and hardware linked to iris recognition systems to increase the accuracy and speed in the applications.

A. The Iris like Biological Organ with Exceptional Properties to Identify the Humans: The human iris is an annular-shaped area between the pupil and the sclera, which is stable from the eighth month of gestation [Daugman, 2002]. A normal iris pattern shows hundreds of random texture features in its pigmentation. These features are unique for each individual, also in the case of homozygote twins. Moreover, the iris is well protected by the cornea and it is not affected by external factors, differently for example, from fingerprints, which are sensitive to skin conditions [Li and Savvides, 2009]. The high degree of randomness of the iris pattern is the key feature exploited in the iris biometric systems to produce reliable and robust biometric templates that allow to obtain a very high accuracy of the recognition process [Donida et al., 2012].

B. Advantages of the Iris for Identification: [http://www.cl.cam.ac.uk/ ~jgd1000/addisadvans.html**]** The iris of the eye has been described as the ideal part of the human body for biometric identification for several reasons [Shirke et al., 2012]:

– The iris is an organ with pre-natal morphogenesis (7th month of gestation).

- Limited genetic penetrance of iris patterns. Means the iris patterns are not hereditary.
- Iris patterns are apparently stable throughout the human life.
- Changing pupil size confirms natural physiology.
- Natural protection from external environment. The iris is an internal organ that is highly protected against damage and covered by a highly transparent and sensitive membrane (the cornea). This distinguishes it from fingerprints, which can be difficult to recognize after years of certain types of manual labor.
- Impossibility of surgically modifying the iris without risk of the vision.
- The iris is externally visible and its patterns can be scanned from a distance. Ease of registering image at some distance.
- The iris is mostly flat, and its geometric configuration is only controlled by two complementary muscles (the sphincter papillae and dilator papillae) that control the diameter of the pupil. This makes the iris shape far more predictable than, for instance, that of the face.
- The iris has a fine texture that —like fingerprints— is determined randomly during embryonic gestation. Like the fingerprint, it is very hard (if not impossible) to prove that the iris is unique. However, there are so many factors that go into the formation of these textures (the iris and fingerprint) that the chance of false matches for either is extremely low. Even genetically identical individuals have completely independent iris textures.
- The iris has high qualities to be accepted by people, because: An iris scan is similar to taking a photograph and can be performed from about 10 cm to a few meters away. There is no need for the person being identified to touch any equipment that has recently been touched by a stranger, thereby eliminating an objection that has been raised in some cultures against fingerprint scanners, where a finger has to touch a surface.

- The iris of each person is unique, because iris patterns possess a high degree of randomness:
    - variability: 244 degrees-of-freedom.
    - entropy: 3.2 bits per square-millimeter.
    - uniqueness: set by combinatorial complexity.
- Encoding and decision-making are tractable:
    - image analysis and encoding time: 30 milliseconds.
    - decidability index (d-prime): d' = 6 to 8 typically.
    - search speed: 1 million IrisCodes per second, with a 3 GHz CPU.

This set of positive properties of the iris, enhance its suitability for iris recognition systems because offer people's acceptability, a fast and secure method for the recognition of individuals, with the ability to perform accurate identification even with databases composed by several millions [Donida et al., 2012] of enrolled iris patterns.

C. Disadvantages of the Iris for Identification (http://www.cl.cam.ac.uk/~jgd1000/addisadvans.html**):**

- Small target (1 cm) to acquire from a distance (i.e., 1 meter).
- Moving target periodically and involuntary (...within another... on yet another).
- Located behind a curved, wet and reflecting surface.
- Obscured by eyelashes, lenses and reflections.
- Partially occluded by eyelids, eyelashes and shadows.
- Deforms non-elastically as pupil changes size.
- Some negative connotations: Generally, the applications use infrared rays to scan the iris of a person. Now consider a case that a person is going in and out of his workplace every day. Now he is in a situation that more amounts of infrared rays fall in his eye if he works at the same place for a long period. There are possibilities that his eye may get damaged due to the passage of infrared

rays and some optical diseases may affect him. This is the main disadvantage of iris technology yet.

D. Evolution of the Iris Technology

Iris recognition has been widely used for a large number of applications considering that the iris as a reliable personal identification method. Since a variety of iris devices produced by different vendors may be used for some large-scale applications, it is necessary to match heterogeneous iris images against the variations of sensors, illuminators, imaging distance and imaging conditions [Xiao et al., 2012].

E. Computational Evolution of the Iris Recognition Systems

The competitions NICE.I and NICE.II showed that the first iris isolation algorithms and iris matching algorithms have evolved from simple algorithms toward more complex algorithms every time. Certainly, the application conditions have been changed from NIR light and indoor ambients, toward natural light and outdoor ambients; from iris images captured without reflections and collaborative setups, without-the-move, towards iris images input with reflections and non-ideal conditions such as unconstrained, on-the-move, or noncollaborative setups and also at distance (1~3 mts). In the beginnings the iris recognition systems were designed to operate in ideal conditions, but the development has advanced toward security applications and video-surveillance in uncontrained conditions maintaining their high accuracy and speediness.

Under those new conditions the iris segmentation methods should solve problems of specular reflections, severe occlusions of many sources (eyelids, eyelashes, shadow, glass frame) and others problems like off-axis view angle, motion ghost and pupil deformations. For those causes, the iris segmentation algorithm could possess several sub-modules to stand face to face those challenges and/or the integration of several segmentation methods to find the inner and outter borders.

The strategies for iris features extraction could have a single feature extractor method or be integrated for several feature extractors methods. The last strategy extracts features of different nature for examples: numeric features like Gabor filter, qualitative feature like color, semamtics features like information on eyelashes localization. This variety of feature’s source contribute to high capacity to describes the iris patterns.

But the use of several iris features establish the necessity to do an appropriate maching process with each iris feature type. Besides, this demands the construction of a score level fusion keeping in mind each feature source in order to obtain a global fusion score, so that the iris system makes a decision: acepted or rejected. Equally, this means that the iris maching process has gone evolving from a single maching with a kind of iris matching distance, toward a coalition of iris matching distances with origins in several semantic sources. A process more powerful, but also more complex and more successful.

At the NICE.I competition the winner presented an iris segmentation algorithm that used several sub-modules to solve the occlusions and isolate the iris texture (clustering based coarse iris localization, inner and outer iris borders localization, eyelid localization and eyelash and shadow detection) [Tan et al., 2010]. While, at the NICE.II competition the winner presented an iris matching algorithm that used multiple iris features (texton histogram, semantic information, ordinal features, color histogram) [Tan et al., 2011] and a complex iris matching process considering each feature (Chi2 distance, XOR, SOBoost, Diffusion distance respectively). This computational evolution of the iris recognition systems is adapting to the new conditions with less restrictions for the practical applications in the real human activity.

F. Performance Evaluation of Iris Recognition Systems

Performance evaluation of iris recognition systems or algorithms determines their accuracy and usability. The performance measures are calculated for the evaluation of the identification and verification tasks, either to: a) know the state-of-art of biometric technologies, or b) quantify the effectiveness of a biometric system to execute the requirements of specific applications. Then, evaluation protocols and biometric databases for testing should be carefully designed to avoid influenced results or conclusions.

The elements that define a taxonomic classification of performance measures are their nature, and the phases of the evaluation process that are estimated by them, this classification allows their better selection for the evaluation of a biometric recognition system. In this study are picked up a set of a) fundamental performance measures; b) performance measures for verification systems; c) performance measures for identification systems; and d) graphic performance measures. On the other hand, we are also picked up a sep of benchmark software.

A benchmark is an obligatory reference because it is a software that has been rigorously evaluated using datasets and protocols that also fulfill requirements of high quality. The benchmarks for iris recognition normally are accompanied with open-source reference systems, publicly available databases for purpose of research, provide benchmarking assessment protocols which define the blocks of the evaluation framework, and also reports benchmarking results. A benchmarking is a reference point, like a standard through which something can be measured or evaluated as a product. A benchmarking is a rigorous evaluation. The mentioned iris image databases are benchmarkings.

Iris image databases are an important element to the development and advancement of iris-based biometrics. These databases along with evaluation methodologies allow for direct comparison of iris segmentation or recognition algorithm performance. Advances in the state-of-the-art on iris recognition have led to the apparition of a lot of databases, either as part of challenges or published for public use. The databases have evolved over time with algorithms or systems to assess. This evolution has led to more challenging databases with images captured at a distance, more challenging than traditional close-up iris images, more images with more realistic noise factors, visible wavelength iris images captured in heterogeneous lighting conditions, with strong appearance of highly degraded images.

During the last decade various benchmarking on iris technology were carried out with different objectives. The key elements of iris evaluation methodology are: the existence of open-source software, publicly available biometric databases, well defined evaluation protocols, and additional information (such as how-to documents) that allow the reproducibility of the proposed benchmarking experiments.

New implementation of metohodologies and evaluation frameworks offers to the developers the ability to evaluate large databases that are stored in a secured centralized server. As these systems are modality-independent, researchers can use the same protocol to perform different evaluations, and testing purposes. Additionally, such protocols can be plugged directly into end-user applications, minimising technology transfer costs using current international standards. For example, the evaluation protocol is based on ISO/IEC 19784–1, also known as BioAPI [ISO/IEC, 2005]. Developers will feed their compiled algorithms as a Biometric Service Provider (BSP), which is also the way of integrating the algorithm in a future identification or authentication solution.

G. Development of Compact Hardware and Apparatus Linked to Iris Recognition Systems

Of course, iris recognition is an important application in the defense ministries and homeland security. An algorithm that can be both accurate and fast, besides of small and transportable in a hardware designed are crucial to the implementation of an iris recognition tool. As part of an ongoing effort to meet these criteria, researchers have been improve a segment of the iris recognition algorithm. They are looking for a significant speed-up of pupil isolation by implementing this portion of the algorithm on a Field Programmable Gate Array (FPGA). The pupil isolation is the more important portion of any iris recognition algorithm.

Shafer et al., [2010] implemented a portion of the iris segmentation algorithm on an FPGA achieving a speed-up of up to 32 times. The hardware created using the Stratix IV is maximized because of its parallelism allowing for 36 thread-like processes to run simultaneously. The internal memory was maximized to keep access times low and allow for multiple reads per clock cycle. The ability to hardwire data into the design allowed for less look up tables and therefore shorter latency and higher clock frequency.

In the Speed benchmarks for the publically deployed algorithms [Daugman, 2012]. All image processing operations, including segmentation and template extraction, are performed within 30 milliseconds. The bit-parallel matching algorithm allows as many bits as the word-length of the computer (e.g.64 bits) to be compared in a single operation (1 machine instruction) between two IrisCodes. Exploitation of ergodicity in (non-identical) IrisCode comparisons by subsampling and “early exit”, further accelerates matching. Routine matching speeds are a million IrisCodes per second, per ordinary (single-core) CPU. Indexing accelerates this by 1 or 2 orders-of-magnitude, e.g.50 nanoseconds including all rotations.

Within the biometric context, the iris is usually accepted as one of the most accurate traits and has been successfully applied in such distinct domains as airport check-in or refugee control. However, for the sake of accuracy, present iris recognition systems require that subjects stand close (less than two meters) to the imaging device and look for a period of about three seconds until the data is captured. Upon these constrains some contests were performed, whose aim was the evaluation of the recognition accuracy on noise-free data. (e.g., the Iris Challenge Evaluation, ICE).

However, the cooperative behavior demanded to the users and the highly constrained imaging conditions clearly restrict the range of domains where iris recognition can be applied. It is highly probable that image capturing on less constrained conditions (either at-a-distance, on-the-move, with minor users' cooperation and within dynamic imaging environments) lead to the appearance of extremely heterogeneous images and with several other types of data in the captured iris regions (e.g., iris obstructions due to eyelids or eyelashes, reflections, off-angle or motion blurred images). For the terms of this contest, all these factors are considered as noise (http://nice1.di.ubi.pt/).

17 Conclusions

Iris recognition nowadays is considered as one of the most accurate biometric recognition techniques. However, the overall performances of such systems can be reduced in non-ideal conditions, such as unconstrained, on-the-move, or noncollaborative setups.

The four basic modules that compose an iris recognition system are: iris image acquisition, iris image segmentation, iris texture analysis for their features representation and iris matching representations. In the following paragraphs we will expose the main facts of the state-of-art in these 4 modules:

- **Conclusions on Iris Image Acquisition**: The image acquisition module is usually composed by cameras that capture images in the near infrared range (700−900nm). The ISO Iris Image Standard requires that the length of the iris diameter is at least 200 pixels. The user cooperation is usually required in order to properly capture the iris image. Even after 20 years in the iris image adquisition activity exists a frontier that should be overcome to use iris recognition in ambients in which there is not user cooperation, or in open ambients where it is necessary to use cameras that capture images in the visible band of light (400nm –700nm) in unconstrained environments (e.g. outdoors). In this ambient corneal reflections are common, because the cornea is a specular surface. The issues of image acquisition and robustness of iris recognition algorithm in such conditions are still the challenging and unsolved problems in this area. New cameras for iris image capture at distance can be developed in non-ideal conditions.
- **Conclusions on Iris Image Segmentacion**: The image segmentation module performs the localization of the iris in the image and removes the areas corresponding to eyelids and eyelashes occlusions, glass frame occlusion, specular reflections and shadows. Also before segmentation. Typically, the iris segmentation is the most time-consuming step and its effectiveness is relevant

because the obtained accuracy strongly influences the results of the biometric system . An incorrectly segmented iris, in fact, can result in errors of the matching module.

The iris segmentation is usually performed in two steps: first the inner and outer boundaries of the iris region are estimated, then occlusions and reflections are detected and removed. It is possible to divide the methods for the estimation of the inner and outer iris boundaries in six classes: methods based on circumferences, methods based on a-priori models, methods based on the analysis of local characteristics, active contours methods, hybrid and incremental methods, methods that do not fall in any of the above mentioned classes.

The methods based on the approximation of the iris boundaries by two circumferences contains well-known methods for the iris segmentation, such as algorithms based on an integro-differential operator, and on the Hough transform.

However, in the case of degraded or noisy iris images, it can be necessary to use more information in order to obtain accurate results. For this reason, the approaches based on the analysis of local features consider the information related to the iris texture. Moreover, many of these methods do not make any assumptions about the iris shape. Also the methods based on active contours do not perform assumptions regarding the iris shape. These methods combine an iterative contour growing with shape constraints, in order to better match the boundaries of the iris without introducing noise errors due to local image variations. Differently, the hybrid and incremental methods combine techniques from different classes, performing the iris segmentation in an incremental way. Other methods are not easily classifiable, such as a method designed for a special biometric device, a method that performs the iris segmentation by using morphological operators, and a method that combines different new algorithms.

A critical step of the recognition process is the segmentation of the iris pattern in the input face/eye image. This process has to deal with the fact that the iris region of the eye is a relatively small area, wet and constantly in motion due to involuntary eye movements. Moreover, eyelids, eyelashes and reflections are occlusions of the iris pattern that can cause errors in the segmentation process. As a result, an incorrect segmentation can produce erroneous biometric recognitions and seriously reduce the final accuracy of the system.

- **Conclusions on Feature Extraction and Representation:** The feature extraction module is based on algorithms that analyze the segmented iris image and extract the distinctive texture features from the iris pattern. These features are then used in order to compute an abstract representation called template during enrollment of individuals, and called input patterns in authentication-identification process. One of the most commonly used templates is the IrisCode designed by [Daugman, 1993].
- **Conclusions on Iris Matching Representation**: This last module computes a matching distance between two or more templates, in order to determine if they belong to the same person. In most of the cases, the matching value is computed as the Hamming Distance between input and template patterns.

From among methods of recognizing human characteristics, methods using irises have been actively studied theoretic and practically, because the methods using irises have been higher accuracy, higher stability and higher authentication speeds. However, the methods using irises have disadvantages in that the methods are sensitive to surrounding environment such as ambient light or reflected light of illumination and noisy generated due to the eye blinking of a user reduces the accuracy of iris recognition. In order to increase a recognize accuracy some methods of detecting pupil region which are robust against reflected light and a method of detecting eyelid and eyelashes in noisy iris images for noncooperative iris recognition have been suggested. However, recognition accuracy is still reduced because an iris region is occluded by eye blinking or ambient noise is generated when an iris image is acquired from an eye image.

Iris-based biometric recognition outperforms other biometric methods in terms of accuracy, and therefore iris recognition systems have made tremendous inroads over the past decade, but work remains to improve their accuracy in environments characterized by unfavorable lighting, large stand-off distances, and moving subjects.

18 Challenging in Iris Recognition

Measuring real progress achieved with new research methods and pinpointing the unsolved problems is only possible within a well defined evaluation methodology [Petrovska- Delacretaz´ et al., 2009]. This point is even more crucial in the field of biometrics, where development and evaluation of new biometric techniques are challenging research areas.

One of the most critical tasks of the iris recognition process is the extraction of the area occupied by the iris pattern in eye/face images, task called iris segmentation or also iris isolation. An incorrect estimation of this area, can result in erroneously recognitions. Iris segmentation methods have to deal with the fact that the iris region of the eye is a relatively small area, wet and constantly in motion due to involuntary eye movements. Moreover, reflections and occlusions caused by eyelids and eyelashes can be present in the captured images. These problems are more important for the images captured in non-ideal conditions, such as unconstrained, on-the-move, or non-collaborative setups [Donida et al., 2012].

A medullary question is, how to improve the convenience of iris image acquisition and robustness of iris recognition algorithm?. These both issues, acquisition and robustness, are still the challenging and unsolved problems in this area. It is needed more research and develop advanced iris recognition system, being able to identify subjects at a distance (1~3m) with a user-friendly interface. The researchers attempt to break the constraint that subjects must stop and stare at iris camera for iris recognition. They tries to obtain a "new manner that machine could be self-adaptive to the distance, height, pose and motion of users" [Tan et al., 2013].

Today are active research areas in iris acquisition with less constrained imaging conditions the followings:

- iris on-the-move (normal walking, 1 meter/sec).
- iris at-a-distance (3 meters, even 10+ meters?).
- iris off-axis (deviated gaze: not looking at camera).
- iris recognition in ambient under uncontrolled illumination.
- iris recognition in unsupervised conditions (countermeasures against spoofing attacks).
- iris recognition at reduced resolution.

The "Grand Challenge" in iris recognition is to have an effective algorithm for individual verification or identification under a broad range of image and environmental conditions [Lee et al., 2011]. Researchers are working hard in both baseline performance results (verification and identification) for increase the iris systems accuracy.

The research of last decade indicates that using a combination of biometric avenues for human identification is more effective, but more challenging. The main teaching is that the future of identification systems is currently progressing beyond the dependency of a unimodal biometric identifier, as fingerprint or iris, or face, towards multimodal biometrics (iris, periocular, facial, fingerprint, palmpring, voice, etc.).

Considering that Iris recognition is still relatively new (20 years old) there is a need for continued research and tests in the following areas: new challenges, limitations well-known and answer the unknown questions.

Daugman summarized these aspects with its words: "expanding the envelope for iris acquisition: getting beyond the "in your face" iris camera and the "stop and stare" user interface; achievements of "iris at a distance" and "iris on the move." Doing all the image processing and encoding at the video frame-rate (30 Hz). Bit-parallel match logic and parallelisability of database searches, with benchmark 1 million iris comparisons per second per single-core CPU. Use of codex and indexing methods when even that is not fast enough. What can we say about the uniqueness and non-collision of iris patterns when (so far) only 1.2 millions-million iris pair comparisons have been performed. Anti-spoofing countermeasures [Daugman, 2012].

Through the determination and commitment of research organizations, scientific evaluations, and organized standards bodies, growth and progress will continue, raising the supporter for iris recognition Technology.

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