

N° d'ordre :

REPUBLIQUE ALGERIENNE DEMOCRATIQUE & POPULAIRE
MINISTÈRE DE L'ENSEIGNEMENT SUPERIEUR & DE LA RECHERCHE
SCIENTIFIQUE



UNIVERSITE DJILLALI LIABES
FACULTE DES SCIENCES EXACTES
SIDI BEL ABBES

THESE DE DOCTORAT

DE 3ème CYCLE

Présentée par

ZOUBIDA LEILA

Domaine : Informatique

Filière : Informatique

Intitulé de la formation : Informatique

Intitulée

Reconnaissance des Formes Appliquée à la Biométrie

Soutenue le : 24-Juin-2018

Devant le jury composé de :

P résident : -Dr Toumouh Adil MCA Université Djillali Liabes de Sidi Bel Abbès

Examinateurs :

- Dr Amar Bensaber Djamel	MCA	ESI De Sidi Bel Abbès
- Dr Keskes Nabil	MCA	ESI De Sidi Bel Abbès

Directeur de thèse :

- Pr. Feraoun M. Kamel	Prof	Université Djillali Liabes de Sidi Bel Abbès
------------------------	------	--

Co-Directeur de thèse :

- Dr. Adjoudj Réda	MCA	Université Djillali Liabes de Sidi Bel Abbès
--------------------	-----	--

Année universitaire : 2017/2018

Abstract:

The pattern recognition is an active area of research. Its main goal is to develop intelligent systems which can be able to learn and to reason. Indeed, the pattern recognition methods find applications in several areas. An important part of these applications is attracted to the biometric which is used in several areas and especially in the security applications. The biometric is based on the use of the physical or the behavioral biometric modalities. The choice of modalities is important for the success of the security systems. Among the different biometric traits, we choose to combine the face with the both irises which are considered as the most used biometric modalities.

This thesis proposes a multi-biometric technique based on the integration of the face with the both irises (the left and the right irises) in order to realize the authentication task. This fusion allows combining the advantages of the both modalities. For the both instances of the iris, the segmentation step is realized by a modified method. While the features extraction of the face and the iris is done by a global approach (the Daubechies wavelets). The scores for the fusion are obtained by the Support Vector Machines SVMs. Then, the scores obtained are normalized by the Min-Max method. The fusion is performed at the score level by an integration technique, combining two approaches, namely combination, and classification. The obtained results have confirmed that the proposed multi-biometrics systems are better than the mono-modal systems.

ملخص:

التعرف على الأشكال يمثل مجالاً نشطاً للأبحاث. هدف الرئيسي هو تطوير الأنظمة الذكية التي تكون قادرة على التعلم والتفكير. في الواقع أن أساليب التعرف على الأشكال لديها تطبيقات في عدة مجالات . يندرج جزء هام من هذه التطبيقات إلى القياسات الحيوية التي يتم استخدامها في العديد من المجالات وخاصة في التطبيقات الأمنية. تُعتمد القياسات الحيوية على استخدام طرق القياس الحيوي الفيزيائية أو السلوكية. اختيار القياسات يعتبر مهمًا لنجاح الأنظمة الأمنية. من بين هذه القياسات المختلفة اخترنا دمج الوجه وكلا العينين التي تعتبر من القياسات الحيوية الأكثر استعمالاً.

تقرح هذه الأطروحة تقنية متعددة القياسات الحيوية والتي تجمع بين الوجه والعينين (الفرجع اليسرى والفرجع اليمنى) للتحقق من الهوية. هذا الدمج يسمح بالجمع بين مزايا كلا القياسين. مرحلة تجزئة الفرجتين تمت بطريقة معدلة في حين أن استخراج ميزات الوجه والفرجع تم بطريقة عامة (الموجبات). تم الحصول على النتائج من أجل الدمج بطريقة شاع الدعم الآلي. ثم تم تطبيق النتائج المتحصل عليها بطريقة الدلائل الأخرى والحد الأدنى. الدمج كان على مستوى النتائج خلال تقنية تجمع بين طريقتين: طريقة الجمع وطريقة التصنيف. وأكيدت النتائج المتحصل عليها أن الأنظمة متعددة القياسات الحيوية المقترنة أفضل من الأنظمة أحدادية القياسات الحيوية.

Résumé:

La reconnaissance des formes est un domaine de recherche actif. Son principal objectif est de développer des systèmes intelligents capables d'apprendre et de raisonner. En effet, les méthodes de reconnaissance des formes trouvent des applications dans plusieurs domaines. Une partie importante de ces applications est reliée à la biométrie, cette dernière est utilisée dans plusieurs domaines et spécialement dans la sécurité. La biométrie est basée sur l'utilisation des modalités biométriques physiques ou comportementales. Le choix des modalités est important pour le succès des systèmes de sécurité. Parmi les différents traits biométriques, nous combinons le visage et les deux yeux qui sont considérés comme des modalités biométriques les plus utilisées.

Cette thèse propose une technique multi-biométriques basée sur l'intégration du visage et les deux yeux (l'œil gauche et l'œil droit) dans le but de l'authentification des personnes. Cette intégration ou fusion combine les avantages des deux modalités. Pour les deux instances de l'œil, l'étape de segmentation est réalisée par une méthode modifiée. Tandis que l'extraction des caractéristiques du visage et de l'œil se fait par une approche globale (les ondelettes de Daubechies). Les scores de fusion sont obtenus par la méthode des machines à vecteurs de support SVMs. Ensuite, les scores obtenus sont normalisés par la méthode MIN-MAX. La fusion est réalisée au niveau des scores par une technique d'intégration, combinant les deux approches, la combinaison et la classification. Les résultats obtenus confirment que les systèmes multi-biométriques sont mieux cotés que les systèmes mono-modaux.

ACKNOWLEDGMENTS

First and foremost, I would like to thank ALLAHE Almighty for giving me the strength, courage, and patience to finish this work.

Second, I would like to express my sincere appreciation to my thesis supervisors, Pr. FERAOUN MOHAMED KAMEL and Dr. ADJOUDJ REDA for their guidance, encouragement, inspiration, and continuous support through the course of this work. I also thank them for their human qualities and for always encouraging me to move forward.

I would then like to thank the members of the jury Dr. TOUMOUH ADIL, Dr. AMAR BENSABER DJAMEL, and Dr. KESKES NABIL for the honor of agreeing to judge this work.

Special Thanks are also extended to Dr. CHIKHAOUI AHMED of Ibn Khaldoun university of Tiaret for his help. Also I would like to think Mr. OKACHA BEN AHMED DAHO of university of Limoges.

Finally, this work is dedicated to my dear parents who have been the pillar of strength in all my endeavors. I am always deeply indebted to them for all that they have given me. I also thank my sister, and my brothers for their endless confidence, encouragement, and patience.

LEILA

TABLE OF CONTENTS:

INTRODUCTION	2
--------------------	---

CHAPTER I: THE PATTERN RECOGNITION

1.1 Introduction	6
1.2 Principles & Definitions	6
1.3 Steps of the Pattern Recognition Process	8
1.3.1 Acquisition	9
1.3.2 Features Extraction.....	10
1.3.3 Classification	10
1.3.4 Decision.....	11
1.4. Applications of the Pattern Recognition.....	12
1.5 Conclusion.....	13

CHAPTER II: THE BIOMETRICS

2.1 Introduction	15
2.2 Principles & Definitions	15
2.3 Properties of the Biometric Modalities.....	16
2.4 Why We Use the Biometrics?	17
2.5 Different Biometric Modalities	18
2.5.1 Face (Facial Recognition, Facial Thermography, Iris, and Retina).....	20
2.5.1.1 Facial Recognition.....	20
2.5.1.2 Facial Thermography.....	20
2.5.1.3 Iris.....	20
2.5.1.4 Retina.....	21
2.5.2 Hand (Fingerprints, Hand Geometry, Veins, and Nails)	21
2.5.2.1 Fingerprints	21
2.5.2.2 Hand Geometry	23
2.5.2.3 Veins.....	23
2.5.2.4 Nails.....	24
2.5.3 Bio-dynamics (Voice, Signature, and Gait).....	24
2.5.3.1 Voice	24
2.5.3.2 Signature.....	24
2.5.3.3 Gait.....	25
2.5.4 Keystroke.....	25
2.5.5 Corporal Odor.....	25
2.5.6 Ear	25

2.5.7	DNA	25
2.5.8	Heartbeat	26
2.6	Biometric Characteristics	30
2.7	Biometrics Systems and their Operating Modes	31
2.7.1	Modules of the Biometric Systems.....	31
2.7.2	Operating Modes of the Biometric Systems.....	32
2.7.2.1	Enrolment	33
2.7.2.2	Authentication	33
2.7.2.3	Identification	34
2.8	Limitations of the Biometric Systems	34
2.9	Evaluation of The Biometric Systems	36
2.9.1	Performance.....	37
2.9.1.1	Errors Rates Measures.....	38
2.9.1.1.1	Fundamental Errors Rates.....	38
2.9.1.1.2	Errors Rates of the Authentication System	38
2.9.1.1.3	Errors Rates of the Identification System	39
2.9.1.2	Processing Time and Memory Occupation Measures	39
2.9.1.3	Performance Curves	39
2.9.1.4	Performance Points.....	40
2.9.2	Data Quality	41
2.9.2.1	Definition of Data Quality.....	42
2.9.2.2	Factors Degrading the Data Quality	42
2.9.3	Usability	44
2.9.4	Security.....	45
2.10	Biometric Applications.....	45
2.11	Conclusion.....	46

CHAPTER III: THE MULTI-BIOMETRICS

3.1	Introduction	48
3.2	Multi-Modality	48
3.3	Design of the Multi-Biometrics Systems	51
3.4	Classification of the Multi-Biometrics Systems.....	52
3.4.1	Multi-Sensors Systems	52
3.4.2	Multi-Algorithms Systems	53
3.4.3	Multi-Samples Systems	55
3.4.4	Multi-Units Systems	55
3.4.5	Multimodal Systems	55
3.4.6	Hybrid Systems	57
3.5	Fusion Levels	58
3.5.1	Before the Matching	58

3.5.1.1	Sensor Level	58
3.5.1.2	Feature Level.....	58
3.5.2	After the Matching	59
3.5.2.1	Dynamic Selection of Classifiers	60
3.5.2.2	Rank Level	60
3.5.2.3	Score Level.....	60
3.5.2.4	Decision Level.....	60
3.6	Architectures	65
3.7	Multimodal Database Design	66
3.8	Conclusion.....	68

CHAPTER IV: THE MODALITIES CHOSEN FOR THE AUTHENTICATION

4.1	Introduction	70
4.1	Why this choice?	70
4.2	Facial Authentication	72
4.2.1	Related Works	72
4.2.2	Face Databases	74
4.2.3	Face Recognition Process.....	76
4.3	Iris Authentication	77
4.3.1	The Iris	78
4.3.2	Related Works	79
4.3.3	Iris Recognition Process.....	82
4.3.3.1	Iris Segmentation.....	82
4.3.3.2	Iris Normalization.....	87
4.3.3.3	Features Extraction.....	88
4.3.3.4	Matching.....	89
4.3.4	Difficulties of the Iris Recognition Process.....	90
4.3.5	Iris Databases	91
4.4	Conclusion.....	97

CHAPTER V: THE PROPOSED APPROACH

5.1	Introduction	99
5.1	Fusion Level	99
5.2	Related Works	100
5.3	The Proposed Approach	105
5.3.1	Architecture and Structure of the System.....	105
5.3.2	Steps of the Proposed Approach.....	107
5.3.2.1	Capture Module	108
5.3.2.2	Detection Module	108

5.3.2.2.1	The Face.....	108
5.3.2.2.2	The Iris.....	108
5.3.2.3	Features Extraction Module	112
5.3.2.4	Matching Module	112
5.3.2.4.1	Description of the Support Vector Machines.....	113
5.3.2.4.2	Binary Classification.....	113
5.3.2.4.3	Multi-Class.....	115
5.3.2.5	Scores Normalization	116
5.3.2.6	Fusion Module.....	116
5.3.2.6.1	Fusion Approaches.....	116
5.3.2.6.1.1	Combination Approach.....	117
5.3.2.6.1.2	Classification Approach.....	117
5.3.2.6.2	The Proposed Fusion Approach.....	118
5.3.2.7	Decision Module	121
5.5.	Conclusion.....	121

CHAPTER VI: THE EXPERIMENTAL RESULTS

6.1	Introduction	123
6.2	Experimental Results.....	123
6.2.1	Multi-Units System (the Left and the Right Irises)	123
6.2.1.1	Description of Databases	123
6.2.1.2	Results and Discussions	124
6.2.2	Multi-biometrics System (the Face, the Left, and the Right Irises).....	129
6.2.2.1	Description of Database	129
6.2.2.2	Results and Discussions	132
6.2.2.2.1	Variations Results	132
6.2.2.2.2	Settings Results.....	141
6.3	Comparison	147
6.4	Conclusion.....	149
	CONCLUSION	150
	REFERENCES	152

LIST OF FIGURES:

Figure1. 1: The pattern recognition process.....	9
Figure 2. 1: The different biometric modalities.....	19
Figure 2. 2: Generic architecture of the biometric system.	32
Figure 2. 3: The enrolment of person in the biometric system.	33
Figure 2. 4: Authentication of an individual by the biometric system.	33
Figure 2. 5: Identification of an individual by the biometric system.	34
Figure 2. 6: Evaluation of the biometric system.....	37
 Figure 3. 1: Sources of multiple evidences of identity in the multi-biometrics systems.....	52
Figure 3. 2: Architecture of the feature level fusion system.	59
Figure 3. 3: Architecture of the score level fusion system.	60
Figure 3. 4: Architecture of the decision level fusion system.	61
Figure 3. 5: Summary of the fusion approaches in the multi-biometrics systems.....	64
Figure 3. 6: Architecture of fusion in parallel.	65
Figure 3. 7: Architecture of fusion in series, incremental, or sequential.....	66
Figure 3. 8: The architectures of the multimodal databases design.....	67
 Figure 4. 1: The Zephyr Analysis: comparison of the different modalities.....	71
Figure 4. 2: The face authentication process	77
Figure 4. 3: The iris pattern.	79
Figure 4. 4: An image of the eye.	83
Figure 4. 5: Image of the eye (a), various images of edges by canny method: diagonal edges (b), horizontal edges (c) or vertical edges (d).	86
Figure 4. 6: The image of the eye , a segmented iris image, and a normalized iris image.....	88
Figure 4. 7: Example of iris images (CASIA4).	94
Figure 4. 8: Examples of the different iris databases.	96
 Figure 5. 1: The architecture of the multi-biometrics system.....	105
Figure 5. 2: The multi-biometrics system structure.....	107
Figure 5. 3: The diagram of the iris segmentation process.....	111
Figure 5. 4: Examples of the iris segmentation.	112
 Figure 6. 1: ROC plot showing the performance of: the left iris authentication, the right iris authentication, the fusion by (SVM, CP, CS, CMI, and CMA) on (a): CASIA Database; (b): SDUMLA-HMT Database; (c): MMU1 Database; (d): MMU2 Database.....	127
Figure 6. 2: Evaluation using the AUROC.....	129
Figure 6. 3: The first subject of the face SDUMLA-HMT database with the different variations.....	131
Figure 6. 4: The first subject of the iris SDUMLA-HMT database.....	132
Figure 6. 5. ROC plot showing the performance of the authentication on SDUMLA-HMT Database:(a):BD1, (b):BD2,(c):BD3, (d):BD4, (e):BD5, (f):BD6, (g):BD7, (h):BD8, (i):BD9, (j):BD10, (k):BD11, (l):BD12.....	137
Figure 6. 6: Camera settings.....	142
Figure 6. 7: The subject (N°103) of the face SDUMLA-HMT database captured according to the camera settings.	142
Figure 6. 8: ROC plot showing the performance of the authentication by: the face, the left iris, and the right iris, the fusion by (SVM, CP, CS, CMI, CMA, and CME) on SDUMLA-HMT Database:(a):C1, (b):C2,(c):C3, (d):C4, (e):C5, (f):C6, (g):C7.....	144

LIST OF TABLES:

Table 2. 1: Comparing the traditional methods with the biometric.....	18
Table 2. 2: Comparing some biometric technologies.....	29
Table 2. 3: The characteristics of some biometric modalities.....	31
Table 2. 4: Some factors having an impact on the biometric data quality.....	44
Table 3. 1: Examples of the multi-sensors systems.....	53
Table 3. 2: Examples of the multi-algorithms systems	54
Table 3. 3: Examples of the multi-units and the multi-samples systems.....	55
Table 3. 4: Examples of the multimodal systems.....	56
Table 3. 5: Comparison of the multi-biometrics systems.....	57
Table 3. 6: Some studies with their fusion levels, and their fusion methodologies.....	63
Table 4. 1: Facial recognition techniques.....	74
Table 4. 2: Examples of the iris recognition methodologies.....	82
Table 4. 3: Examples of the iris detection methods.....	84
Table 4. 4: Examples of the iris features extraction methods.....	89
Table 4. 5: Statistics of CASIA-Iris1, CASIA-Iris2, CASIA-Iris3, and CASIA-Iris4	93
Table 5. 1: Examples of multi-biometrics studies based on the integration of face with iris.....	104
Table 6. 1: Description of databases used for the evaluation of the multi-units system.	124
Table 6. 2: Evaluation of performance of multi-units system using EER and AUROCC criteria	128
Table 6. 3: Description of some characteristics of the database used for the test of our multi-biometrics system.	133
Table 6. 4: Evaluation of the performance of the multi-biometrics (variation) system using EER and AUROCC criteria.	138
Table 6. 5: Evaluation of the performance of the CS approach (variation result) using FAR, FRR, Accuracy, and error rate.	140
Table 6. 6: Confusion Matrix (CS Approach on the database BD10).	140
Table 6. 7: Evaluation of the performance of the multi-biometrics (setting) system using EER and AUROCC criteria.	145
Table 6. 8: Evaluation of the performance of the CS approach (setting result) using FAR, FRR, Accuracy, and error rate.	146
Table 6. 9 : Confusion Matrix (CS Approach on the database C4)....	146
Table 6. 10: Summary of some results of the multi-biometrics systems based on the fusion of the face and the iris between 2003 and 2017, including our proposed approach.....	148

GLOSSARY OF THE IMPORTANT TERMS:

ACC:	Accuracy.
AUROCC/AUC:	Area Under the ROC Curve.
CMA:	Classification + Max.
CME:	Classification + Mean.
CMI:	Classification + Min.
CP:	Classification + Product.
CS:	Classification + Sum.
EER:	Equal Error Rate.
FAR:	False Acceptance Rate.
FN:	False Negative.
FP:	False Positive.
FRR:	False Rejection Rate.
NPV:	Negative Predictive Value.
PPV:	Positive Predictive Value.
PR:	Pattern Recognition.
ROC:	Receiver Operating Curve.
SVM:	Support Vector Machines.
TER:	Total Error Rate.
TN:	True Negative.
TNR:	True Negative Rate.
TP:	True Positive.
TPR:	True Positive Rate.

INTRODUCTION

The pattern recognition is an active area of research, its goal is to design and develop intelligent systems which can be able to learn and to reason. Today, there are several methods in the pattern recognition field, but the state of the art of several works in this field indicates that there is no generic method which can be applicable to all the pattern recognition problems. Therefore, the sentence stated by kanal “*a bag of tools and a bag of problems*” (**Kanal,1974**) is still valid after years of research despite the many works in this field.

However, the pattern recognition methods find applications in several areas. An important part of these applications is attracted to the biometric, so the biometric is considered as one of the most important applications in the domain of the pattern recognition. It has a wide use and especially in the security applications. For several years, there are many efforts made in the biometric research due to the security situation in the social and the business sectors in the world which is currently a strong reason that led to work on this topic.

The biometric is the measure of the physical characteristics (the face, the iris, the retina, and the fingerprints, etc.) or the behavioral characteristics (the signature, the gait, and the keystroke, etc.) in order to identify or authenticate a person. The biometric systems that used one biometric trait are called unimodal systems. The unimodal biometric systems are certainly more performance than the use of the traditional means of identification such as the cards, the keys, and the passwords, due to the performant link between the individual and his identity, but these systems present certain limitations. Firstly and most importantly, they cannot ensure an excellent recognition rate. Then, they are affected by several problems such as the non-universality and the sensitivity to noises; also they are vulnerable to the attacks. However, the most of these problems can be reduced by the integration of multiple biometric modalities. So the multimodal systems can solve the problems of the unimodal systems.

The choice of modalities is one of the most important key for the success of the biometric system. In this thesis, we choose to combine the face modality with the both units of the iris modality. We choose these two modalities due to the natural link between them. Also, the face modality is one of the most natural ways to recognize a person, it is non-intrusive, and it doesn't reach the privacy of the individual. Then, the iris modality is currently considered as one of the most accurate because it characterized by a high level of precision, and it is

difficult to falsify. In addition, the iris is stable during the life of person, and its texture is one of the richest distinctive textures of the human body due to the combination of several elements. Therefore, the iris has a unique feature which is protected from the outside, and at the same time it is relatively easy to acquire compared to other internal organs such as the retina. As well the both modalities can be acquired using the same camera simultaneously, and this is can be considered as independent biometric traits. So, one capture device with very high resolution would analyze simultaneously the texture of the iris and the face of the person. This is allowed to work with a unique system of capture instead of two. In addition, this choice is confirmed by the Zephyr analysis. So, we use these two modalities to create a multi-biometrics system. The challenge is to improve the performance of this biometric system by finding an original fusion method that gives a recognition rate of the fused modalities higher than the recognition rate of the modalities taken separately.

The iris recognition made the objective of one of the proposed monomodal biometric systems. In this context, we have met several problems, especially in the iris localization phase due to the various noises such as the eyelashes, the eyelids, the reflections, and the uncontrolled movements of the eyes. Therefore, we proposed a modified method for the iris segmentation to overcome these different difficulties.

This work proposes a standard method that can apply to the both modalities, concerning the features extraction and the matching steps. Therefore, the Daubechies wavelets are used for the features extraction step, and the matching score for each modality is calculated by using the SVM method, then the scores obtained are normalized by the Min-Max method. The final score is generated by using the integration of two methods which are: the combination method and the classification method, which is then passed to the decision module.

This thesis proposes a multi-biometrics technique which combines the face modality with the both irises (the left and the right irises). The fusion of these two traits biometrics combines the advantages of the both instances of the iris with the face modality. This technique is operated in the authentication mode, and it addresses the score level fusion. However, we have proposed an integration approach of the face and the both units of the iris modality (the left and the right irises) which is operated at the score level by the integration of two approaches, namely combination, and classification. However, this classification method is used for the first time in this field.

Indeed, this work is based on a multi-biometric technique that follows the principle of multi-units system, combined with multi-samples system, added to multi-algorithms system,

and multi-modal system. In fact, the system is interested in recognizing persons by their both irises (the principle of multi-units). It is also attracted to the facial recognition by taking account of the changes in the facial pose such as the front, the left, and the right profile of the face (the principle of multi-samples). In addition, it integrated the both modalities: the face and the iris (the principle of multi-modal). For this, the SVM was used to obtain the scores, while the fusion is based on the integration of two methods: a combination method with classification method (the principle of multiple algorithms). So, the system can be classified as hybrid as follows the four scenarios (the multi-units, the multi-samples, the multi-modal, and the multi-algorithms).

This thesis contains six chapters which are:

- Chapter 1 “*The pattern recognition*”: This first chapter is an introduction to the pattern recognition field. However, it presents some principles and definitions in this area. Also, it describes the different steps of the pattern recognition process. In addition, it gives some applications in this field.
 - Chapter 2 “*The biometrics*”: It defines the biometric, and it presents the different modalities with their characteristics, their advantages, their disadvantages, and their applications. It also describes the different operating modes of the unimodal biometric systems, their limitations, and their evaluation in order to decrease these limitations. Then, it gives some biometric applications.
 - Chapter 3 “*The multi-biometrics*”: This chapter gives the state of the arts of the multi-biometrics fusion. It presents the multi-biometrics systems, their design, their classification, their fusion levels, and their architectures.
 - Chapter 4 “*The modalities chosen for the authentication*”: It presents the state of the arts by insisting on the facial recognition and the iris recognition since we choose to integrate these two modalities.
 - Chapter 5 “*The proposed approach*”: This chapter describes the proposed approach, and it details its different steps.
 - Chapter 6 “*Implementation and results*”: It is the last chapter which is dedicated to the implementation, it shows the experimental results and the discussions, also it compares the results obtained by our system to other systems in the literature which are based on the integration of the face with the iris modalities.
 - Finally, an overall conclusion will present the results of this work and few prospects.
-

CHAPTER I: THE PATTERN RECOGNITION

This chapter is an introduction to the pattern recognition. However, it presents some principles and definitions in this field. Also, it illustrates the different steps of the pattern recognition process. In addition, it describes some applications in this field. This first chapter is organized as follows:

Summary:

- 1.1 Introduction
 - 1.2 Principles & Definitions
 - 1.3 Steps of the Pattern Recognition Process
 - 1.3.1 Acquisition
 - 1.3.2 Features Extraction
 - 1.3.3 Classification
 - 1.3.4 Decision
 - 1.4 Applications of the Pattern Recognition
 - 1.5 Conclusion
-

1.1 INTRODUCTION

The pattern recognition is an active area of research which includes various applications. It is a branch of the artificial intelligence that appeals to the techniques of the machine learning and statistics. Its aim is to design and develop intelligent systems which can be able to learn and to reason. So we can define the pattern recognition as the set of techniques that allow replicating the human perception.

This first chapter presents an introduction to the pattern recognition. In the first part of this chapter, we will describe some principles of the pattern recognition. We will then enumerate the different steps of the pattern recognition process. In addition, we will present some tools used to classify the patterns that exist in the literature. Finally, we will give some examples of the applications of the pattern recognition field.

1.2 PRINCIPLES & DEFINITIONS

The principle of the pattern recognition is to classify new forms using a classifier that generates a function of belonging to each class. Thus the classification of a new point may be based on the value of belonging that it gets from each class.

In the literature, there is no lack of definitions for the pattern recognition (PR). In this section, we will cite some definitions that exist in the literature:

- The definition of the PR in the opinion of *Fukunaga* (1972) is mentioned in (**Bezdek,2006**): “pattern recognition consists of two parts: Feature selection and classifier design” (**Fukunaga,1972**).
 - The definition of the PR according to *Duda* and *Hart* (1973) is cited in (**Bezdek,2006**): “pattern recognition, a field concerned with machine recognition of meaningful regularities in noisy or complex environments” (**Duda,1973**).
 - According to *Pavlidis* (1977), the definition of the PR is quoted in (**Bezdek,2006**): “The word pattern is derived from the same root as the word patron and, in its original use, means something which is set up as a perfect example to be imitated. Thus pattern recognition means the identification of the ideal which a given object was made after” (**Pavlidis,1977**).
 - The definition of the PR by *Gonzalez* and *Thomason* (1978) is cited in (**Bezdek,2006**): “Pattern recognition can be defined as the categorization of input data into identifiable
-

classes via the extraction of significant features or attributes of the data from a background of irrelevant detail” (**Gonzalez,1978**).

- The definition of the PR as stated by *Bezdek* (1981) is: “pattern recognition is a search for structure in data” (**Bezdek,1981**).
- In (**Theodoridis,1982**), *Theodoridis* said that the PR is a scientific discipline, and its aim is the classification of the objects into a lot of classes.
- In (**Watanabe,1985**), *Watanabe* (1985) defined the PR by using these expressions: categorization problem, discrimination method, induction process, and structure analysis problem.
- *Fukunaga* (1990) was defined the PR as: “a problem of estimating density functions in a high-dimensional space and dividing the space into the regions of categories or classes” (**Fukunaga,1990**).
- In (**Srihari,1993**), the PR was looked as a discipline which learns machines to recognize patterns in complex environments.
- *Schalkoff* (1992) regarded the Pattern recognition (PR) as the science that “concerns the description or classification (recognition) of measurements”(**Schalkoff, 1992**).
- The PR was described by *Ripley* (1996): “Given some examples of complex signals and the correct decisions for them, make decisions automatically for a stream of future examples” (**Ripley,1996**).
- The definition of PR according to *Duin* (2002) is: “Although this is only one of the possible definitions for PR, it points out well the “engineering” nature of this scientific discipline, because it says that the final goal of PR is the design of “machines””” (**Duin,2002**).

However, the pattern recognition is a common ability to all organisms. For example, we can recognize another person by his face, his voice, or his manuscript. But a dog can recognize a person or another dog by its smell. These examples are classified in the recognition domain. The object inspected in the process of recognition is called a *pattern*.

The definition of the pattern by *Norbert Wiener* (2000) is: “A pattern is essentially an arrangement. It is characterized by the order of the elements of which it is made, rather than by the intrinsic nature of these elements” (**Jain,2000**).

Watanabe defines a pattern as “ it is an entity, vaguely defined, that could be given a name” (**Watanabe, 1985**).

The patterns can be geometric shapes like:

- Line;
- Circle;
- Ellipse;
- Curve.

They can also be more complex such as:

- Letter;
- Number;
- Fingerprints;
- Human face;
- Speech signal;
- DNA sequence.

There are several parameters which characterize the pattern such as:

- The form parameters: like the:
 - Area;
 - Perimeter;
 - Intersection lines;
 - Axis;
 - Hole;
 - Squareness;
 - Circularity.
- The color parameters:
 - RGB (Red, Green, Blue);
 - HSV (Hue, Saturation, Value);
 - HSL (Hue, Saturation, Lightness).
- The texture parameters.

1.3 STEPS OF THE PATTERN RECOGNITION PROCESS

The pattern recognition (PR) can be defined as the science which has as a goal the design of algorithms to highlight a structure within a set of data. The pattern recognition methods have wide applications.

The PR is carried out in two phases: the learning from the known data, and the classification of the new data. Prior to these two phases, a preprocessing step is used to find

the minimum set of informative parameters which are necessary to the establishment of the representation space.

According to (**Bow, 1992**), the steps of the pattern recognition process are:

- Acquisition;
- Processing;
- Classification;
- Decision.

All of the major steps of a pattern recognition approach are presented in figure 1.1.

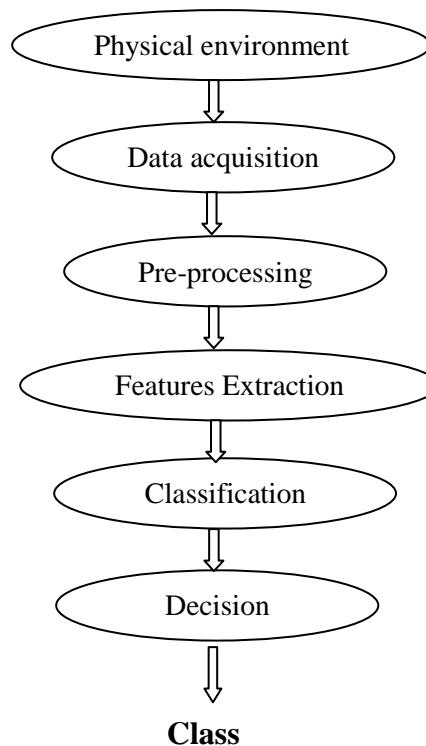


Figure1. 1: The pattern recognition process.

1.3.1 ACQUISITION

In this first phase, the data of the physical environment are collected and converted into digital format to be processing by the machine.

The analysis phase includes the following points:

- Define the system;
- Specify the modes of operation of this system;
- Choose the source of information;
- Specify the representation space.

By analyzing the pattern recognition process, we can deduce that there are two main steps which are: the features extraction and the classification step (**Gorman,2003**). We will then discuss these steps in the following sections.

1.3.2 FEATURES EXTRACTION

The goal of the pattern recognition is to place the patterns in classes. Therefore, we want to achieve the capacity of human recognition. For this, we must interpret a number of features extracted from an unknown form, so as to produce a hypothesis on its class.

In practice, there are several difficulties as:

- The choice of the features which must be representative of all the forms to recognize them. This choice is very important because it determines the recognition methodology.
- Supposing that these features are known, it is often difficult to define the rules which exploit them.

There are many types of features which could be used to represent the patterns for a specific problem of recognition. The features extraction is also called coding. The good coding is determined according to the following points:

- The discriminating power: The coding must be different for the examples of the different classes. This is called by high variance inter-classes.
- The unifying power: The coding must be approximately similar for the examples of the same class. This is called by low variance intra-class.
- The invariance / stability: The coding must be the most insensitive as possible to the noise. This is depending on the applications, the rotation, the invariance in translation, and the scaling.
- The low dimension: More the coding or the features vector is small; more the calculation time will be low. However, the increase of the dimension can damage the results of recognition.

1.3.3 CLASSIFICATION

Once the representation space has been established, it is possible to work with the pattern recognition. There are several classification algorithms which are used in the pattern recognition applications. Based on the prior information available on the system, we distinguish three types of pattern recognition methods: the supervised, the unsupervised, and

the semi-supervised methods. When the classes of forms are known, initially, the pattern recognition is supervised (**Therrien,1989**). Otherwise, when no information is available on the classes of the system, the PR is unsupervised (**Bezdek,1981**) (**Frigui,1996**) (**Frigui,1997**) (**Vachkov,2009**). The third type of the PR methods concerns semi-supervised methods (**Cozman,2003**) (**Gabrys,2000**) (**Liu,00**), this type use the known information (known forms and classes) in order to estimate the characteristics of the classes and their functions of belonging, while also using unsupervised learning to detect the new classes and learn their functions of belonging.

In addition, each group includes many algorithms based on a variety of methodologies. For example, we can also categorize the supervised classification methods as: parametric and nonparametric:

- Parametric: Such as:
 - Quadratic Discriminate Analysis;
 - Linear Discriminate Analysis.
- Nonparametric: Such as:
 - Decision Trees;
 - Naïve Bayes Classifier;
 - K-nearest Neighbor;
 - Neural Networks;
 - Support Vector Machines.

The classification methods can apply to various applications like: the pattern recognition, the artificial intelligence, the medicine, the statistics, and the vision, etc.

However, it is not easy to choose the appropriate method for a problem. Depending on the applications, the developed methods have varying performance. In the literature, the researchers compared the different classification methods in various areas. There are various comparative studies of the different classification methods in the domain of the pattern recognition such as: (**Denoeux,1995**) (**Gascuel,1998**) (**Kuncheva,1998**) (**Billaudel,1999**) (**Denoeux,2000**) (**Devillez,2004**).

1.3.4 DECISION

This phase consists of choosing one or multiple discrimination techniques and finds the decision function by learning of the available data. The choice of the decision technique should be done according to:

- The performance;
- The training time;
- The calculation time of the decision function.

The most used decision systems are: The parametric methods based on the Bayes rule, the non-parametric methods based on the estimation of probability laws such as the kernel methods, the methods based on the direct calculation of the boundaries of the representation space, the neural networks, and the support vectors machine(SVM),etc.

The operating phase allows associating for any new observation a known classes by applying the decision rule. Therefore, the reserved system must be able to adapt its decision function taking account the enrichment of the database and the emergence of new classes. So the classification is the main concept in the pattern recognition field. We can define a class as a number of patterns (objects) similar grouped together. However, the choice of the input of the recognition process is very important. The work is to divide the data into larger classes and to establish their borders. If we know a prior the number of groups then the task is simple and this is called: the supervised learning, otherwise, we do the no supervised learning.

1.4. APPLICATIONS OF THE PATTERN RECOGNITION

The pattern recognition is used in several applications such as:

- Biometrics: Personal identification or authentication.
 - Computer vision: The first system in this type of application was the supposition of the objects with geometric shapes and the optimization of the edges extracted from the images (**Robert,1965**).
 - Bioinformatics: DNA Sequence Analysis.
 - Character recognition used for example in banking and postal applications.
 - Speech recognition: Universal access, Human computer interaction.
 - Medical diagnosis: Medical imaging, EEG signal analysis.
 - Geography: Earthquake analysis.
 - Astronomy: Automatic spectroscopy.
 - Agriculture: Soil evaluating, output analysis.
 - Document classification: Internet search.
 - Engineering: Recognition of automobile type.
 - Military: Automatic target recognition, Aviation photography analysis.
 - The robot navigation.
-

1.5 CONCLUSION

The process of the pattern recognition includes two most important steps which are: the features extraction and the classification step. However, there are many methods for the features extraction in the pattern recognition domain, but the states of the art of several works indicate that there is not a generic method which can be applicable to all the pattern recognition problems. Also, the algorithms of classification are several. However, the choice of method for a problem is very difficult. The developed methods have varying performance depending on the type of application. So there is not an ideal classification method applicable to all the problems of the pattern recognition.

Today, the pattern recognition methods find applications in several areas. The biometrics is one of the most important applications in the pattern recognition field. The biometrics will be the subject of the next chapter.

CHAPTER II: THE BIOMETRICS

This chapter defines the biometric; also it describes its properties and its goals. Then, it presents the different modalities with their characteristics, their advantages, their disadvantages, and their applications. In addition, it expresses the operating modes of the unimodal biometric systems, their limitations, and their evaluation in order to decrease these limitations. Also, it gives some examples of the biometric applications. The plan of this chapter is articulated as follows

Summary:

- 2.1 Introduction
 - 2.2 Principles and Definitions
 - 2.3 Proprieties of the Biometric Modalities
 - 2.4 Why We Use the Biometrics?
 - 2.5 Different Biometric Modalities
 - 2.5.1 Face (Facial Recognition, Facial Thermography, Iris, and Retina)
 - 2.5.2 Hand (Fingerprints, Hand geometry, Veins, and Nails)
 - 2.5.3 Bio-dynamics (Voice, Signature, and Gait)
 - 2.5.4 Keystroke
 - 2.5.5 Corporal Odor
 - 2.5.6 Ear
 - 2.5.7 DNA
 - 2.5.8 Heartbeat
 - 2.6 Biometric Characteristics
 - 2.7 Biometric Systems and their Operating Modes
 - 2.7.1 Modules of the Biometric Systems
 - 2.7.2 Operating Modes of the Biometric Systems
 - 2.7.2.1 Enrolment
 - 2.7.2.2 Authentication
 - 2.7.2.3 Identification
 - 2.8 Limitations of the Biometric Systems
 - 2.9 Evaluation of the Biometric Systems
 - 2.9.1 Performance
 - 2.9.1.1 Errors Rates Measures
 - 2.9.1.1.1 Fundamental Errors Rates
 - 2.9.1.1.2 Errors Rates of the Authentication System
 - 2.9.1.1.3 Errors Rates of the Identification System
 - 2.9.1.2 Processing Time and Memory Occupation Measures
 - 2.9.1.3 Performance Curves
 - 2.9.1.4 Performance Points
 - 2.9.2 Data quality
 - 2.9.2.1 Definition of Data Quality
 - 2.9.2.2 Factors Degrading the Data Quality
 - 2.9.3 Usability
 - 2.9.4 Security
 - 2.10 Biometric Applications
 - 2.11 Conclusion
-

2.1 INTRODUCTION

The biometric system is one of the most important applications in the pattern recognition field. It uses the biometric data of the persons to recognize them. Today, there are several applications which use the biometric. However, the biometric is not really new; its appearance was in the 19th century with the first studies called "Anthropometry". The biometric is the technology that measures the characteristics of an individual. It is becoming a security solution due to the attacks of September 2001.

The biometric can be defined as the measure of the physical or the behavioral characteristics of an individual such as: his face, his iris, his fingerprints, his DNA, his signature, his voice, etc. The biometric is especially used in the security, the control access to certain places or some objects (for examples, some laptops require a fingerprint to use them), and the combating crime (for example, the use of the fingerprints banks of criminals is the most known in this area).

In this chapter, we introduce the basic concepts and definitions which are related with the biometrics. Also, we will present its properties and its goals. Then, we will describe the different biometric modalities, their characteristics, their advantages, their disadvantages, and their applications. In addition, we will express the operating modes of the unimodal biometric systems, their limitations, and their evaluation in order to decrease these limitations. Finally, we will give some examples of the biometric applications.

2.2 PRINCIPLES & DEFINITIONS

In the literature, there is no lack of definitions for the biometrics. In this section, we will present some definitions that exist in the literature:

- "Biometrics is the science of measuring physical properties of living beings" (**Web01**).
- "Biometrics is the measurement and statistical analysis of people's physical and behavioral characteristics. The technology is mainly used for identification and access control, or for identifying individuals that are under surveillance. The basic premise of biometric authentication is that everyone is unique and an individual can be identified by his or her intrinsic physical or behavioral traits. (The term "biometrics" is derived from the Greek words "bio" meaning life and "metric" meaning to measure)". (**Web02**)

- “Any automatically measurable, robust and distinctive physical characteristic or personal trait that can be used to identify an individual or verify the claimed identity of an individual” (**Woodward,2003**).
- “A method of verifying an individual’s identity based on measurements of the individual’s physical features or repeatable actions where those features and/or actions are both unique to that individual and measurable” (**Web03**).

The biometric is a *Greek* word which concatenates two words “*bio*” and “*metric*”, the first word means “life” and the signification of the second word is “to measure”. However, this term was used to describe these technologies since 1980. So the biometric can be defined as the verification of person’s identity by using their physical or their behavioral characteristics. The recognition of person by their physical characteristics is always used by human also by animals to recognize their own kind. So the face, the voice, the gait, or the body odors are the universal means to identify a person.

These physical or behavioral characteristics which allow identifying a person are named *biometric modalities*.

The idea to characterize persons by their physical characteristics is not new. It was already used in ancient civilizations, and it has been particularly developed in the 19th century with the arrived of the ancestor of biometrics: *Anthropometry*.

Since the end of the 19th century, the police use the fingerprints as means of identification of criminals. This recognition was manual, and it carried out by experts. Today, these procedures were been automated by several techniques and technologies.

2.3 PROPERTIES OF THE BIOMETRIC MODALITIES

There are three basic means of identification:

- The first is “*something you have*” such as the cards, the badges, or the keys.
- The second one is defined as “*something you know*”, for example, the personal identification number PIN codes, the passwords, or the user ID.
- The last mean is “*who are you*”, this mean encompasses the biometric, such as the face, the iris, or the fingerprints.

The biometric authentication is more performance than the use of the traditional means of identification such as the cards, the keys, or the passwords, due to the permanent link between the individual and his identity.

The main properties of the biometric modality are:

- The universality: Every individual must have the modality (the physical or the behavioral characteristics).
- The permanence / the stability: The biometric modality should not change or vary in time, and it must be stable for the same person regardless of the circumstances of the acquisition (for example, the external conditions, the emotional condition of the person for the face modality, etc).
- The distinctiveness / the uniqueness: Two persons should have different representation of their characteristics.
- The non-reproducibility: It concerns the falsification of the biometric modality.
- The acceptability and the ease of use: It relates to the acquisition constraints.

So, we can deduce that:

- No biometric modality is ideal but it is more or less adapted to the applications.
- All the traits biometric haven't all these types of properties, or they have them with different degrees.
- According to the requirement of each application, the compromise between the presence or the absence of some of these properties is done in the choice of the biometric modality.

2.4 WHY WE USE THE BIOMETRICS?

The arguments for the use of the biometrics may be summarized in two categories:

- The practicality and the comfort: The passwords, the identity cards, or the keys can be forgotten, copied, stolen, or lost. In addition, today according to the requirements of life, we must have several cards and keys; also we must remember many passwords. On the other hand, the biometrics would be immune to this kind of difficulties. Also, it would be practical and simple because there is no cards and password to remember.
- The security: The biometrics offer more security compared with the traditional methods because it gives a precise identification without the presence of the identification papers or cards. Also, it limits the fraud, for example, it would improve the safety of the documents protected by biometric. Then, it may avoid the fraud in many systems by avoiding duplication. Therefore, we can say that the biometric would be able to reduce the crime and the terrorism.

Table 2.1 compares the traditional means of identification with the biometric:

	Copied	Stolen	Forgotten	Lost
Key	X	X	X	X
Badge		X	X	X
Code / password	X		X	
Biometric				

Table 2. 1: Comparing the traditional methods with the biometric.

2.5 DIFFERENT BIOMETRIC MODALITIES

The biometric techniques are divided into two main groups according to the cooperation of the user:

- Intrusive: This group includes the techniques which require the physical contact, and their use is generally not accepted because it raises hygienic issues, such as the fingerprints, the retina, and the hand geometry, etc.
- Non-intrusive: This group includes the techniques which can be done remotely by sensors so there is no direct contact requirement, such as the face, the voice, and the gait, etc.

The different biometric modalities can be classified into the following categories:

- The physical biometric is the kind of the biometrics which used a part of the human body, such as the face, the fingerprint, the iris, and the retina, etc.
- The behavioral biometric is the biometrics which used a personal trait of behavior, such as the signature and the gait, etc.
- The morpho-behavioral biometrics such as: the voice which is related to the morphology of the vocal cords but also by the fact that the voice can easily be changed by the person according to his emotional states, his age.
- The biological biometrics such as the DNA, the blood, and the saliva.

Figure 2.1 summarizes these categories by giving some examples of the different biometric modalities.

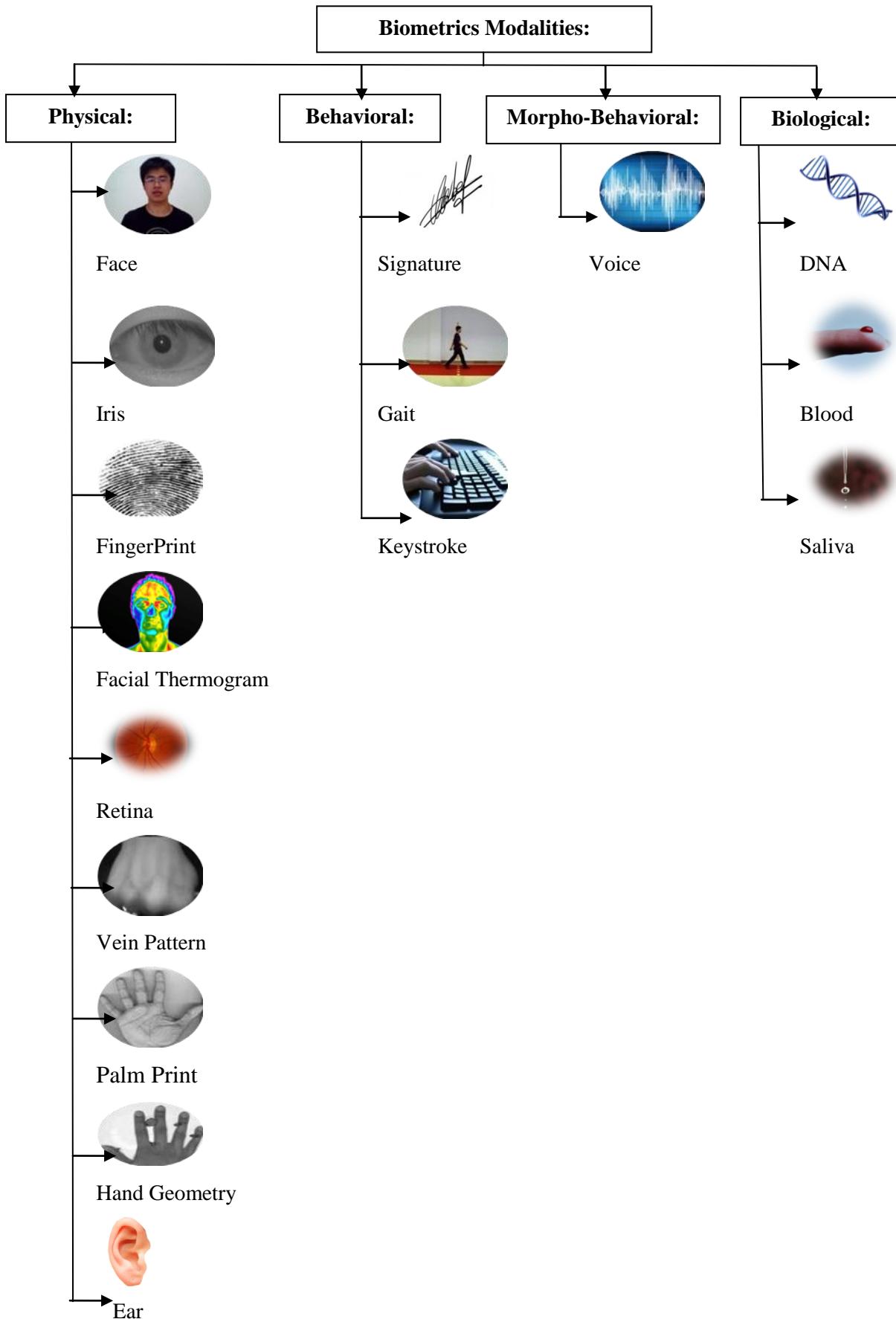


Figure 2. 1: The different biometric modalities.

2.5.1 FACE (FACIAL RECOGNITION, FACIAL THERMOGRAPHY, IRIS, AND RETINA)

2.5.1.1 FACIAL RECOGNITION

The face modality is the most natural way that is used to recognize a person, so the facial images are the biometric characteristics used by humans to perform a personal identification.

In 1888, *Francis Galton* introduced the beginnings of what should be the facial recognition in his book “*Personal identification and description*”. Then in 1910, he provided more details and clarification in another book entitled “*Normalized profiles for classification and recognition*”.

In 1960, the technicians had manually established the key points on the face image (the nose, the mouth, etc.) and the system calculated the distances and ratios between these points. Then, the obtained data was compared with those kept in the facial database.

In 1988, *L. Sirovich* and *M. Kirby* have applied a linear algebraic technique which showed that less than one hundred data could be used to encode a normalized facial image; this is the technique of *Eigenfaces*. Three years later, *M. Turk* and *A. Pentland* found that they could detect faces in an image using the residual error of the *Eigenfaces* technique.

In 1993, the *Counterdrug Technology Development Program Office* of the department of defense of the United States established the FERET (FacE REcogniTion) program.

The facial recognition methods are divided into two main categories: the geometric and the photometric, the first one is based on the features of the face, and the second is based on the view.

2.5.1.2 FACIAL THERMOGRAPHY

It is a specialized face recognition technique. The principle of this method is to sense the heat emitted from the flow of blood under the skin, and this is captured by an infrared camera. It developed in 1990. It is not like the facial recognition, so this system can be used in poor visibility conditions or darkness.

2.5.1.3 IRIS

In 1885, the French physician *Alphonse Bertillon* suggested the idea of using the iris modality as a means of distinguishing human identifier (**Bertillon, 1886**).

In 1936, the ophthalmologist *Frank Burch* described the concept of the iris modality as identification means.

In 1985, the ophthalmologists *Léonard Flom* and *Aran Safir* have declared that each iris is unique, and it could be used for the person identification task.

In 1987, the doctor *John Daugman* contacted Dr. *Flom* to find an algorithm for the iris recognition. In 1995, the three scientists of the Defense Nuclear Agency complete and test successfully the algorithm of the automatic iris recognition. In the same year, the product of this research is marketed with the appearance of the first iris reader, and Dr. *Daugman* who owns the patent.

2.5.1.4 RETINA

The retina is the sensory layer of the eye, and it is located on bottom of the eye. Its goal is to receive light, then it converts this light into neural signals, and it sends these signals on to the brain for the visual recognition. The elements that distinguish two retinas are the veins lining them. The layout of these veins is stable and unique from one individual to another.

In 1935, the identification by the blood vessels on the retina was raised in an article in the *New York State Journal of Medicine*. There are multiple researches in this area, and the conclusion of these researches proved that each retina would be unique, and it would not change during the life except by certain injuries or diseases. Nevertheless, until 1984 that the first commercial retina reader (Eyedentification 7,5) is developed by the EyeIdentify company which is formed in 1976. For example, this technology is used for some military and government facilities.

2.5.2 HAND (FINGERPRINTS, HAND GEOMETRY, VEINS, AND NAILS)

The hand Analysis is very used in multiple biometric applications for the following reasons:

- It presents the main link with the physical word (press keys, take things, etc).
- It is not intrusive.
- It is easy to use.
- It leaves its trace everywhere.

2.5.2.1 FINGERPRINTS

The fingerprint is the traces or the marks left by the fingers when they touch an object. The formation of the fingerprints depends on the initial condition of the embryogenic development, and this makes them unique to each person and even to each finger. The fingerprint recognition is one of the first biometric systems that are used for the person authentication. However, the patterns designed by the ridges and the folds of skin found on the finger are different for each individual. Therefore, it is the most used by the criminal

police since the 19th century. The ridges are called minutia points: where a ridge end (ridge endings) and where a ridge splits in two (ridge bifurcations). There are three basic patterns of fingerprints ridges: the arch, the loop, and the whorl.

There are many types of minutiae which are:

- Dots: are very small ridges.
- Islands: are located in the middle space between two temporarily divergent ridges.
- Lakes / Ponds: are the empty spaces that located between two temporarily divergent ridges.
- Spurs: are the notches protruding from a ridge.
- Bridges: are small ridges combined two longer adjacent ridges.
- Crossovers: are two ridges that cross each other.
- Endings: are the points at which a ridge stops.
- Bifurcations: are the points at which one ridge divides into two.

In 1686, the Italian professor of anatomy at the University of Bologna, *Marcello Malpighi* was the first who noticed some distinction between the fingerprints.

In 1823, the Czech physiologist, *Johannes Evangelista Purkinje* was the first who used the classification system for the fingerprints.

In 1877, *William Herschel* imposed the fingerprints as authentication authorities. Then in 1880, he wrote an article “*skin furrow of the hand*”, where he sanctioned the use of fingerprints as a method of signature and identification. In the same year, the individuality of fingerprints was suggested for the first time scientifically by *Henry Fauld*. In 1958, *William Herschel* began to use the fingerprints in his role as Chief Magistrate.

Thereafter, *Francis Galton* managed to get more than 8000 sets of fingerprints, and he was able to establish the scientific basis used to compare two fingerprints. He showed statistically that each fingerprint is unique. He also published a book “*Fingerprints*”. He listed the first classification system, which has been modified by *Henry* to use for the identification of criminals (**Lee,2001**). Also, *Henry* published a book “*the classification and uses of finger printing*”. Then, *Juan Vucetich* also invented a classification system which groups the fingerprints by categories to make an easier consultation.

In 1994, the FBI *Federal Bureau of Investigation* is undertaking a major contribution to the fingerprints recognition. It is the beginning of the IAFIS *Integrated Automated Fingerprint*

Identification System which is based on three aspects: the fingerprint acquisition, the features extraction, and the comparison. This system was built by *Lockheed Martin*.

In 1999, the major components of the IAFIS become operational. The next version of the IAFIS would include the prints from the palms of the hand. There is even a "*National Palm Print*" integrated service IAFIS include integration of the prints from the palms of the hand.

2.5.2.2 HAND GEOMETRY

The hand geometry recognition is one of the oldest biometric systems. It is widely implemented for its public acceptance and ease of use. The first system is marketed in 1974. This system was done for the access control, the identification of persons, the control of the presence, and the time spent by employees in the workplace.

The hand geometry is developed by *David Sidlauskas* in 1985, and the first system of this technology is commercially available a year later.

The silhouette of the hand is a characteristic of each individual. This technology uses a camera by taking a picture of the silhouette of the hand, this system measure:

- The length of the hand.
- The width of the hand.
- The thickness of the hand.
- The surface of the hand.

In fact, this technology takes two photos; the first is on the top of the hand, the second on the side of the hand using a mirror at angles. The technology of hand geometry is widely used. But it has some shortcomings, one of these limitations is that it is not highly unique, so that is limited the use of this technology to the verification tasks only.

2.5.2.3 VEINS

The recognition by the veins of the hand is a biometric technology. In 1992, the doctor *K. Shimizu* has published an article about trans-body imaging and this published paper demonstrated the potential for the use of the hand vascular technology (**Shimizu,1992**).

In 1995, the thermographic imaging technology is introduced by *Cross* and *Smith* for the acquisition of the subcutaneous vascular network on the back of the hand (**Cross,1995**).

In 1997, *Alex Hwansoo Choi* has introduced BK-100 which is one of the first commercial products in the field of hand vascular pattern technology.

In 2000, the biometric aspect is clear with the first research paper that shows how they invented a system that uses subcutaneous blood vessels in the back of the hand for the identification of an individual (**Im,2001**).

In 2003, the first commercial product based on the use of the vascular pattern in the palm is announced by *Fujitsu* (**Watanabe,2005**). In the same year, the first commercial product based on the use of the vascular pattern in the finger is developed by *Hitachi* (**Miura,2004**).

2.5.2.4 NAILS

This technique is based on the longitudinal streaks of the nails, which depend on the structure of the underlying epidermis. The relief of the nail can be revealed with an interferometer.

2.5.3 BIO-DYNAMICS (VOICE, SIGNATURE, AND GAIT)

The bio-dynamic biometrics are based on a dynamic component (for example, the force used when signing), but also a static (the form of signature) to authenticate or identify a person.

2.5.3.1 VOICE

The voice recognition is the identification of persons by using their voice characteristics. It is also called *speaker recognition*. The voice print contains several components such as: the person's (accent, rhythm, and inflection), physical factors (the shape and the size of the person's nasal and the vocal cords). In 1960, the Swedish Professor *Gunnar Fant* shows the physiognomy of the sounds and the voice production by using the X-rays. Dr. *Joseph Perkell* which also used the X-rays built Fant model by including also the language and the jaw. In 1980, the NIST developed a system of speech recognition with his “*speech group*”.

2.5.3.2 SIGNATURE

Each person has a unique writing style, so the signature can be used as a mean of identification. In addition, it is used in many countries as legal or administrative element. This biometric technology belongs to the behavioral biometric. There are two types of this recognition system: the online and the offline.

The history of the signature recognition began in 1965. It focused on the geometric and the static characteristics of the signature (its physical form). The appearance of the touch sensitive technology allowed spending how the signature was made, namely the dynamic elements of

signature such as the pencil pressure, the speed, and other characteristics. In 1977, the first patent is granted for the signature recognition with dynamic features.

2.5.3.3 GAIT

This technique is the recognition of person by his manner of walking and moving (the acceleration, the speed, and the movements of the body, etc) by analyzing the sequence of images. The approach would indeed closely associate with the natural muscles, but the loose clothing for example can affect the task of recognition. In 1990, *Niyogi* and *Adelson* were done the first effort of the gait recognition in the computer vision (**Niyogi,1994**).

2.5.4 KEYSTROKE

The keystroke is unique to each individual. This technique becomes more and more requested because we write more often with a keyboard than with a pen. It is a recognition technique based on the striking rhythm which is unique. For example, it is applied to the passwords which make them more difficult to imitate. The analyzed elements are: the typing speed, the striking time, the letter sequence, the pauses, etc.

2.5.5 CORPORAL ODOR

Each person is characterized by his odor that characterizes its chemical composition, and it could be used to distinguish various individuals, so the biometric systems exploit the chemicals components contained in the smell and turn them into comparative data by analyzing them. It is captured from non-intrusive parts of the body, such as the back of the hand.

2.5.6 EAR

The form of each ear is unique, thus make this technique more effective. In 1890, the French criminologist *Alphonse Bertillon* recognized the potential of the ear for the identification, and he wrote in (**Bertillon,1890**): “The ear, thanks to these multiple small valleys and hills which furrow across it, is the most significant factor from the point of view of identification. Immutable in its form since birth, resistant to the influences of environment and education, this organ remains, during the entire life, like the intangible legacy of heredity and of the intrauterine life”. In 1949, *Iannarelli* developed the ear classification system based on manual measurements (**Iannarelli,1989**).

2.5.7 DNA

The DNA (DeoxyriboNucleic Acid) is specific to an individual to another. It is present in the cells of the body, and it can identify from a simple fragment of blood, hair, skin, nails or a

drop of saliva. The DNA is studied for more than a century, whether through the theory of the evolution of *Charles Darwin* (1859) or the concept of heredity of *Gregor Mendel* (1866).

But it is only in 1953, the DNA has been conceptualized for the purpose of identification, and this is after the publication of the article of the DNA structure by *James Watson* and *Francis Crick*.

In 1980, the geneticists found a region of DNA that varies between the different individuals, but it doesn't contain genetic information.

Then in 1984, *Alec Jeffreys* was the first who found a manner to identify people with their DNA, it is the method *Restriction Fragment Length Polymorphism* (RFLP), and after one year the British police use the DNA profiling.

In 1986, *Kary Iviullis* invented the process of amplification by polymerase *Polymerase Chain Reactio* (PCRI). This discovery allows multiplying a region of DNA, which makes his analysis immeasurably easier. It was in 1987 that the British police managed to truly introduce the DNA in the judicial system.

In 1995, the first Bank of DNA in the world is starting to collect DNA samples in Britain. The United States would follow in 1998 with the National DNA Index System of the FBI, which allows to police to compare the DNA profiles electronically. In 2000, the DNA of Britain Bank had 1 million genetic profiles.

The DNA analysis is too slow to give results to be used as a mean of identification and authentication in real time. When we use the DNA as a mean of identification, we must be careful, because the crime scene may contaminate by another source of DNA. There is also the risk of fabricating evidence as demonstrated by Dr. *John Schneeberger* in 1992.

2.5.8 HEARTBEAT

The idea of using the heartbeat as a biometric tool has quickly made its way. It is like the fingerprints, it is unique to each person. Indeed, the researchers found that the form of an electrocardiogram (EGC) peaks are unique to each individual. Different researches laboratories in North America and Europe are working in this area, and they confirm that the cardiac profile does not change with age or even if the pace of the heart races after an effort or emotion.

Table 2.2 compares some biometric technologies according to their: goodness, weakness, and applications.

Traits	Advantages	Disadvantages	Interferences	Applications
Face	<ul style="list-style-type: none"> ○ Less intrusive. ○ Cheap technology. ○ Simple acquisition. ○ Easy to use. ○ No physical contact. 	<ul style="list-style-type: none"> ○ More suited for authentication than identification mode. ○ Easy to change for example by wearing a mask, illumination, person's hair, age, cosmetics, pose, facial expression, etc. ○ Most people are uncomfortable because their picture was taken. ○ Difficult to identify a person on the move. ○ Manipulation by surgery. ○ Uniqueness is not guaranteed (identical twins). ○ Religious or cultural inhibitions. 	<ul style="list-style-type: none"> ○ Twins. ○ Facial hair. ○ Facial expressions. ○ Pose. ○ Glasses. ○ Lighting. ○ Aging. ○ Makeup. 	<ul style="list-style-type: none"> ○ Access to restricted areas and buildings, banks, embassies, military sites, airports, stadiums, and commercial centers, etc. ○ Human-Computer Interaction. ○ Law enforcement. ○ Criminal identification. ○ Surveillance.
Iris	<ul style="list-style-type: none"> ○ High accuracy. ○ High uniqueness and distinctiveness (even for twins). ○ Iris texture is perfectly stable over time and not editable (even by surgery). ○ It contains a large quantity of information, and its texture is independent of the genetic code. ○ Difficult to falsify. ○ No physical contact. 	<ul style="list-style-type: none"> ○ Difficulty of acquisition: the iris size is variable according to the light, state of fatigue, movement of user, etc. ○ Intrusive for some person. ○ Distance between the eye and the camera. ○ High cost capture device. ○ Sensor is inadequate for the safety of the small objects. ○ Scanner can become bothersome due to its hard adjustment according to the different heights of the people. ○ Iris recognition is susceptible to poor image quality like the photographic biometric technologies. ○ High quality images can fool the scanner. ○ Affected with diabetes, hypertension. ○ Problem with blind persons. 	<ul style="list-style-type: none"> ○ Glasses. ○ Lenses. ○ Diabetes. ○ Hypertension ○ Blind. ○ Iritis. ○ Reflections. 	<ul style="list-style-type: none"> ○ Medical services. ○ Nuclear installation. ○ Penitentiary centers and correctional facilities. ○ Identity cards and passports. ○ Border security. ○ Facility access control. ○ Computer login. ○ ATMs. ○ High security application.
Retina	<ul style="list-style-type: none"> ○ Very high accuracy. ○ High uniqueness and distinctiveness (even for twins). ○ Stable over time. ○ Difficulty of spoofing and protection from the environment. ○ High security. 	<ul style="list-style-type: none"> ○ Very intrusive. ○ Very expensive technology. ○ Difficult to use (no glasses, Low distance, focus). ○ Eye is sensitive to light, so it is difficult for a user to not close the eye during the acquisition. ○ Discomfort technology. ○ Affected by (diabetes, hypertension, cataracts, glaucoma, etc.). ○ Not appropriate for covert applications. 	<ul style="list-style-type: none"> ○ Irritation. ○ Diabetes. ○ Hypertension ○ Glasses. ○ Cataracts. ○ Glaucoma. ○ Retinitis. ○ Pregnancy. 	<ul style="list-style-type: none"> ○ Medical services. ○ Ophthalmological diagnostics. ○ Nuclear installation. ○ Penitentiary centers. ○ High security area: FBI (Federal Bureau of Investigation). ○ Some banks and rich area. ○ High security application and military.

Traits	Advantages	Disadvantages	Interferences	Applications
Fingerprints	<ul style="list-style-type: none"> ○ High accuracy. ○ High distinctiveness (even twins). ○ Proven and mature technology. ○ Stable over time. ○ Easy to use. ○ Small size of the reader. ○ Economical method. 	<ul style="list-style-type: none"> ○ Intrusive for some person. ○ Hygiene problems. ○ Difficulties can be caused by dry skin, dirt, and cuts. ○ Absence of finger, cuts, and scars can hinder the recognition process. ○ Deformations of the fingerprints can indeed occur with the age, the nature of the work, and the accidents, etc. ○ Use of false fingerprints (artificial fingers). 	<ul style="list-style-type: none"> ○ Dirtiness. ○ Injury. ○ Roughness. ○ Cuts. ○ Scars. 	<ul style="list-style-type: none"> ○ Used in devices such as: cell phones, USB flash drives, notebook computers. ○ Law enforcement. ○ Healthcare and welfare. ○ Electronic commerce. ○ Access control ○ Border control and visa issuance.
Hand Geometry	<ul style="list-style-type: none"> ○ Easy to use. ○ Non intrusive. ○ Low FTE rates (Failure to enroll). ○ It can be easily integrated into other systems because it requires special hardware to use. ○ External factors such as skin moisture and dirt on the hand don't affect the result. 	<ul style="list-style-type: none"> ○ Limited accuracy. ○ Low distinctiveness and high FAR. ○ Change over time. ○ Hygiene problems. ○ Scanner that is larger than the finger scanner, making it inaccessible technology to portable systems. ○ Candidate's hand with jewelry, arthritis, and user's age can affect errors. ○ It is not effective for the growing children. ○ Operate only in the verification mode. 	<ul style="list-style-type: none"> ○ Arthritis. ○ Jewelry. ○ Age. 	<ul style="list-style-type: none"> ○ Access control to restricted areas and buildings: apartment buildings, offices, airports, hospitals, some nuclear power plants, and military, etc. ○ Time management.
Vein	<ul style="list-style-type: none"> ○ Highly accurate and low FAR. ○ High distinctiveness and uniqueness (even for twins). ○ Stable over time. ○ Difficult to forge. ○ Without trace. ○ No hygiene problem because there is no contact. ○ Veins are not easily observed, changed, obscured, or damaged. 	<ul style="list-style-type: none"> ○ More expensive than fingerprints technology. ○ Scanner is relatively bulky compared to the fingerprint sensor, and it is sensible for light. ○ Surgery, gloved, covered, or extremely dirty hands cannot be identified using a hand vein pattern recognition system. ○ Drugs, mental health, and medical conditions affected the accuracy. 	<ul style="list-style-type: none"> ○ Gloved or covered. ○ Dirty. ○ Medical conditions and drugs. ○ Surgery. 	<ul style="list-style-type: none"> ○ Physical access control and time attendance. ○ Security systems. ○ Login and information protection. ○ Healthcare. ○ Banking and finance. ○ Travel and transportation.

Traits	Advantages	Disadvantages	Interferences	Applications
Voice	<ul style="list-style-type: none"> ○ Non intrusive and high acceptability. ○ Cheap technology. ○ Low training requirements. ○ Easy to use. 	<ul style="list-style-type: none"> ○ Low accuracy. ○ Low distinctiveness. ○ Language and voice not stable. ○ Noise, age, emotional state, throat, or flu infection can affect the result. ○ Variation in the quality of the communication connection, microphones, or telephone can affect accuracy. ○ Easy manipulation and spoofing attacks. ○ Not suitable for identification. 	<ul style="list-style-type: none"> ○ Noise. ○ Flu or throat. ○ Emotional state. ○ Age. 	<ul style="list-style-type: none"> ○ Remote access. ○ Financial transactions: funds transfer, account access, bill payment. ○ Credit card processing: balance transfers, address changes. ○ Online education systems.
Signature	<ul style="list-style-type: none"> ○ Non intrusive and high acceptability. ○ Cheap technology. ○ It works well in business transactions. ○ Difficult to mimic the behavioral patterns. 	<ul style="list-style-type: none"> ○ Low accuracy. ○ Change over time. ○ Easy to forge. ○ Different persons may sign with the same manner. ○ Change in behavior while signing. ○ Users are unaccustomed to use the signature tablet. ○ Enrolment and verification must be in the same type of environment and conditions. 	<ul style="list-style-type: none"> ○ Variability or easy of signature ○ Muscular diseases. ○ Illiteracy. 	<ul style="list-style-type: none"> ○ Verification, authorization, and access to document. ○ Agreement/contract execution. ○ Banking services.
Keystroke	<ul style="list-style-type: none"> ○ Non intrusive. ○ Cheap technology. ○ No additional hardware, simple software enough. ○ It reduces the need for password changes. 	<ul style="list-style-type: none"> ○ Depends on the state (physical, emotional, fatigue,...) ○ The different formats of keyboards (AZERTY, QWERTY, etc.) affect the system. ○ Should not be disturbed when typing, this can cause a refusal of his own password. 	<ul style="list-style-type: none"> ○ Emotional state. ○ Formats of keyboard. 	<ul style="list-style-type: none"> ○ Administrative documents, banking, insurance.
DNA	<ul style="list-style-type: none"> ○ Very high accuracy. ○ It impossible that the system made mistakes. 	<ul style="list-style-type: none"> ○ Extremely intrusive. ○ Very expensive. ○ Cannot distinguish between identical twins. ○ Need for real time for the matching. ○ Easy to steal (hair). 	<ul style="list-style-type: none"> ○ Twins. 	<ul style="list-style-type: none"> ○ Paternity testing. ○ Identification of missing or dead people. ○ Prove innocence or guilt. ○ Involving organ transplants or donors. ○ Healthcare applications.

Table 2. 2: Comparing some biometric technologies according to their: goodness, weakness, and applications.

2.6 BIOMETRIC CHARACTERISTICS

The biometric system must meet the following requirements to be reliable: (**Radha,2011**) (**Ailahafzah,2012**):

- Universality or availability: the biometric modality should exist for each person.
- Distinctiveness or uniqueness: the biometric modality should differentiate one individual from another.
- Permanence or robustness: the biometric modality should be stable over time.
- Collectability or accessible: the biometric modality can be measured quantitatively.
- Performance: the recognition accuracy of the biometric system.
- Acceptability: the biometric modality should have no objection to collect by the persons.
- Circumvention: how the system resists against fraudulent methods.

Table 2.3 presents the different characteristics of some biometric modalities according to (**Jain,2004c**) and (**Delac,2004**).

Biometric Traits	Universality	Distinctiveness	Permanence	Collectability	Performance	Acceptability	Circumvention
Face	High	Low	Medium	High	Low	High	High
Facial Thermogram	High	High	Low	High	Medium	High	Low
Iris	High	High	High	Medium	High	Low	Low
Retina	High	High	Medium	Low	High	Low	Low
FingerPrint	Medium	High	High	Medium	High	Medium	Medium
Hand Geometry	Medium	Medium	Medium	High	Medium	Medium	Medium
Hand Vein	Medium	Medium	Medium	Medium	Medium	Medium	Low
Palm Print	Medium	High	High	Medium	High	Medium	Medium
DNA	High	High	High	Low	High	Low	Low
Gait	Medium	Low	Low	High	Low	High	Medium
Odor	High	High	High	Low	Low	Medium	Low
Ear	Medium	Medium	High	Medium	Medium	High	Medium
Keystroke	Low	Low	Low	Medium	Low	Medium	Medium
Voice	Medium	Low	Low	Medium	Low	High	High
Signature	Low	Low	Low	High	Low	High	High

Table 2. 3: The characteristics of some biometric modalities.

According to the table 2.3, the cited biometric modalities have the proprieties of selection with different degrees. No biometric is ideal, but it is less or more suitable for applications. However, the choice of modalities is a key for the success of the biometric system, and it depends by the need of the applications.

2.7 BIOMETRICS SYSTEMS AND THEIR OPERATING MODES

2.7.1 MODULES OF THE BIOMETRIC SYSTEMS

The biometric system can be represented by four modules which are:

1. ***The capture module:*** This is the first module in the biometric system, and it can be defined as the interface between the biometric system and the user. It is responsible for the acquisition of the biometric data of an individual (a camera, an iris scanner, a fingerprint reader, etc.).

2. ***The features extraction module:*** This module processes the acquired biometric data obtained by the previous module, and it extracts the features set. So, the input of this module is the biometric data obtained by the capture module, and its goal is to form a new representation of these data by the extraction of the relevant information. Ideally, this new representation is supposed to be unique to each person, and relatively invariant to changes intra-class.
3. ***The correspondence module:*** This module compares the features extracted with the stored templates in the database of the system, and it determines the degree of similarity between the both.
4. ***The decision module:*** This is the last module in the biometric system. It takes the decision for the authentication or the identification mode. So, it verifies the identity affirmed by the user (authentication), or it determines the identity of the person (identification), based on the degree of similarity between the stored models and the extracted features models.

2.7.2 OPERATING MODES OF THE BIOMETRIC SYSTEMS

The biometric systems can operate in three modes, namely:

- Enrolment.
- Authentication.
- Identification.

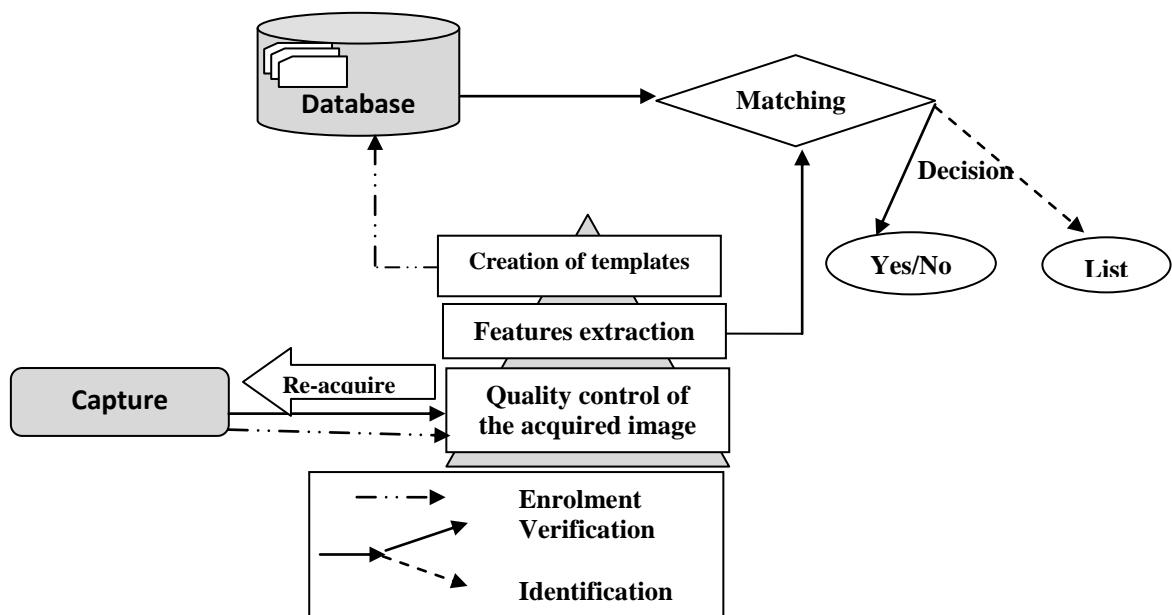


Figure 2. 2: Generic architecture of the biometric system.

2.7.2.1 ENROLMENT

The enrolment is the first phase of any biometric system. This mode can be defined as the phase when the user is enrolled in the system for the first time. It is a common phase to the both modes: the identification and the authentication mode. Figure 2.3 presents the process of the enrolment mode.

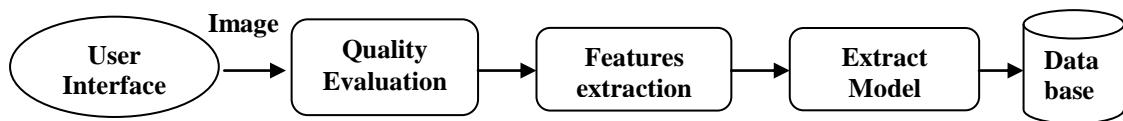


Figure 2. 3: The enrolment of person in the biometric system.

2.7.2.2 AUTHENTICATION

The authentication is the process which verifies the identity of the person. This operating mode can be defined as the step when the user asserts its identity, and the system confirms if this assertion is valid or no. Therefore, the user present his biometric sample to the biometric system which will compare with the biometric sample corresponding to the identifier of the user enrolled in the biometric database. This is also called 1:1 correspondence. In order to illustrate the principle of the authentication mode, we give an example: the user (X) wants to access to his PC, therefore he must enter the password, and present his biometric modality. So, the system acquires the biometric modality presented by the user, and it will be compared only with the stored model corresponding to the person X. Finally, if the biometric input and the stored template in the database have a high degree of similarity, the assertion is valid and the user is considered as an authentic. Otherwise, the user is considered as an imposter.

Figure 2.4 illustrates the different steps of the authentication mode.

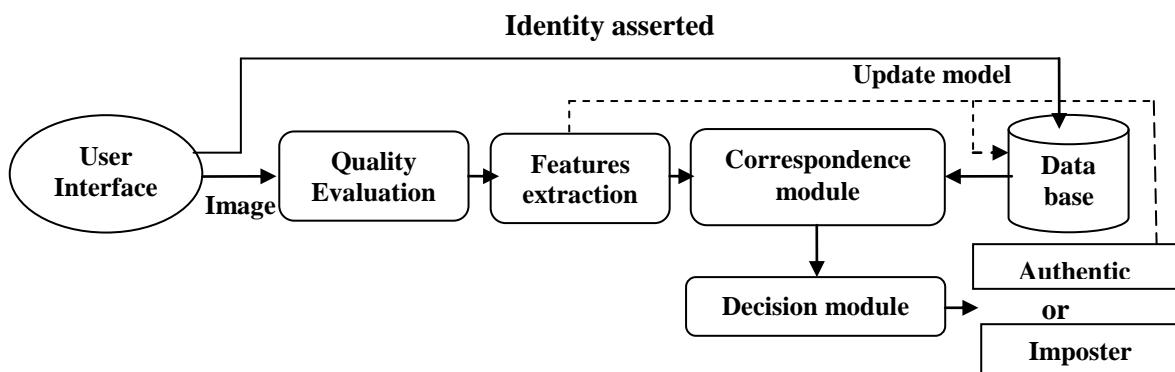


Figure 2. 4: Authentication of an individual by the biometric system.

2.7.2.3 IDENTIFICATION

The identification is the process which determines the identity of the person. In this operating mode, the user provides a biometric sample that will be compared with all the enrolled models which are stored in the database. This is also called 1:N correspondence. The output of this biometric system is represented by the identity of the person whose model has the highest degree of similarity with the input biometric modality. Typically, if the greatest similarity between all models is less than the minimum of the safety threshold, the person is rejected, which means that the user is rejected, and he isn't one of the persons enrolled by the system. Otherwise, the person is accepted. An example of the identification biometric system, we suppose that the previous computer is used by several persons. Therefore, all the users who are allowed to use this computer are enrolled by the system. When an individual tries to access to this computer, he must present its biometric data to the system. The system allowed or refused the access according to the determination of the identity of the user.

Figure 2.5 demonstrates the process of the identification mode.

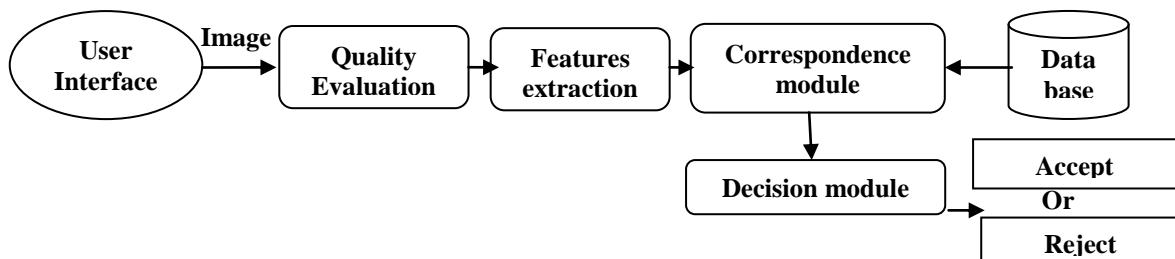


Figure 2. 5: Identification of an individual by the biometric system.

In summary, the biometric system that operates in the authentication mode gives the answer of the question “*are you person X ?*”. However, the identification system answers the question “*Who are you?*”.

2.8 LIMITATIONS OF THE BIOMETRIC SYSTEMS

There are several advantages of the biometric systems compared to the traditional means of identification; these advantages can be summarized in the following points:

- The biometric modality cannot be lost except the case of serious accident.
- The biometric modality cannot be copied; it is difficult to spoof the biometric characteristics, especially the new technologies which can ensure that the biometric data is from a live person.

- The biometric modality cannot be used or shared by others, so it is secure.
- The biometric modality cannot be forgotten, it is always available to the individual so there are no requirements to remember passwords.
- Unique: there is no probability that two people have the same biometric data.
- The biometric is permanent and consistent.
- The ease of use and the comfort, for example, it is easier to present the biometric modality than remembering many passwords. So, the biometric is practical and simple because there are no cards and passwords to remember.

The biometric gives a safer identification compared to the cards or the keys by making a physical connection between the person and his identity. It has several advantages over traditional means. But there is no biometric totally reliable because the modality biometric likes all living organism:

- It adapts to the environment.
- It ages.
- It undergoes trauma more or less important.
- It evolves and changes.

However, the biometric systems present some limitations which prevent them to be used in certain applications; these limitations can be summarized by the following points:

- **The performance:** The most important limitation of the biometric system is the performance. Indeed, if the problems of security of the passwords, the keys, the cards, and the badges are related to their loss, falsification, or theft, they are 100% effective in term of recognition. For example, if the password is correct, the answer is yes, otherwise, the answer is no. However, the biometric systems cannot give this exact recognition because they are based on the similarity scores. For this reason, the biometric systems include the decision module which fixed a threshold that applied to the similarity score. If the score is greater than the threshold, the two compared samples correspond to the same person, and this means that the identity is verified, and the user is accepted. Otherwise, the person is rejected, and his identity has not been verified. This absence of the exact match between the biometric data is due to several parameters such as:

- The variability intra-class: It means the variability of the biometric data for the same person.
 - The similarity inter-class: It means the similarity of the biometric data for the different individuals.
-

- The variability during the acquisition: this is due to the following reasons:
 - ✓ The physical deformation during the acquisition.
 - ✓ The acquisition noise.
 - ✓ The use of several captures.
- **The non-universality:** There are certain biometric modalities that can't be used by certain category of the population. The NIST *National Institute of Standards and Technology* shows that there is about 2% of the population can't use the modality of fingerprints as a mean of identification (**Web04**). For example, there are several persons who can't present their fingerprints to the biometric system due to the absence of fingers, cuts, or scars. For the iris and the retina modalities, there are certain diseases can hinder the recognition process.
- **The environmental conditions during the acquisition:** The acquisition of certain biometric data can be impossible due to the environmental conditions. For example, when it is dark, it is impossible to use the face recognition systems. In the noise place, it is impossible to use the voice recognition systems. So, the environmental conditions get an important place during the acquisition.
- **The possibility of fraud:** The reproduction of certain biometric modalities is possible. For example, it is relatively simple to imitate the voice of a person or to reproduce his signature. However, it is more difficult to reproduce his fingerprints or his iris, but it is possible. Indeed, some studies have shown that it was possible to reproduce the fingerprints modality by using the silicone (**Matsumoto,2002**).
- **The cultural limitation or the usage limitation:** Certain civilizations prevent the use of the biometric modalities which leave the traces such as the fingerprints except in the application of high security, for example, the VISA and the passports. So, this is limited the use of the fingerprints in the application less secure because it represents a risk for the bad use of data. In addition, there are some modalities are considered as intrusive due to the hygiene problems because there is a physical contact. Also, the use of the iris and the retina modality is considered as intrusive for some persons due to its acquisition which is very near to the eye, and that gene some persons.

2.9 EVALUATION OF THE BIOMETRIC SYSTEMS

The goal of the evaluation of the biometric system is to decrease the limitations presented in the previous section.

Figure 2.6 presents four main categories of evaluation, namely: performance, data quality, usability, and security.

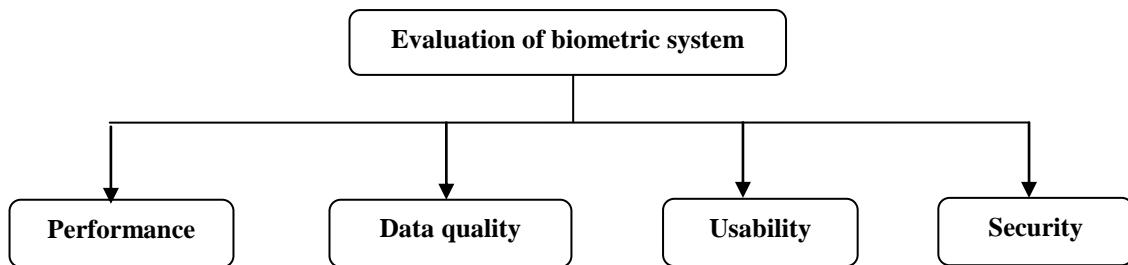


Figure 2. 6: Evaluation of the biometric system.

In this section, we focus the evaluation around the four aspects which are:

- The performance in term of errors.
- The quality of the biometric data.
- The use in term of acceptability.
- The security in term of robustness against fraud.

2.9.1 PERFORMANCE

In practice, the traditional methods which are based on the use of the keys, the password, and the cards return a precise response yes or no, so they give a perfect match between two templates. But the biometric systems can't give this exact recognition because they are based on the similarity scores. So, there is no biometric system can be entirely reliable. Therefore, it is necessary to use the different indicators in order to measure the performance of the biometric systems.

However, the performance is determined by the effectiveness of the biometric system in term of errors.

In the literature, there are various indicators of performance which differ according to the operating modes of the biometric system: the identification or the authentication mode (**Web05**). So, there are several metrics of various kinds (**Egan,1975**) (**Martin,1997**) (**Perronnin,2002**) (**Bhatnagar,2009**):

- The errors rates.
- The processing time and the memory occupation.
- The performance curves.
- The associated operating points.

2.9.1.1 ERRORS RATES MEASURES

According to the international organization of normalization ISO/IEC 19795-1 (**Web06**), there are three main categories of the error rates measures which are:

- The fundamental errors rates.
- The errors rates of the authentication systems.
- The errors rates of the identification systems.

2.9.1.1.1 Fundamental Errors Rates

- **FMR** (*False Match Rate*): The false matching between the acquired biometric data and the stored model of another individual. It can happen in the matching or the decision module. For example, an imposter is falsely accepted by the system.
- **FNMR** (*False Non-Match Rate*): The false non-matching between the acquired biometric data and its correspondent model. It can happen in the matching or the decision module. For example, a genuine is wrongly rejected by the system.
- **FTE** (*Failure To Enroll rate*): The biometric system cannot generate the biometric model during the enrolment phase. For example, the absence of the fingerprints due to genetic reason or the absence of the fingers, the iris that is too dark.

2.9.1.1.2 Errors Rates of the Authentication System

- **FAR** (*False Acceptance Rate*): The biometric system can accept the imposters wrongly.
 - **FRR** (*False Rejection Rate*): The biometric system can reject the costumers wrongly.
- The FAR and the FRR are the most used for evaluating the performance of methods. The both rates are related to the decision threshold, so they are changed significantly by varying the threshold of security.

However, the choice of the FAR and the FRR levels depends on the application, and the level of security desired, for example:

- ✓ If we want a biometric system with ultra security, we will impose a security threshold corresponding to FAR near of zero, this case makes the biometric system robust to imposters, but it can allow the rejection of some costumers.
 - ✓ If we want a relative ease of use, and we don't want that the user restarts the authentication process several times, we chose a security threshold corresponding to low FRR and high FAR, this case can allow a few imposters to cheat the system.
-

2.9.1.1.3 Errors Rates of the Identification System

- **FPIR** (*False Positive Identification error Rate*): It is the proportion for which the returned identifiers list is not empty.
- **FNIR** (*False Negative Identification error Rate*): It is the proportion for which the identifier of the user does not figure in the returned list.
- **IR** (*Identification Rate*): The identification rate at rank “r” is the proportion for which the identifier of the user figures in one of the “r” identifiers of the returned list.

2.9.1.2 PROCESSING TIME AND MEMORY OCCUPATION MEASURES

One of the most important factors for the evaluation of the biometric systems is the processing time of the information which is usually measured in:

- **Average enrolment time**: It is the average time needed to generate the biometric models of persons.
- **Average verification time**: It is the average time required for the verification process, and this time doesn't depend on the number of persons in the database.
- **Average identification time**: It is the average time required for the identification process, and this time depends on the number of persons in the database.

In addition, the memory space required by the system is also an important factor to evaluate the biometric systems. It is usually measured by maximum memory allocated during the three phases which are: the enrolment, the verification, and the identification.

2.9.1.3 PERFORMANCE CURVES

The curves are generally used to illustrate graphically the performance of the biometric systems. In addition, they used to make the performance more usable and more readable. However, they are especially used in the comparison of the biometric systems which have similar performance.

- **ROC Curve** (*Receiver Operating Characteristic Curve*): It is one of the means used for the evaluation of the authentication systems, and it presents the link between the FAR and the FRR for the different values of the security threshold. The ROC curve traces the false rejection rate FRR (in the Y-axis) against the false acceptance rate FAR (in the X-axis) (**Perronnin,2002**). Sometimes, the DET (*Detection Error Tradeoff*) term is used instead of the ROC curve. In this case, the ROC curve is reserved to present (1-FRR) against (FAR). The advantage of this method is the

comparison between the different biometric systems which are represented in one curve.

- **CMC Curve** (*Cumulative match Characteristic Curve*): This curve is used for the evaluation of the identification systems. It indicates for an integer “i” the probability that the system returns the right identifier for an observation in the “i” first answers offered by the identification system. The CMC curve gives the percentage of persons according to a variable called the rank. For example, the system recognizes with rank “1”, this means that it chooses the nearest image as a result of the recognition. The system recognizes with rank 2 when it chooses one of two images which correspond to the input image. So, we can say that more the rank increases, more the recognition rate corresponding is linked to a low security level.

A comparative study which clarifies the link between the both curves (CMC and ROC) can be found in (**Bolle,2005**).

2.9.1.4 PERFORMANCE POINTS

The performance points are used to illustrate the performance of the biometric systems. There are several metrics in the literature such as: the AUROCC “*Area Under the ROC Curve*”, the EER “*Error Equal Rate*”, the WER “*Weighted Error Rate*”, the HTER “*Half Total Error Rate*”, and the fixed FAR or FRR.

- **AUROCC** (*Area Under the ROC Curve*): This metric is a good indicator for the evaluation and the comparison of the biometric systems. It describes how accurate a biometric system performs. More the AUROCC is high then more the algorithm is efficient.
- **EER** (*Equal Error Rate*): This error rate is the most commonly used by the researches for the illustration of the performance of the biometric system. This rate is the value where the both error rates (FAR and FRR) are identical. In the literature, this metric is frequently used for the comparison of the authentication systems. The EER is achieved at the intersection of the ROC curve and the right of $\text{FAR} = \text{FRR}$. However, more the EER is low then more the system is efficient.
- **HTER** (*Half Total Error Rate*): It is the average between the FAR and the FRR for fixed threshold. Theoretically, this error rate is used to approximate the EER where the both error rates, the FAR and the FRR are the same order of greatness.
- **Fixed FAR or FRR**: The EER estimated the error rate on the curve where there are so many false rejects compared with false acceptance. But, this error rate doesn't give

much information on the interaction between the biometric data of the different users such as the intra-class or the inter-class. These motivate some applications to fixe one of the two rates the FAR or the FRR.

- **WER (Weighted Error Rate):** This rate corresponds to the threshold where the FRR is proportional to the FAR with a coefficient which depends on the application. For a coefficient equal to 1, the WER threshold is equal to the EER threshold.

According to the researches in the literature, the use of the EER may be sufficient to decide that a system is better than another, and this is only right for the biometric systems which give different error rates. But in the case while the different biometric systems have the same EER, the use of a complimentary metrics becomes indispensable. There are several metrics in the literature, for example, we can combine the AUROCC (**Tronci,2009**) with the ERR in order to compare the different biometric systems.

When the performance indicators are selected, it remains to evaluate them. So we need a test database for the evaluation step. However, there are several public databases which are used by the researchers to compare the results of a method to another. The test protocol must be defined. A good test protocol must separate the data into three bases:

- The learning base which contains the data for the generation of classifiers.
- The validation base that estimates the parameters of the classifiers.
- The test base on which the performance indicators are calculated.

When the database used by the system contains very large numbers of data, the creation of these three bases doesn't pose a problem. Otherwise, there is a problem to divide the database and for this reason, there are several strategies in order to keep a good estimate of performance (**Stone,1977**) (**Martens,1998**) (**Eriksson,2000**). These include:

- The cross validation.
- The leave one out.
- The separation into random groups.

2.9.2 DATA QUALITY

The biometric system cannot be reliable 100% compared to the traditional methods; this is due to the artifact acquisition. For example, in the case of the fingerprints recognition, the quality of the fingerprint image can vary depending on the dirty of skin, its moisture level, its oily appearance, or the pressure applied on the sensor during the acquisition phase.

The evaluation of the biometric data quality is a recent area that attracts the attention of several researches.

In the following step, we will define the quality of the biometric data. Then, we will present some factors that can degrade the data quality.

2.9.2.1 DEFINITION OF DATA QUALITY

The data quality is receiving more attention because it is one of the mains factors that affect the performance of the biometric systems. According to the *international organization of normalization ISO/IEC 29794-1*(**Web07**), the data quality can be categorized into three main groups, which are:

- **Character:** It is the characteristics of the source or the physical characteristics of the individual.
- **Fidelity:** The degree of similarity between the acquired biometric model and its corresponding.
- **Utility:** The impact of the acquired biometric data on the performance of the biometric system. In the biometric system, the data quality is usually linked to the utility (**Grother,2007**).

2.9.2.2 FACTORS DEGRADING THE DATA QUALITY

There are several factors which can degrade the performance of the biometric systems. Some of these factors can be controlled and others are uncontrollable. These factors can be divided into four classes according to (**Fernandez,2008**):

- **Factors related to user:** In this category, there are two groups which are:
 - *Physiological factors:* These factors are difficult to control because they are totally linked to the person.
 - *Behavioral factors:* These factors are also difficult to control because they are linked to the behavior of the individual.
- **Factors related to the user-sensor interaction:** These factors are easier to control than the factors which are related to users. There are two types:
 - *Environmental factors:* These factors are linked to the acquisition phase. Some of these factors may be controllable.
 - *Operational factors:* These factors are also linked to the acquisition module. They can be controlled if we have an influence on the acquisition phase.

- **Factors related to the acquisition sensor:** For example, the ease of use, the size of the acquired image or its resolution, and the time needed for the acquisition, etc.
- **Factors related to the processing system:** For example, the data format, and the algorithm applied to the data processing, etc.

However, the factors related to the user affect the character of the biometric data, and the others types of factors have an impact on the fidelity between the biometric sample and its source.

Table 2.4 presents some examples about the factors described above, according to (Fernandez,2008):

	Factors	Fingerprint	Iris	Face	Voice	Signature	Hand
Physiological	Age	X	X	X	X	X	X
	Gender			X	X		
	Rate		X	X			
	Amputation	X				X	X
	Skin condition	X					X
	Diseases	X	X	X	X	X	X
	Injuries	X	X	X	X	X	X
Behavioural	Tiredness	X	X	X	X	X	X
	Distraction	X	X	X	X	X	X
	Cooperatively	X	X	X	X	X	X
	Motivation	X	X	X	X	X	X
	Nervousness	X	X	X	X	X	X
	Distance		X	X	X		
	Frontalness		X	X			
	Closing the eyes		X	X			
	Pressure on the sensor	X				X	X
	Inconsistent contact	X					X
	Pose, gaze		X	X			
	Illiteracy				X	X	
	Manual work	X					X
	Facial expression			X			
	Ethnic origin		X	X	X	X	
	Hairstyle, beard, and make-up			X			
	Clothes			X			
	Hat			X			

	Factors	Fingerprint	Iris	Face	Voice	Signature	Hand
Environmental	Jewellery	X		X			X
	Glasses or contact lenses		X	X			
	Indoor/Outdoor	X	X	X	X	X	X
	Background			X			
	Temperature	X					X
	Humidity	X					X
	Illumination	X	X	X			
	Light reflection		X	X			
Operational	Ambient noise				X		
	Object occlusion			X			
	User familiarity	X	X				X
	Supervision by an operator	X	X	X	X	X	X
	Sensor cleaning	X					X
	Physical guides	X	X	X			X
	Time between acquisitions	X	X	X	X	X	X

Table 2. 4: Some factors having an impact on the biometric data quality according to (Fernandez,2008).

In the literature, there are several studies that evaluate the quality of the biometric data, such as: (Fernandez,2007) (Shen,2001) (Chen,2005c) (Tabassi,2005) (Chen,2006b) (Kalka,2006) (Lee,2006) (Krichen,2007) (He,2008) (Zhang,2009).

2.9.3 USABILITY

The usability is determined by the acceptability and the satisfaction of the users during the use of the biometric systems. However, the biometric system requires the use of the sensors to acquire the biometric data. *Kukula* and *Proctor* (Kukula,2009) suggest that the development of the biometric systems must take into account the manner in which the individuals interact with the sensor. The authors confirmed that the absence of this study will degrade the performance of the biometric system, and this increases some errors rate such as: the FTE, the FTA, and the FRR.

The evaluation of the use of the biometric systems reduces the complexity of using these systems. So, this allows increasing the acceptability of users, and it will improve the performance of these biometric systems in terms of errors (FTA, FTE, EER).

In the literature, there are several studies based on the evaluation of the use of the biometric systems such as: (Deane,1995) (Coventry,2003a) (Coventry,2003b) (Coventry,2003c)

(Moody,2004) (Schimke,2004) (Elliott,2007) (Jones,2007) (Heckle,2007)(Theofanous,2007) (Theofanous,2008) (Pons,2008).

2.9.4 SECURITY

The security is determined by the power of the biometric system against the frauds and the spoofing. Despite the various benefits of the biometric systems compared to the traditional systems, they are still vulnerable to specific attacks that can significantly degrade their functionality. According to (Ratha,2001), the attacks on the biometric system are grouped into 8 classes which are:

- Falsified the biometric data: For example, face mask, fake finger, imitate the voice, and copied the signature.
- Transmission of intercepted biometric data: For example, the presentation of an old image of the fingerprint.
- The attack on the features extraction module.
- Alteration of extracted features.
- The similarity calculation module is replaced by a malicious module.
- Alteration of the database.
- The attack on the channel between the database and the similarity calculation module.
- Alteration of the decision.

These attacks are usually based on several factors:

- The biometric modality (it is more difficult to reproduce retina or vein patterns).
- The sensor type (2D or 3D, 3D sensors allow better to detect the fraud attempts).
- The security parameters (FAR) of the system.

2.10 BIOMETRIC APPLICATIONS

The biometric can be used in several applications which require the security or to know the person's identity. These applications can be divided into three main groups which are:

- **Commercial applications:** such as the access to the computer network, the mobile phone, the internet access, the electronic commerce, the security of the electronic data, and the credit cards, etc.
 - **Legal applications:** such as the criminal research, and the terrorist identification, etc.
 - **Government applications:** such as the passport, the driver's license card, the social security, etc.
-

2.11 CONCLUSION

In this chapter, we have presented the biometrics in general. Therefore, we presented some principles and definitions of the biometric. Then, we gave a view of the different modalities biometric, their advantages, their disadvantages, and their applications. We have also defined the structure of the biometric systems, and their operating modes. Also, we presented some limitations of these systems when they use only a single biometric trait. In addition, we have detailed the different aspects for the evaluation of the biometric systems. Finally, we have presented some examples of the biometric applications.

The unimodal biometric systems allow recognizing a person using a single biometric modality, but it presents certain limitations. The most of these problems can be reduced by using multiple biometric modalities of the same person. However, the multi-biometrics will be the subject of the next chapter.

CHAPTER III: THE MULTI-BIOMETRICS

This chapter presents the multi-biometrics systems, their design, their classification, their fusion levels, and their architectures. This chapter is organized as follows:

Summary:

- 3.1 Introduction
 - 3.2 Multi-Modality
 - 3.3 Design of the Multi-Biometrics Systems
 - 3.4 Classification of the Multi-Biometrics Systems
 - 3.4.1 Multi-Sensors Systems
 - 3.4.2 Multi-Algorithms Systems
 - 3.4.3 Multi-Samples Systems
 - 3.4.4 Multi-Units Systems
 - 3.4.5 Multi-Modal Systems
 - 3.4.6 Hybrid Systems
 - 3.5 Fusion Levels
 - 3.5.1 Before the Matching
 - 3.5.1.1 Sensor Level
 - 3.5.1.2 Feature Level
 - 3.5.2 After the Matching
 - 3.5.2.1 Dynamic Selection of Classifiers
 - 3.5.2.2 Rank Level
 - 3.5.2.3 Score Level
 - 3.5.2.4 Decision Level
 - 3.6 Architectures
 - 3.7 Multimodal Database Design
 - 3.8 Conclusion
-

3.1 INTRODUCTION

The biometric is a research area in full expansion, and it uses in various applications to release the identification or the authentication tasks. Today, there are more needs of security in the modern society, and this encourages the use of the biometrics, but the use of single biometric modality decreases the performance of these systems. This is motivated the combination of multiple modalities within the same biometric system. Indeed, we need more than one characteristic biometric (physical or behavioral) to recognize a person because one modality biometric can't always realize a reliable task of recognition.

However, the integration of information presented by the different biometric modalities may realize a reliable task of recognition. So, we can say that the multimodal biometrics systems are more efficient due to the presence of multiple evidence elements (**Hong,1999**). The first work of fusion is the integration of the face with the voice modality in 1995 (**Brunelli,1995**), and since this date, many studies are conducted by integrating different modalities, by varying the level of data fusion, and by testing several rules of fusion (**Ross,2006a**).

In this chapter, we will present the basic concepts which are related to the multi-biometrics. Also, we will describe the design of the multi-biometrics systems, their classification, their fusion levels, and their architectures. Finally, we will express the structure of the multimodal databases.

3.2 MULTI-MODALITY

The multimodal biometric is the system that integrated more than one physiological or behavioral biometric modality in one of the three operating modes: the enrolment, the identification, or the authentication. So, the multimodality is the combination of multiple biometrics systems. Its goal is to reduce the limitations related to the use of single biometric modality which are seen in the previous chapter (paragraph 2.8).

Indeed, the integration of multiple modalities is intended to improve the performance of recognition. In addition, it reduces the risk of failure to enrolment. Also, it increases the robustness against the fraud.

The biometric systems promise to be successful compared with the traditional methods (the passwords, the badges, and the keys). But the biometric systems that are based on the use of

one biometric modality can't currently improve an excellent rate of recognition because these systems are often affected by the following issues (**Jain,2004a**):

- **The non-universality:** The universality is one of the most necessary conditions for the task of recognition. A modality will be considered as universal when each individual of the population is able to present this modality to the system. However, all the biometric modalities are not really universal. For example, the *National Institute of Standards and Technologies* (NIST) reported that there are about 2% of the population cannot present the fingerprints modality with good quality (people with disabilities related to the hand) (**Web04**). Similarly, the long eyelashes, abnormalities of the eyes, or eye diseases (such as cataracts and glaucoma) can't offer the iris or the retina images with good quality for the task of recognition. Therefore, the non-universality causes the enrolment errors FTE “*Failure to Enroll*” and the capture errors FTA “*Failure to Acquire*” in the biometric system.
- **Lack of individuality or the interclass similarities:** It means the similarity between the features extracted from the biometric data of the different individuals. This lack of uniqueness increases the rate of false acceptance FAR “*False Accept Rate*” of the biometric system. For example, some individuals can have the same appearance facial due to the genetic factors (identical twins, father and son, etc).
- **Lack of invariant representation or intra-class variation:** it means that the biometric data acquired during the phase of recognition are not identical to the data that were used to build the model of this same user during the enrolment phase. The intra-class variation generally increased the false rejection rate (FRR) of the biometric system. However, these variations may be due to the following reasons:
 - The user-sensor interaction: For example, change of the facial expressions, and the pose during the facial recognition.
 - The use of different sensors during the enrolment and the verification phases.
 - The inherent change of the biometric modality: For example, the presence of hair in the face picture, the appearance of wrinkles due to old age.
 - The environmental conditions: For example, change of the illumination for the facial recognition, or the reflections of light for the iris recognition.
- **Noise introduced by the sensor:** There are several noises can affect the acquired biometric data. For example, the bad cameras focus result a blurred image of face or iris modality, the accumulation of dust on the fingerprints sensor. So the quality of

the images of the biometric data affects the recognition rate of the biometric system. Also, the presence of the noise can seriously compromise the accuracy of the biometric system (**Chen,2005c**).

- **The spoofing:** The biometric modality is not like the traditional methods such as the keys and the badges which can be stolen or the passwords and the codes which can be forgotten. So, it is really very difficult to steal the biometric modalities, but it is possible to use the spoofed biometric modalities. However, the behavioral biometric modalities (such as the signature and the voice) are more sensitive to this kind of attack compared with the physiological biometric modalities. There are several studies in this area, such as (**Putte,2000**) (**Matsumoto,2002**) demonstrated that it was possible to produce false fingerprints and use them to cheat the fingerprints recognition systems.

There are several reasons that motivate the integration of the biometric modalities; these can be summarized by the following points:

- **The accuracy:** The integration of two or more biometric modalities is more accurate than the use of one biometric modality, according to the error rates obtained like: the FTE, the FTA, and the FMR, etc.
- **The security:** The use of multiple modalities biometric can preserve a higher security. It is unlikely that a person can spoof multiple biometric traits at once.
- **The vulnerability:** The spoofing can be defined as an unauthorized person who can masquerade as authorized user. For example, the use of the artificial fingerprints to cheat a fingerprints recognition systems. There are several studies that demonstrated that the use of the liveness detection can eliminate the spoofing (for example, by measuring the biometric features such as: the temperature, the humidity, and the pulse, etc). The multi-modal biometric systems require the use of multiple biometric traits randomly which ensures the liveness detection, and this protects the biometric system from hackers and spoofing.
- **The universality:** If a person cannot present a trait to the multimodal biometric system due to disease or disability, the system can use other biometric traits for the recognition task, so we can say that the multimodal biometric system is universal in its nature.
- **The reliable recognition:** The multimodal biometric systems integrate multiple biometric modalities, and each single trait can offer an additional evidence for the

recognition task. For example, the voice of two different individuals can be similar. So, the unimodal voice recognition system may lead to a false recognition. However, if we add for the same biometric system other modality such as the iris or the fingerprints modalities, the recognition rate of the system would be certainly increased, because it is nearly impossible that two different persons have the same voice as well as the iris or the fingerprints patterns.

- **The user's acceptance:** We are mentioned in the previous points that the multimodal biometric systems are reliable, have a high security, more accurate, and avoid the spoofing attacks. Therefore, these systems are more accepted compared with the unimodal biometric systems.

3.3 DESIGN OF THE MULTI-BIOMETRICS SYSTEMS

The integration of the biometric information produces several issues concerning the design of the biometric system. The first important point is the design of the interface between the user and the machine (**Oviatt,2003**). There are several factors which have an impact on the structure of the multimodal biometric system such as:

- **The cost:** The cost is based on:
 - The number of the sensors employed.
 - The time needed for the acquisition of the biometric data.
 - The storage requirements.
 - The processing time of the algorithms.
 - The degree of convenience perceived by the user.
 - **The choice of the biometric modalities:** The determination of the biometric information sources is done according to the type of applications.
 - **The architecture:** The acquisition and the data processing are done simultaneously or serially.
 - **The fusion level:** The determination of the type of the information that should be integrated (the features, the scores, the decision, etc).
 - **The methods used for the fusion:** The choice of the methods that will be used for the integration of the information presented by multiple biometric sources.
 - **Verification Vs Identification mode:** The choice of the operating mode.
 - **The security and the reliability level desired.**
 - **The multimodal database.**
-

3.4 CLASSIFICATION OF THE MULTI-BIOMETRICS SYSTEMS

In fact, there are many possible scenarios for the multi-biometrics systems. Figure 3.1 illustrates these different scenarios.

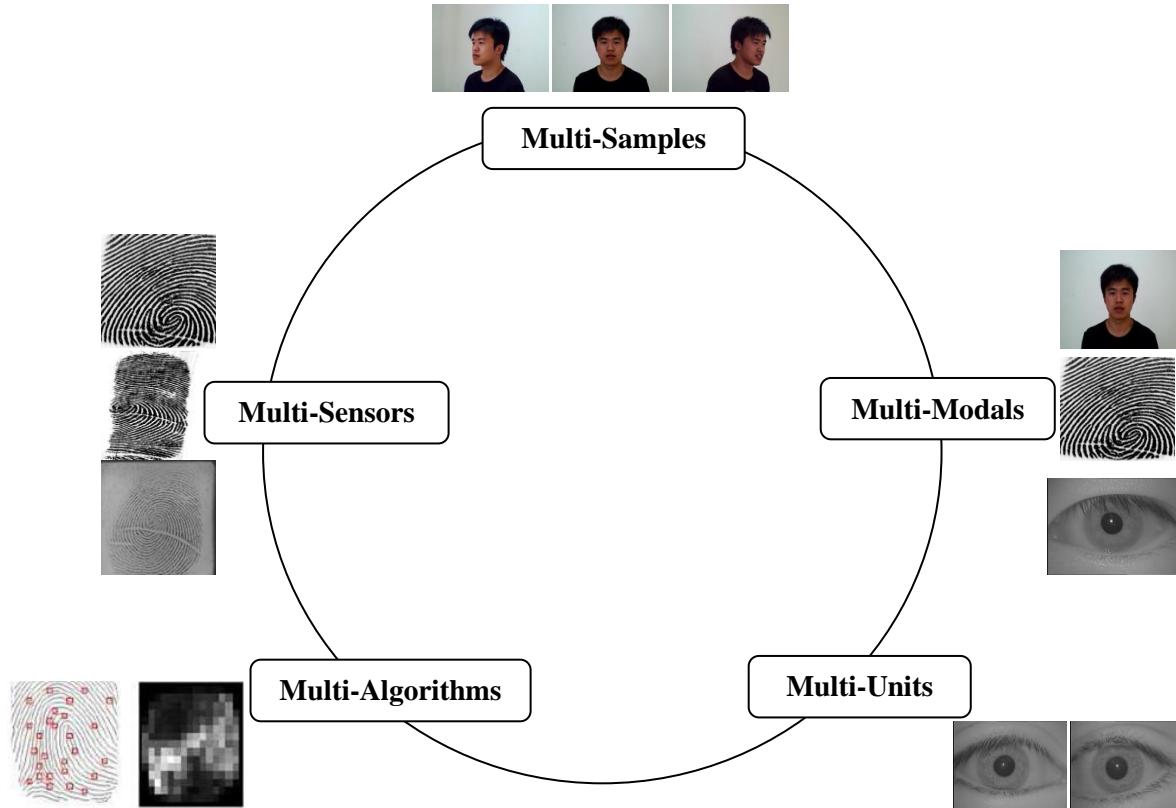


Figure 3. 1: Sources of multiple evidences of identity in the multi-biometrics systems.

The multi-modal systems are intended to identify or authenticate persons by using multiple modalities biometric (**Jain,2006**) (**Ross,2009**).

Ross and Jain (**Ross,2003a**) identify multiple classes of the multi-biometric systems which are:

3.4.1 MULTI-SENSORS SYSTEMS

In these systems, there are several sensors that are used to acquire the same biometric trait. For example, the use of two different scanners (optical and thermal) for the fingerprints recognition. The following table gives some examples of the multi-sensors systems that exist in the literature.

Modalities	Sensors Fused	Papers
Fingerprints	Optical sensor + Capacitive sensor.	(Marcialis,2004a)
Face	2D camera + Range scanner.	(Chang,2003a)
	IR camera + Canon Powershot G2 digital camera.	(Chen,2003)
	2D camera + Range scanner +IR camera.	(Chang,2004)
	Red + Green + Blue channels.	(Kittler,2004)
		(Socolinsky,2003)
	2D camera + IR camera.	(Chen,2005b)
		(Fathima,2014)
	2D camera + Range scanner.	(Chang,2005) (Lu,2005)

Table 3. 1: Examples of the multi-sensors systems.

3.4.2 MULTI-ALGORITHMS SYSTEMS

In these systems, there are several algorithms that are used to verify the same trait biometric. The following table gives some examples of the multi-algorithms systems that exist in the literature.

Modalities	Matchers Fused	Papers
Fingerprint	Minutiae and Texture features.	(Prabhakar,2002)
		(Ross,2003b)
		(Marcialis,2005)
Face	PCA (Principal Component Analysis), LDA (Linear Discriminant Analysis), ICA (Independent Component Analysis).	(Lu,2003) (Marcialis,2004b) (Ross,2005)
	LDA (Linear Discriminant Analysis), PM (Probabilistic Matching), HST (Colour Histogram).	(Czyz,2004)
	Global and local features.	(Fang,2002)
	Two different sets of PCA (Principal Component Analysis)-based features.	(Yang,2003)
Signature	Global and local features.	(Ouamane,2014)
		(Fuentes,2002) (Aguilar,2005b)
Hand	Geometry and Texture features.	(Kumar,2003)
Voice	MFCC (Mel Frequency Cepstral Coefficients), CMS (Cepstral Mean Subtraction), MACV (Maximum Auto-Correlation Values) features.	(Sanderson,2001)
	Spectral features-GMM (Gaussian Mixture Models) and utterance verification-HMM (Hidden Markov Model).	(Linares,2003)
	Acoustic, Prosodic, Phonetic, Lexical, Conversational features.	(Reynolds,2003)
	SVM and GMM (Gaussian Mixture Models).	(Campbell,2004)
Palmprint	LPCC (Linear Predictive Cepstral Coefficients), MFCC (Mel Frequency Cepstral Coefficients), ARCSIN (Arcus Sine reflection coefficients), FMT (Formant frequencies) features.	(Kinnunen,2004)
	Global Geometry, Global and Local Texture Energy, Fuzzy Interest Line.	(You,2004)
	Gabor, Line, Appearance-based features.	(Kumar,2005)
Face and Iris	“Cognitec and PittPatt” for face, “VeriEye and Irisbee” for iris.	(Connaughton,2012)

Table 3. 2: Examples of the multi-algorithms systems.

3.4.3 MULTI-SAMPLES SYSTEMS

In this category, the same capture can be used to acquire several variants of the same trait biometric. For example, for the facial recognition system, the front, the left, and the right profile of the face modality are captured to take account the changes in the facial pose.

3.4.4 MULTI-UNITS SYSTEMS

In this type of systems, multiple instances of the same trait biometric are acquired. For example, the left and the right irises of person are used to verify his identity. The following table gives some examples of the multi-samples and the multi-units systems that exist in the literature.

Modalities	Instances	Papers
Fingerprints	10 fingers	(Wilson,2004)
	2 fingers	(Garris,2004)
	2 impressions, 2 fingers.	(Prabhakar,2002)
	2 impressions	(Jain,2002)
		(Moon,2004)
Face	Sequence of images from video.	(Zhou,2003) (Li,2003)
Voice	Multiple utterances.	(Cheung,2004)
Iris	Left and right Irises.	(Rattani,2009)
Face and iris	<ul style="list-style-type: none"> • Sequence of images from video. • Left and Right irises. 	(Connaughton,2012)

Table 3. 3: Examples of the multi-units and the multi-samples systems.

3.4.5 MULTIMODAL SYSTEMS

In these systems, several traits biometric are acquired by different sensors. This type of system was particularly the subject of several researches because it allows combining multiple evidences presented by the different biometric modalities. In addition, the recognition accuracy can be improved by using an increasing number of the biometric features. However, there are multiple consideration that can limit the number of the traits biometric used in a specific application such as: the cost of deployment, the enrollment time, or the errors rate. The following table gives some examples of the multi-modal systems that exist in the literature.

Modalities	Papers
Face and Voice	Brunelli and Falavigna (Brunelli,1995)
	Kittler and al. (Kittler,1998)
	Ben-Yacoub and al. (Yacoub,1999)
	Bigun and al. (Bigün,1997)
Face and Fingerprints.	Hong and Jain(Hong,1998)
	Snelick and al. (Snelick,2005)
Face and Gait.	Shakhnarovich et al. (Shakhnarovich,2001)
	Kale et al. (Kale,2004)
Face and Ear.	Chang et al. (Chang,2003b)
	Islam and al. (Islam,2013)
Face and Palmprint	Feng et al. (Feng,2004)
	Poinsot and al. (Poinsot,2009)
	Shen (Shen,2011)
Face, Fingerprints, and Voice.	Jain and al. (Jain,1999)
Face, Voice, and Lip movement.	Frischholz and Dieckmann (Frischholz,2000)
Face, Fingerprints, and Hand geometry.	Ross and Jain(Ross,2003a)
Fingerprint and Hand geometry.	Toh et al. (Toh,2003)
Fingerprints, Hand geometry, and Voice.	Toh et al. (Toh,2004)
Fingerprint and Signature.	Fierrez-Aguilar et al. (Aguilar,2005a)
Voice and Signature.	Krawczyk and Jain(Krawczyk,2005)
Fingerprint and Voice.	Toh and Yau (Toh,2005)
Palm print and Fingerprint	Dhameliya et Chaudhari(Dhameliya,2013)
Face, Fingerprints, and Iris.	Fathima and al. (Fathima,2014)
Face and Iris.	Wang and al. (Wang,2003)
	Son et lee(Son,2005)
	Chen et chu (Chen,2006a)
	Gan and liang (Gan,2006)
	Zhang et al. (Zhang,2007)
	Lin et al. (Lin,2009)
	Morizet (Morizet,2009)
	Rattani et Tistarelli(Rattani,2009)
	Eskandari et Toygar (Eskandari,2014)

Table 3. 4: Examples of the multimodal systems.

3.4.6 HYBRID SYSTEMS

The term of the hybrid systems (**Chang,2005**) is used to refer to systems that integrate a subset of the five scenarios mentioned above.

Table 3.5 compares the different categories of the multi-biometrics systems:

Category	Sensors	Algorithms	Modalities	Biometric traits
Multi-samples	1	1	1	2 or more samples same trait
Multi-sensors	2 or more	1 or more	1	1
Multi-algorithms	1	2 or more	1	1
Multi-units	1 or more	1	1	2 or more instances same trait
Multi-modals	2 or more	2 or more	2 or more	2 or more

Table 3. 5: Comparison of the multi-biometrics systems.

There are different criteria that can be used to compare the different types of the multi-biometrics systems, these criteria are based on:

- The difference in term of the cost,
- The discomfort for the user,
- The quantity of the information compared to the unimodal biometric systems.

For the multi-sensors and the multi-modal scenarios, we can see that they will add an additional cost since they require several acquisition systems. For the multi-units scenario it all depends on the number of the sensors used. For example, if there are several sensors used simultaneously, or if single sensor is used to make successive measurements. The multi-algorithms and the multi-modal scenarios have an additional software cost because they use several algorithms.

In term of discomfort for the user, the multi-samples scenario is the most difficult because it increases the duration of the identification process. In the other hand, the multi algorithms scenario is the most appreciated because it is simple to use by the user. For the three other scenarios, the difference will be more or less important depending on whether the various acquisitions can be performed simultaneously or successively.

Finally, in terms of quantity of information, the multimodal scenario is the richest, and the both scenarios multi-samples and multi-algorithms are the poorest. The multi-units scenario can also provide a large amount of information.

Despite the inadequacies of these fusion scenarios, the multi-biometrics offers a high level of security and an authentication system more performance than that based on a single biometric modality.

3.5 FUSION LEVELS

In the pattern recognition systems, the quantity of information available reduces during the progression from the first module (the sensor module) to the last module (the decision module). In the multi-biometrics system, the integration can be done by using the available information in any modules of the recognition system. In this section, we will detail these fusion levels which can be divided into two large categories: the fusion before the matching, and the fusion after the matching step (**Sanderson,2002**).

3.5.1 BEFORE THE MATCHING

The fusion before the matching step means that the information can be integrated at one of the both levels: the sensor level or the feature level.

3.5.1.1 SENSOR LEVEL

The fusion at the sensor level is the integration of the raw data acquired by the sensors (**Lyengar,1995**). However, the fusion at this level can be done only if the multiple instances of the same biometric trait are obtained from the same or multiple compatible sensors. If the multiple instances are incompatible, the fusion at this level is not possible. For example, in the face recognition system, the face images which captured by multiple cameras can be combined to form a 3D model of the face modality, but this task is difficult when these images are captured by multiple cameras with different resolutions.

3.5.1.2 FEATURE LEVEL

The principle of the fusion at this level is the integration of the different features vectors which are obtained from one of the following sources:

- Multiple sensors of the same biometric trait.
- Multiple samples of the same biometric trait.
- Multiple units of the same biometric trait.
- Multiple biometric traits.

The concatenation of multiple features vectors is possible when the feature vectors are homogeneous (for example, multiple fingerprints images). However, the concatenation of multiple feature vectors is not possible when the feature vectors are heterogeneous (for

example, the feature vectors of the different biometric modalities like the face and the fingerprints).

The integration of the biometric information at the prior step is more effective than the fusion at the abstract level. There are several researches which used this fusion level such as: **(Fang,2002)** **(Yang,2003)** **(Feng,2004)** **(Son,2005)** **(Chen,2006a)** **(Gan,2006)** **(Anwar,2009)** **(Rattani,2009)** **(Chorasa,2010)** **(Dhameliya,2013)** **(Huang,2013)** **(Kalra,2014)****(Kumari,2014)** **(Lu,2014)** **(Makinde,2014)**.

In practice, the feature level fusion is difficult to achieve due to the following reasons:

- This level of fusion is suffered from the curse of the dimensionality which is a general problem in the most applications of the pattern recognition, for example, the concatenation of two features vectors can generate a features vector with a large dimension.
- The most commercial biometric systems do not provide access to the features vectors used in their systems. Also, there are very few researchers which have studied the feature level fusion compared with the fusion after the matching step. So, the most of researches attract to the fusion after the matching step, we will present this type of fusion in the next section. Figure 3.2 illustrates the architecture of the multi-biometrics system which is based on the fusion at the feature level.

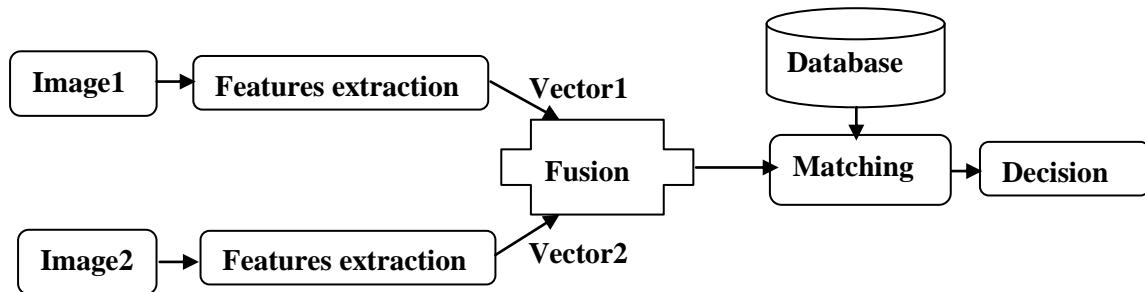


Figure 3. 2: Architecture of the feature level fusion system.

3.5.2 AFTER THE MATCHING

The integration of information after the matching can be divided into four categories which are:

- The dynamic selection of classifiers.
- The rank level fusion.
- The score level fusion.
- The decision level fusion.

3.5.2.1 DYNAMIC SELECTION OF CLASSIFIERS

This category selects the classifier that is the most likely to give the correct decision (**Woods,1997**). This is called by “*winner-take-all*” approach, and the system that makes this selection is named “*associative switch*” (**Chen,1997**).

3.5.2.2 RANK LEVEL

If the output of each biometric matcher is a subset of possible correspondences sorted in descending order, the integration of information can be done at the rank level. *Ho* and al. (**Ho,1994**) described three methods to integrate the information at the rank level: the “*Borda count*”, the “*highest rank method*”, and the “*logistic regression*” method. In the literature, there are some studies which used this fusion level such as: (**Monwar,2009**) (**Monwar,2010**) (**Kumar,2011**) (**Monwar,2012**) (**Radha,2012**).

3.5.2.3 SCORE LEVEL

In fact, the score level fusion gives the best compromise between the ease of implementation and the riches of information because the scores contain the rich information about the input model after the feature vectors. In addition, it is relatively easy to access and combine the scores generated by the different matchers. Consequently, the integration of information at score level is the most common approach in the multi-biometrics systems because there are several researches which attract to the fusion at this level.

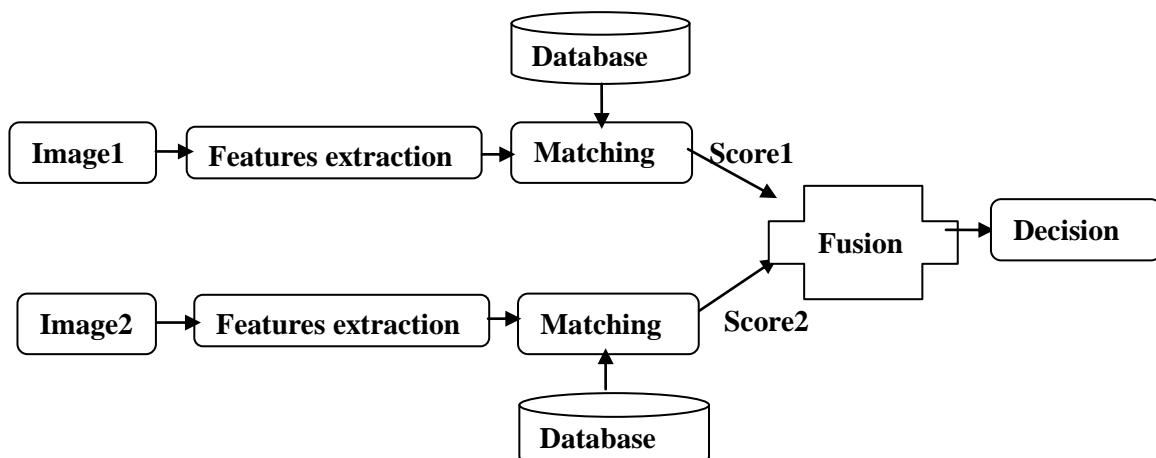


Figure 3. 3: Architecture of the score level fusion system.

3.5.2.4 DECISION LEVEL

This level also called by the abstract level. The integration of information at this level can be done when each matcher biometric decides individually to the best possible correspondence according to the input model. For example, the methods which can be used to

get the final decision are: the “*majority voting*” (**Lam,1997**), the “*weighted voting*” based on *Dempster-Shafer theory* (**Xu,1998**), the “*behavior knowledge space*” (**Lam,1995**), the “*and*” and the “*or*” rules (**Daugman,1998**). We cite some studies based on the decision level fusion: (**You,2004**) (**Ramli,2009**) (**Grewal,2014**) (**Saleh,2014**) (**Naghate,2014**).

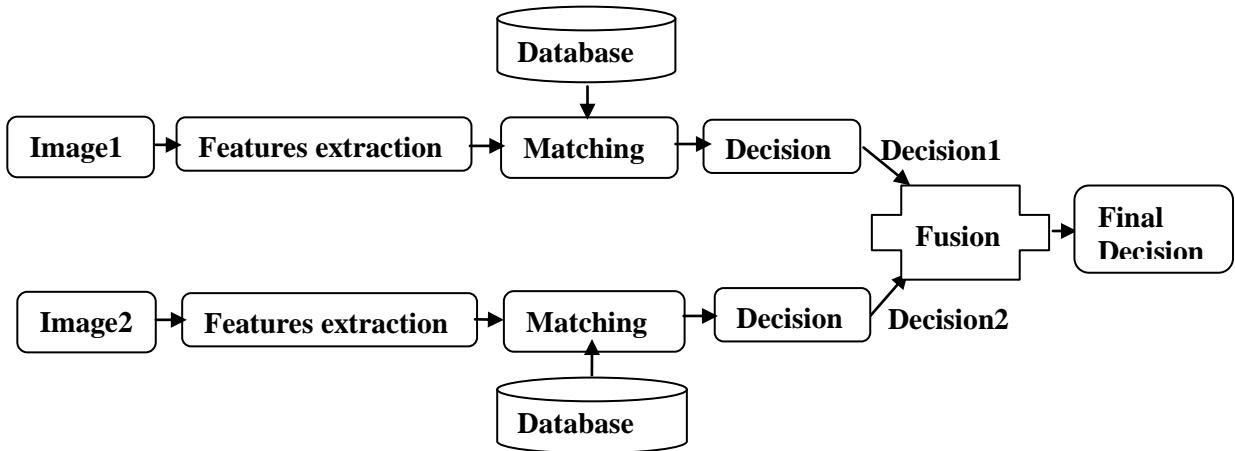


Figure 3. 4: Architecture of the decision level fusion system.

Table 3.6 presents some studies with their different fusion levels by citing their fusion methodologies.

Fusion Levels	Papers	Fusion Methodologies
Sensor	(Chang,2003b)	Concatenation of raw images.
Feature	(Fang,2002)	ANFIS (Adaptive Neuro-Fuzzy Inference system); SVM.
	(Yang,2003)	Features concatenation.
	(Feng,2004)	
	(Rattani,2009)	
	(Moon,2004)	Mosaicing of minutiae sets.
	(Gan,2006)	2-Dimensional Fisher Linear Discriminant Analysis (2DFLDA).
Rank	(Dhameliya,2013)	Weighted sum.
	(Connaughton,2012)	Borda count fusion.
Score	(Bigün,1997)	Statistical model based on Bayesian theory.
	(Hong,1998)	Product rule.
	(Kittler,1998)	Sum, Product, Min, Max, Median, and Majority vote rules.
	(Jain,1999)	Likelihood ratio.
	(Yacoub,1999)	SVM, Minimum cost Bayesian classifier, Fisher's linear discriminate, C4.5 decision tree, Multilayer perceptron.
	(Shakhnarovich,2001)	Weighted Sum rule.
	(Fuentes,2002)	SVM (HMM (Hidden Markov Model) for local features and

Fusion Levels	Papers	Fusion Methodologies
Score		Neural Network for global features)
	(Prabhakar,2002)	Likelihood ratio computed from non-parametric joint density estimates.
	(Chen,2003)	Sum rule.
	(Li,2003)	Temporal integration through construction of identity surfaces.
	(Linares,2003)	Sum, Product, Min, and Max rules; Neural Network.
	(Lu,2003)	Sum rule and RBF (Radial Basis Function) network.
	(Reynolds,2003)	Perceptron.
	(Ross,2003a)	Sum rule; Decision Trees; Linear Discriminate Function.
	(Ross,2003b)	Weighted sum rule.
	(Socolinsky,2003)	Weighted Sum rule.
	(Toh,2003)	Reduced multivariate polynomial model.
	(Wang,2003)	Sum rule; Weighted Sum rule; Fisher's Linear Discriminate; Neural Network.
	(Zhou,2003)	Temporal integration.
	(Campbell,2004)	Weighted Sum rule; Perceptron.
	(Chang,2004)	Weighted Sum rule and Weighted Product.
	(Cheung,2004)	Zero sum fusion after sorting of scores.
	(Czyz,2004)	Sum, Product, Min, Max and Median rules; Quadratic Bayes; Parzen; Weighted Sum rule.
	(Garris,2004)	Sum rule.
	(Kale,2004)	Hierarchical fusion and Holistic fusion (Sum and Product).
	(Kittler,2004)	Sum and Min rules.
	(Marcialis,2004a)	Sum, Product rules, and Logistic Regression.
	(Marcialis,2004b)	Sum rule, Max rule, and Nearest neighbor.
	(Toh,2004)	Weighted sum rule.
	(Wilson,2004)	No details are available.
	(Aguilar,2005a)	SVM.
	(Aguilar,2005b)	Sum and max rules (HMM (Hidden Markov Model) for local features and Parzen window for global features).
	(Chang,2005)	Weighted sum and Product rules.
	(Krawczyk,2005)	Weighted sum rule.
	(Lu,2005)	Weighted Sum rule and Hierarchical matching.
	(Marcialis,2005)	Fusion rules and Perceptron.
	(Snelick,2005)	Sum rule, Min, Max, Matcher Weighting, and User Weighting.

Fusion Levels	Papers	Fusion Methodologies
Score	(Toh,2005)	Functional link network.
	(Zhang,2007)	Sum and Product rule.
	(Lin,2009)	Weighted sum.
	(Morizet,2009)	Wavelet Score Denoising Statistical Fusion (WSDSF).
	(Poinsot,2009)	Sum; Product; Averaged Bayes Classifier (ABC).
	(Eskandari,2014)	Weighted Sum.
	(Fathima,2014)	Weighted average.
	(Ouamane,2014)	(Fisher statistical method+ SVM+ Neural Networks MLP) (Weighted Sum and Fuzzy logic).
Decision	(You,2004)	Hierarchical (serial) matching.
Score+ Decision	(Frischholz,2000)	Weighted sum rule; majority voting.
	(Kumar,2005)	Sum rule (for Gabor and line features) followed by Product rule; SVM; Feed-Forwad Neural Network ; AND rule.
	(Fathima,2014)	Weighted sum; Weighted average fusion.
Sensor+ Feature	(Jain,2002)	Mosaicing of templates at the image level; mosaicing of minutiae sets.
Feature+ Decision	(Shen,2011)	Concatenation; Weighted combination.
Feature+ Score	(Sanderson,2001)	Feature concatenation; Weighted Sum rule
	(Kumar,2003)	Feature concatenation; Sum rule
	(Ross,2005)	Feature selection and concatenation; Sum rule.
	(Islam,2013)	Concatenation; Weighted sum rule.
Score+ Rank.	(Brunelli,1995)	Geometric weighted average; HyperBF networks.
	(Chang,2003a)	Min, Sum, and Product rules.
	(Chen,2005b)	Sum rule and Logistic regression.
Feature+ Score+ Decision	(Kinnunen,2004)	Features concatenation, Sum rule; Majority voting.

Table 3. 6: Some studies with their fusion levels, and their fusion methodologies.

Figure 3.5 summarize the different fusion levels by citing some techniques. The most researches in the multi-biometrics systems focused on the integration of information at the score level because this approach gives a performance better than several approaches (**Jain,2005**) (**Ross,2003a**). In addition, the most score level fusion techniques can be applied only if the mono-modalities can provide reasonably a good recognition performance.

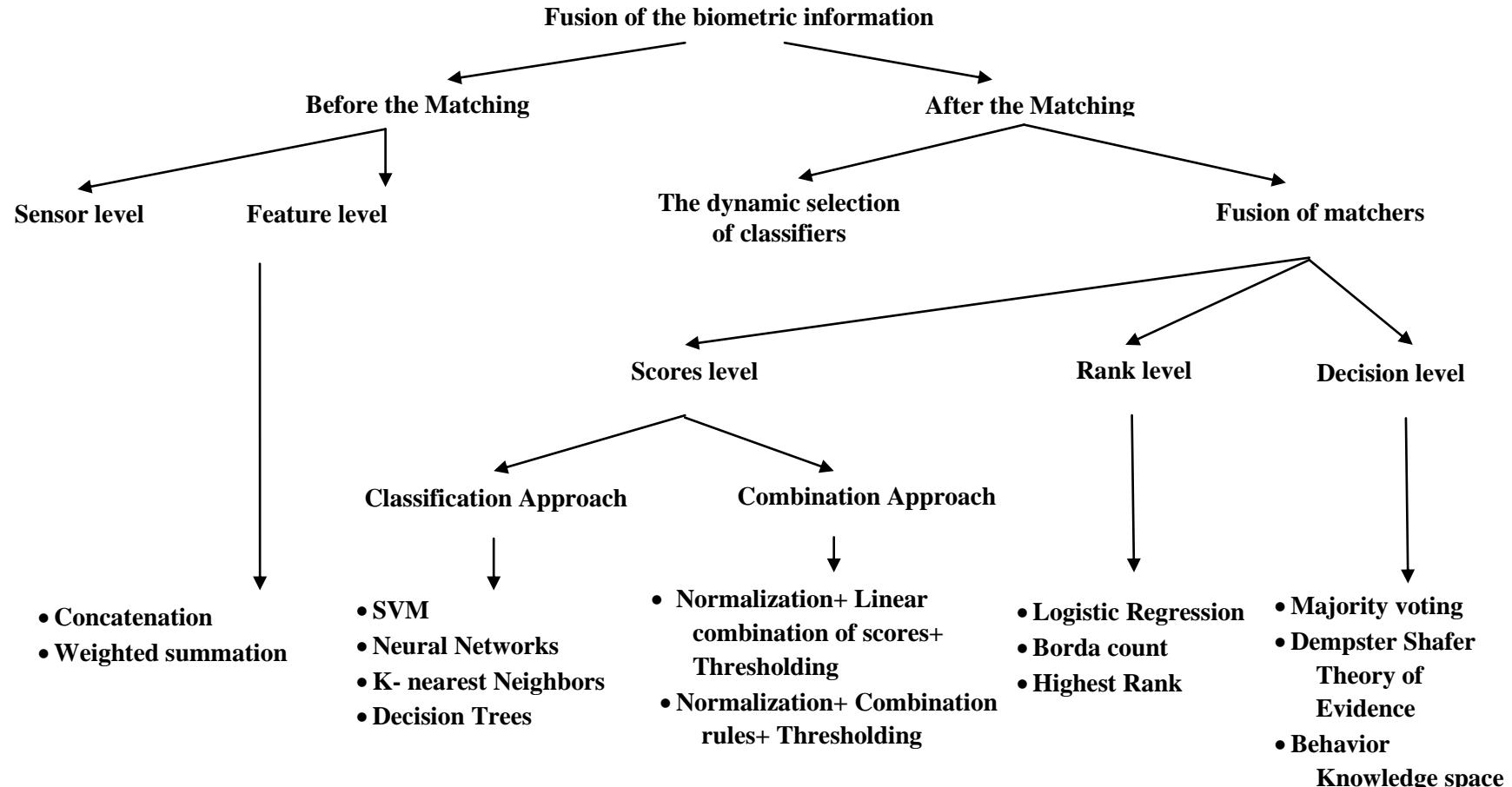


Figure 3. 5: Summary of the fusion approaches in the multi-biometrics systems according to (Jain,2005).

3.6 ARCHITECTURES

The multi-biometrics system combines several biometric systems, and it requires the acquisition and the processing of data. These steps can be done:

- *Successively*: Architecture in series;
- *Simultaneously*: Architecture in parallel.

The acquisition of the biometric data is usually sequential for practical reasons. For example, it is difficult to realize the acquisition at the same time of the fingerprints and the iris in good conditions. However, the acquisitions of the different data that use the same sensor can be done simultaneously, for example, the multi-fingers sensor that allows acquiring multiple fingerprints at the same time. Therefore, the architecture is generally related to the processing step and in particular to the decision. Indeed, the difference between a serial multimodal system and a parallel multimodal system lies in the fact to get a similarity score at the end of each acquisition (the serial fusion), or to proceed with all the acquisition before making the decision (the parallel fusion).

The architecture in parallel (Figure 3.6) is the most used because it uses all the available information, and thus improve the performance of the multi-biometrics system. On the other hand, the acquisition and the processing of large number of biometric data are costly in time and material which limited the usability of the system, and thus motivate the use of the architecture in series (Figure 3.7) in some applications.

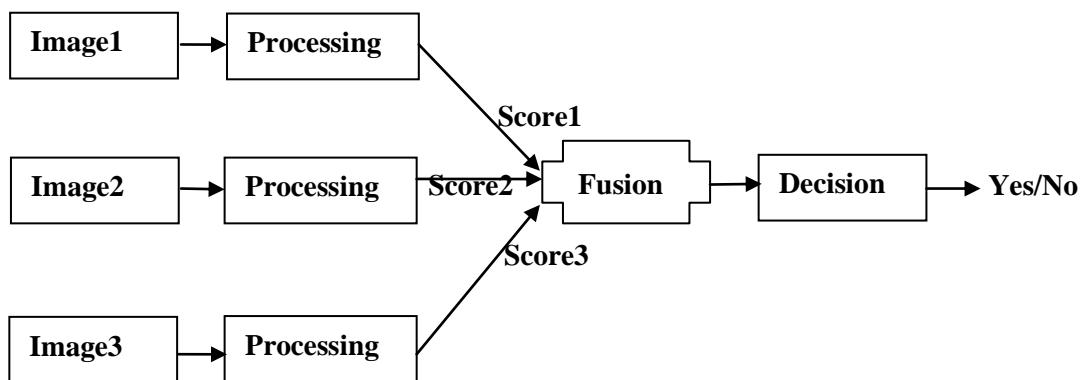


Figure 3. 6: Architecture of fusion in parallel.

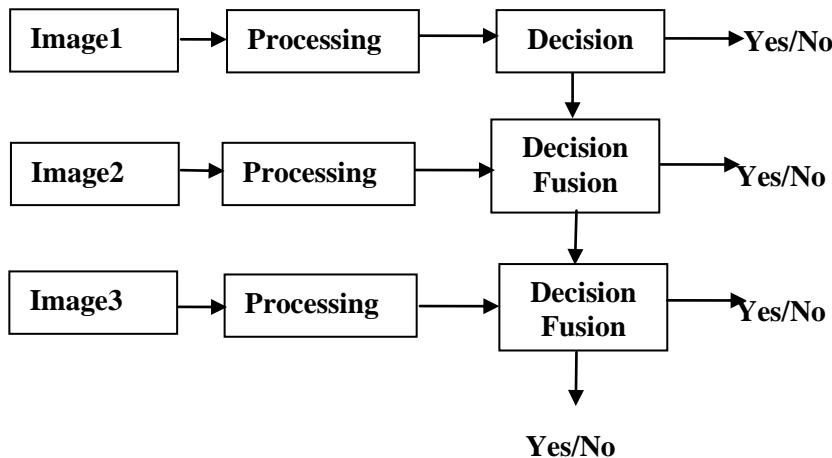


Figure 3. 7: Architecture of fusion in series, incremental, or sequential.

3.7 MULTIMODAL DATABASE DESIGN

At least, there are two architectures which present the structure of the multimodal databases (Figure 3.8):

1. **Architecture I:** In this configuration, there is one database which including a folder per person. Here, each folder contains the different biometric modalities of the same person.
2. **Architecture II:** In this case, there are several databases (a basis by biometric modality). Here, each database includes a folder per person but each folder contains only the biometric information of the corresponding modality database.

The first architecture has the advantage of the ease of implementation. However, this architecture gathered all the biometric data in the same place, and this is made the system more sensitive to the malfunction or the hack attempts.

However, the second architecture is more cumbersome to manage, but the storage of the biometric information of the users can be done on different servers (when the data are sent remotely). This can avoid the focus of all the biometric data in the same place. It also allows increasing the probability of functioning at least one biometric modality.

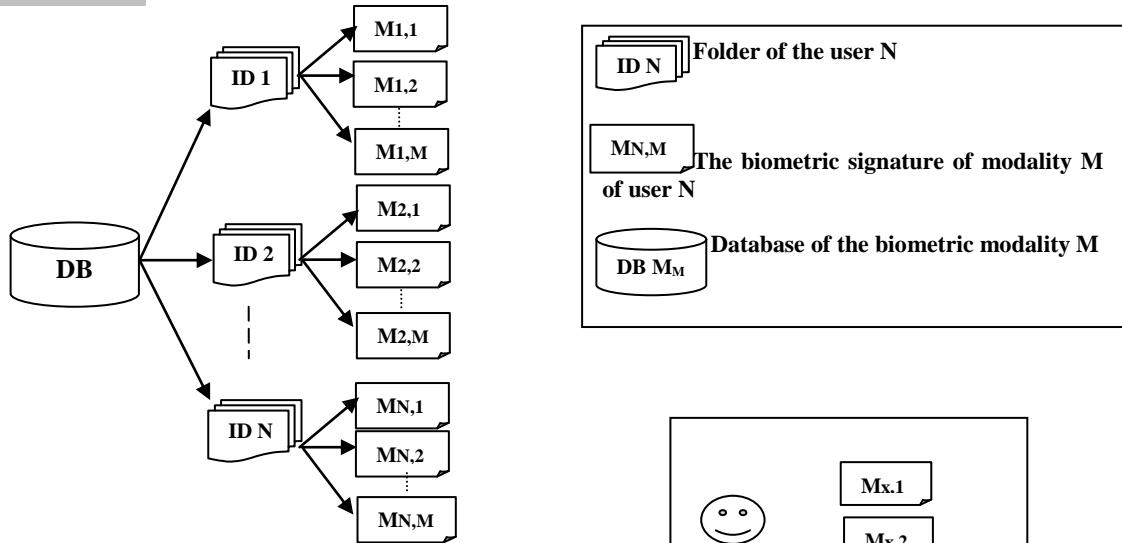
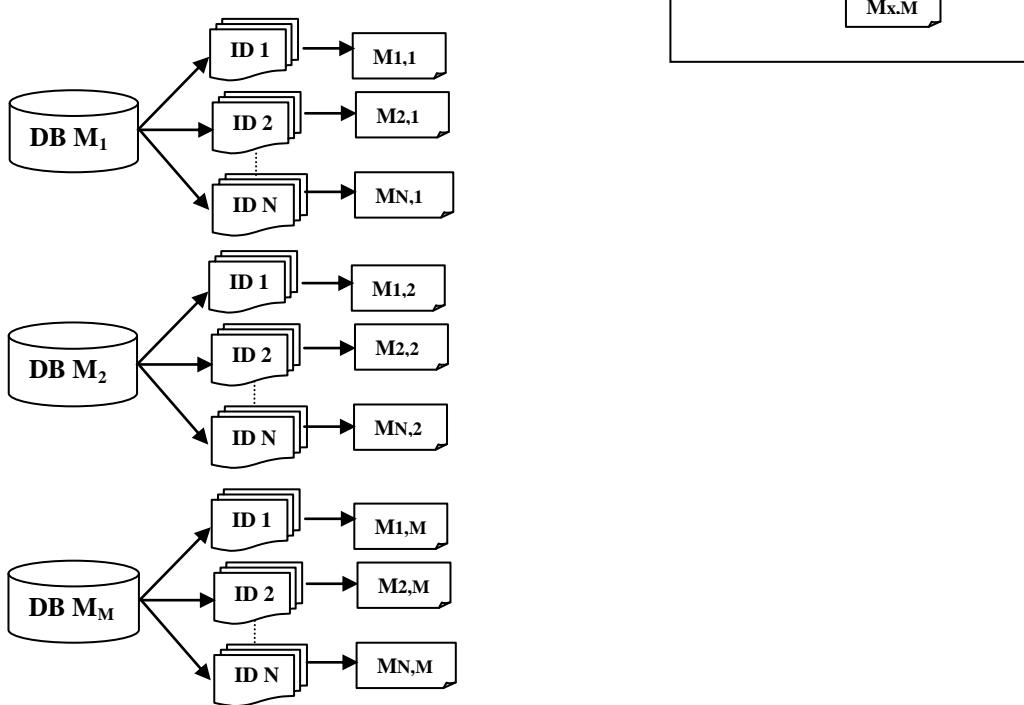
Architecture I:**Architecture II:**

Figure 3. 8: The architectures of the multimodal databases design.

3.8 CONCLUSION

In this chapter, we have presented a way to reduce the limitations related to the unimodal biometric systems by combining several unimodal systems, and this is leading to the multi-biometrics system. The multi-biometrics system can have different natures; we have therefore presented in this chapter the different types of possible combinations of modalities, also there are different architectures, and fusion levels.

The multimodality is the use of multiple biometric systems. Its goal is to reduce the limitations associated to the unimodal systems. Indeed, the use of several systems is intended first to improve the performance of recognition. However, the increase of the discriminative information of each person leads to increase the power of recognition of the system.

The choice of modalities is a key for the success of the biometric system. In this thesis, we choose to combine the face modality with the both units of the iris modality. In the next chapter, we will express in detail these modalities.

CHAPTER IV: THE MODALITIES CHOSEN FOR THE AUTHENTICATION

This chapter details the modalities which are chosen to be integrated in this work. The plan of this chapter is articulated as follows:

Summary:

- 4.1 Introduction
 - 4.2 Why this Choice?
 - 4.3 Facial Authentication
 - 4.3.1 Related Works
 - 4.3.2 Face Databases
 - 4.3.3 Face Recognition Process
 - 4.4 Iris Authentication
 - 4.4.1 The iris
 - 4.4.2 Related Works
 - 4.4.3 Iris Recognition Process
 - 4.4.3.1 Iris Segmentation
 - 4.4.3.2 Iris Normalization
 - 4.4.3.3 Features Extraction
 - 4.4.3.4 Matching
 - 4.4.4 Difficulties of the Iris Recognition
 - 4.4.5 Iris Databases
 - 4.5 Conclusion
-

4.1 INTRODUCTION

The biometric authentication which uses the characteristic of persons to verify their identity by using their behavioral or their physiological characteristics is an important application in the pattern recognition field. There are different biometric modalities used to achieve the task of recognition. Among these different modalities, we find the face and the iris which are considered as the most popular traits biometric. The both modalities are currently used in several applications.

In this work, we propose a multi-biometric technique which is based on the combination of the face with the both units of the iris modality (the left and the right irises) for the authentication mode. Therefore, this chapter details the modalities which are chosen to be integrated in order to form the multi-biometrics system.

4.1 WHY THIS CHOICE?

In this work, we choose to integrate the face modality with the both instances of the iris modality (the left and the right irises). We choose these two modalities for the following reasons:

- The face modality is considered as non-intrusive because it doesn't reach the privacy of the individual.
- The face modality is one of the most natural ways to recognize the persons.
- The iris modality is currently considered as one of the most accurate modalities because it characterized by a high level of precision.
- The iris is stable during the life of person, and its texture is one of the richest distinctive textures of the human body due to the combination of several elements. Therefore, the iris has a unique feature which is protected from the outside, and at the same time it is relatively easy to acquire compared to other internal organs such as the retina.
- The iris is difficult to falsify.
- The iris patterns are easily extracted from the face images.
- The deployment cost of this technology is low: a simple camera attached to a computer may be enough. However, the both modalities can be acquired using the same camera simultaneously, and this is can be considered as independent biometric traits. So one capture device with very high resolution would analyze simultaneously

the texture of the iris and the face of the person. This is allowed to work with a unique system of capture instead of two.

- In addition, this choice is confirmed by the Zephyr analysis (Figure 4.1).

So, we integrate these two modalities in order to create a multi-biometrics system. The challenge is to improve the performance of this system by finding an original fusion method that gives a recognition rate of the fused modalities higher than the recognition rate of the modalities taken separately.

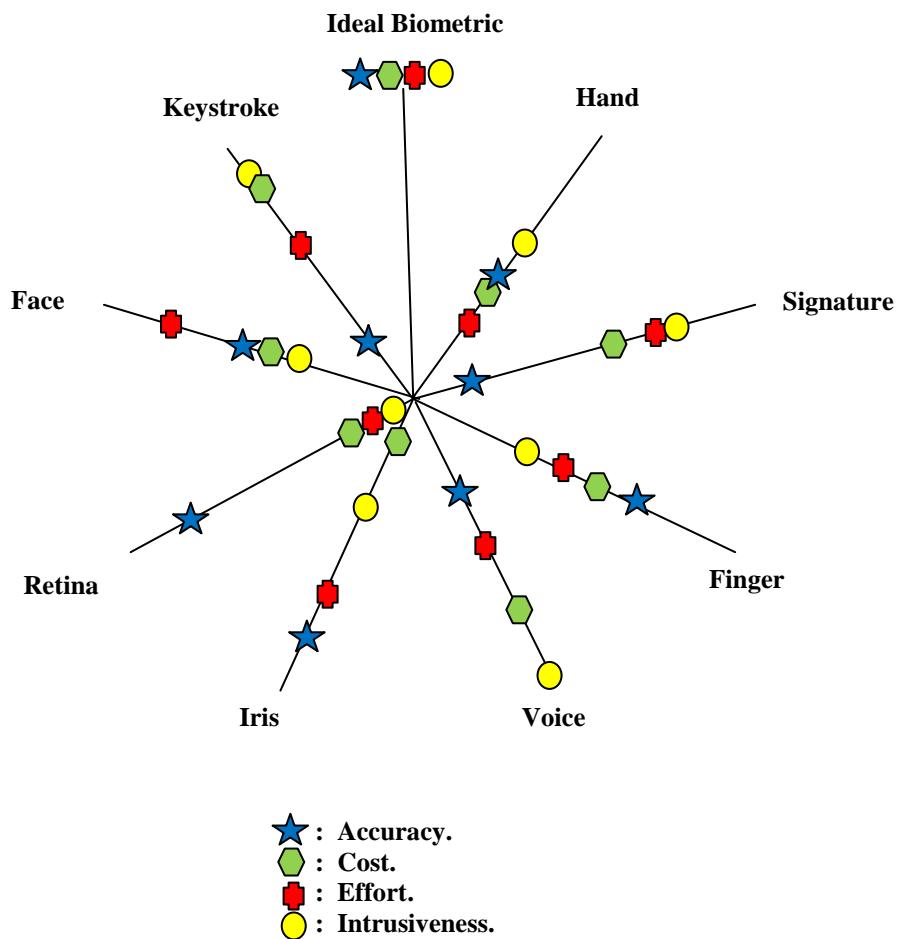


Figure 4. 1: The Zephyr Analysis: comparison of the different modalities according to four criteria: accuracy, cost, effort, and intrusiveness.

Figure 4.1 presents four criteria which can be used to evaluate the different biometric methods:

- **The accuracy:** It indicates the efficiency of the method, so it is related to the errors rates.
- **The cost:** It designates the cost of the technology (the reader, the sensors, etc.).

- **The effort:** It expresses the effort provided by the user during the authentication phase.
- **The intrusion:** It means the acceptance of the system by the users.

Figure 4.1 illustrates that there is no perfect method. However, we can conclude that the methods are divided into two greater categories which are:

- The first category includes the *convivial methods* for the users, and it corresponds to the methods based on the behavioral characteristics such as the voice recognition or the signature recognition. This group is characterized by:
 - The intrusion: Little intrusive method.
 - The accuracy: Bad performance.
 - The cost: Moderate price.
 - The effort: Low effort.
- The second category includes the *safer methods*, and these methods are characterized by:
 - The intrusion: Intrusive methods.
 - The accuracy: Very good performance.
 - The cost: High price.

Indeed, the methods are determined according to the situation desired.

4.2 FACIAL AUTHENTICATION

Really in our life, the face is the modality the most used by humans in order to recognize other persons. It has several advantages compared with other biometric modalities, and these motivate its use in several works. However, it is a natural way to recognize a person, also it is easy to acquire, and it is considered as non-intrusive. These advantages attract the attention of several researches.

The facial recognition is one of the biometric technologies that took an important part in the field of the biometric research. In addition, it used in several technologies due to the increase of the security needs such as the digital cameras, the internet, and the mobile devices, etc.

4.2.1 RELATED WORKS

Today, the face recognition is considered as one of the most common biometric technologies. There are several researches conducted in this area, a few of them is mentioned in the following:

- **2D Face recognition:** (Kanade,1973) (Turk,1991) (Brunelli,1993) (Lades,1993) (Fadzil,1994) (Moses,1994) (Pentland,1994) (Nefian,1996) (Belhumeur,1997) (Lawrence,1997) (Lin,1997) (Wiskott,1997) (Zhang,1997) (Bartlett,1998) (Lorente,1999) (Barlett,2002) (Haddadnia,2002) (Kim,2002) (Moghaddam,2002) (Martinez,2002) (Yacoob,2002) (Yang,2002) (Palanivel,2003) (Adjoudj,2004) (Yang,2004) (Delac,2005) (Heo,2006) (Wang,2006) (Yu,2006).
- **3D Face recognition:** (Cartoux,1989) (Lee,1990) (Gordon,1991) (Beymer,1995) (Tanaka,1998) (Beumier,2001) (Georghiades,2001) (Blanz,2003) (Bronstein,2003a) (Hesher,2003) (Bowyer,2004) (Heisele,2004) (Jain,2004b) (Tsalakanidou,2004) (Bronstein,2005) (Chang,2005) (Lu,2005) (Phillips,2005) (Rama,2005a) (Rama,2005b) (Antini,2006) (Chang,2006) (Feng,2006a) (Gokberk,2006) (Lu,2006a) (Lu,2006b) (Lu,2006c) (Lu,2006d) (Onofrio,2006) (Rama,2006) (Samani,2006) (Mian,2007) (Wong,2007).

However, there are different techniques used to realize the facial recognition system, some of these techniques are presented in table 4. 1.

Research papers	Methodologies
(Murase,1995)	Appearance-based method.
(Turk,1991); (Belhumeur,1997); (Li,2001); (Martinez,2001); (Levin,2002).	Dimensionality reduction techniques.
(He,2003)	Locality Preserving Projections (LPP).
(Roweis,2000)	Locally Linear Embedding (LLE).
(Pang,2005)	Locally Linear Embedding LLE + Support Vector Machine (SVM).
(Rowley,1998); (Lu,2003); (Zhang,2004a); (Fan,2005); (Li,2006).	Neural Networks.
(Zhou,2006)	Radial Basis Function +Neural Network.
(Huang,2006)	Two Neural Networks.
(Park,2006a)	Momentum Back Propagation Neural Network (MBP-ANN).
(Kshirsagar,2011)	Eigenfaces.
(Moon,2001)	Eigenfaces technique+ Nearest-Neighbour distance classifiers.
(Liu,1999)	Independent Component Analysis (ICA).
(Harguess,2011)	Scores for symmetry of the face.
(Ibrahim,2011)	Principle Component Analysis (PCA) + Artificial Neural Networks.
(Gan,2011)	Principal Component Analysis (PCA) + Sparse

	Representation-based Classification (SRC)+ Homotopy algorithm.
(Abdullah,2012)	Principal Component Analysis (PCA)+ Euclidean distance.
(Cootes,2001)	Active Appearance Models (AAM).
(Shakhnarovich,2002), (Osuna,1997), (Lu,2006a)	Support Vector Machine (SVM).
(Schneiderman,1998)	Naive Bayes classifier.
(Rajagopalan,1998)	Higher Order Statistics (HOS); Hidden Markov Model (HMM).
(Colmenarez,1997)	Information-Theoretical based.
(Kanade,1973); (Kotropoulos,1997)	Similar rule-based approaches.
(Leung,1995); (Thu,2002).	Feature-based approaches.
(Yang,1994)	Hierarchical Knowledge-based approach.
(Craw,1992); (Lanitis,1995)	Algorithms based on Template Matching.
(Turk,1991); (Zhao,1998)	Holistic Matching methods.
(Samaria,1994a); (Samaria,1994b)	Feature-based (or structural) Matching methods.
(Blanz,2003)	Hybrid methods.

Table 4. 1: Facial recognition techniques.

There are many other studies in the face recognition area such as : (Lin,2000), (Bronstein,2003b), (Abate,2007), (Dai,2007), (Dominique,2007), (Hiremath,2007), (Kodate,2007), (Padilha,2007), (Park,2007), (Zhang,2011), (Wagner,2012), (Zheng,2012), (Cheney,2015), (Lagerwall,2016).

4.2.2 FACE DATABASES

In the literature there are several face databases, some of them are listed in (Web08) such as:

- Color FERET Database, USA (Web09).
- Yale Face Database (Web10).
- Yale Face Database B (Web11).
- PIE Database, CMU (Web12).
- Project - Face In Action (FIA) Face Video Database, AMP, CMU (Web13).
- AT&T "The Database of Faces" (formerly "The ORL Database of Faces") (Web14).
- Cohn-Kanade AU Coded Facial Expression Database (Web15).

- MIT-CBCL Face Recognition Database (**Web16**).
 - Image Database of Facial Actions and Expressions - Expression Image Database (**Web17**).
 - Face Recognition Data, University of Essex, UK (**Web18**).
 - NIST Mugshot Identification Database (**Web19**).
 - NLPR Face Database (**Web20**).
 - M2VTS Multimodal Face Database (Release 1.00) (**Web21**).
 - Extended M2VTS Database, University of Surrey, UK (**Web22**).
 - AR Face Database, Purdue University, USA (**Web23**).
 - University of Oulu Physics-Based Face Database (**Web24**).
 - CAS-PEAL Face Database (**Web25**).
 - Japanese Female Facial Expression (JAFFE) Database (**Web26**).
 - BioID Face DB - HumanScan AG, Switzerland (**Web27**).
 - Psychological Image Collection at Stirling (PICS) (**Web28**).
 - UMIST Face Database (**Web29**).
 - Caltech Faces (**Web30**).
 - EQUINOX HID Face Database (**Web31**).
 - VALID Database (**Web32**).
 - UCD Colour Face Image Database for Face Detection (**Web33**).
 - Georgia Tech Face Database (**Web34**).
 - Indian Face Database (**Web35**).
 - UPC Face Database (**Web36**).
 - VidTIMIT Database (**Web37**).
 - Labeled Faces in the Wild (**Web38**).
 - LFWcrop Database (**Web39**).
 - Labeled Faces in the Wild-a (LFW-a) (**Web40**).
 - Bosphorus Database (**Web41**).
 - PUT Face Database (**Web42**).
 - Basel Face Model (BFM) (**Web43**).
 - Plastic Surgery Face Database (**Web44**).
 - Hong Kong Polytechnic University NIR Face Database (**Web45**).
 - MOBIO - Mobile Biometry Face and Speech Database (**Web46**).
 - Texas 3D Face Recognition Database (Texas 3DFRD) (**Web47**).
 - Natural Visible and Infrared facial Expression database (USTC-NVIE) (**Web48**).
-

- FEI Face Database (**Web49**).
- ChokePoint (**Web50**).
- UMB database of 3D occluded faces (**Web51**).
- PhotoFace: Face recognition using photometric stereo (**Web52**).
- EURECOM Kinect Face Dataset (EURECOM KFD) (**Web53**).
- Adience image set and benchmark of unfiltered faces for age, gender and subject classification (**Web54**).
- Facial Expression Research Group Database (FERG-DB) (**Web55**).
- 3D Mask Attack Database (3DMAD) (**Web56**).
- FaceScrub - A Dataset With Over 100,000 Face Images of 530 People (**Web57**).
- LFW3D and Adience3D sets (**Web58**).
- YouTube Faces Database (**Web59**).
- YMU (YouTube Makeup) Dataset (**Web60**).
- Senthilkumar Face Database (Version 1.0) (**Web61**).
- SiblingsDB Database (**Web62**).
- McGill Real-world Face Video Database (**Web63**).
- Denver Intensity of Spontaneous Facial Action (DISFA) Database (**Web64**).
- BU-3DFE Database (Static Data) (**Web65**).
- Indian Movie Face database (IMFDB) (**Web66**).
- 10k US Adult Faces Database (**Web67**).
- Senthil IRTT Face Database Version 1.1 (**Web68**).
- UFI - Unconstrained Facial Images (**Web69**).
- IIIT - Cartoon Faces in the Wild (**Web70**).

4.2.3 FACE RECOGNITION PROCESS

The face recognition methods can be different. Nevertheless, they unanimously share the following steps: the capture, the analysis, the comparison against the images referenced in the database, and the decision. In short, this is the basic process used (Figure 4.2.):

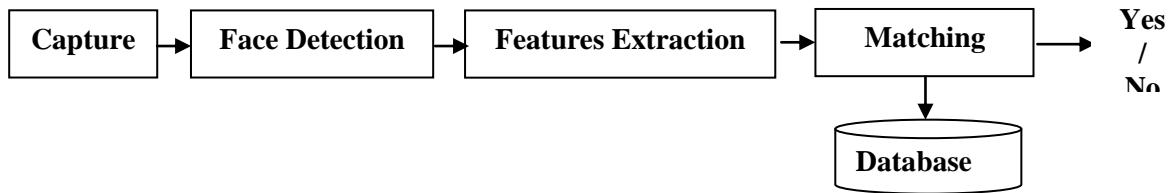


Figure 4. 2: The face authentication process.

- **Capture of the face:** This is the first step in the face recognition process which is very important step in the recognition system. However, we are used the images of the public databases in our work.
- **The face detection:** The image acquired of the face does not only contain the face information. Therefore, it is necessary to segment and isolate this information from the rest of the image. However, our system has been devoted to recognize faces from images addressed for the recognition system, so we can manually detect the face limits.
- **The features extraction:** The goal of this phase is the extraction of the pertinent facial features that can make it different from other people and robust to the variations related to the same person. It is not always easy to work with vectors of large dimensions, therefore we are used the Daubechie wavelet to extract the features vectors.
- **The comparison of features:** According to the features extracted, the comparison algorithms differ. There are several approaches in the literature such as the distance calculation and the similarity calculation. In addition, there are other methods which are based on the classification of characteristics by a single classifier (the support vectors machine (SVM), the baysien classifier, etc.) or by multiple classifiers (Adaboost). In our work, we choose to use the support vectors machine (SVM).

4.3 IRIS AUTHENTICATION

There are several advantages that have motivated the use of the iris modality in several works, and this is made the iris one of the most efficient biometric modalities. The iris is the unique internal organ visible from the outside. In addition, it is characterized by unique texture, and it is stable during the person's life.

However, there are many noises can intervene during the iris acquisition phase, and this is made the recognition process more difficult, we cite some of these noises in the following points:

- *The reflections*: The iris is located behind the cornea, which has a highly reflective mirror, so the iris acquired is often disrupted by reflections.
- *The occulting*: The iris is covered, sometimes in large areas, by eyelids and eyelashes which make the detection of the iris pattern more difficult.
- *The blur*: It can affect the iris image acquired in uncontrolled conditions.

4.3.1 THE IRIS

The word iris means “*Rainbow*” comes from “*IRIS*”. The Greek philosopher *Plutarch* suggested that the word iris come from the Egyptian language, and it means: “*the eye of heaven*”. Whatever its origin, the iris is the colored part of the eye.

The iris is the circular membrane of the anterior of the eyeball. It is pierced in its center of black hole called pupil through which the light penetrates to the retina. The iris is used to adjust the amount of the light, and it is refracting or dilating according to the lighting conditions. For example, when the ambient light is strong, the iris shrinks, that is allow decreasing the light intensity which just hit the center of the retina (**Adler,1965**).

The iris is an organ colored by: grey, blue, green, brown, or black. However, the pigment responsible for these colors is called the melanin. In the absence of this pigment the iris would be red (case of albinism). In some cases, the both irises of the same person have two completely different colors. Also, the iris can be divided into several areas of different colors, or it characterized by the presence of several pupils in the same iris. The aniridia is one of the rare diseases that can affect the eye which causes the absence of the iris. The iris is characterized by:

- It begins to form during the 3rd month of gestation.
 - The special texture of the iris is established in the 8th month of pregnancy.
 - The pigmentations which are responsible for the color of the eyes continue to appear until one year after the birth.
 - The texture of the iris is a combination of several elements which make it one of the richest distinctive textures of the human body. It has the arcs of ligaments, the crypts, the ridges, the furrows, and the flanges. Figure 4.3 shows the iris texture with some of these elements.
-

- The iris is a region of eye that is relatively stable:
 - Stable: its appearance only can quickly change by a few deceases.
 - Relatively: its appearance can change with age (It is estimated about 5 years the natural period of these changes).
- The iris is also the unique internal organ visible from the outside because it is protected by a mirror (the cornea). So the iris present the unique feature that is an organ protected from the outside environment, and at the same time it is relatively easy to acquire compared to other internal organs of the human body such as the retina.

All these advantages have pushed researchers and ophthalmologists to study the feasibility of the iris recognition system since 1930.

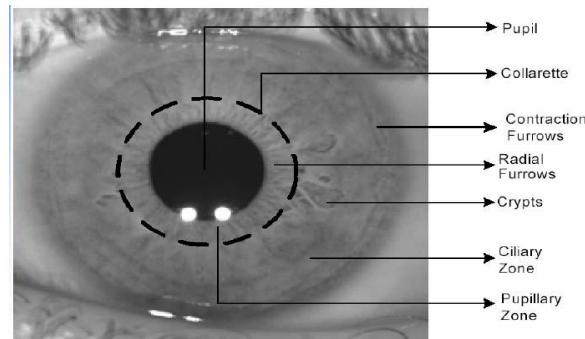
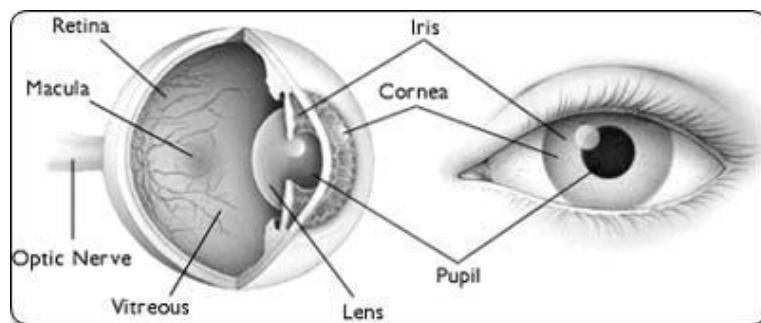


Figure 4. 3: The iris pattern.

4.3.2 RELATED WORKS

The use of the iris as an identification tool has been originally proposed by the American ophthalmologist *Frank Burch*. In 1936, he proposed this method during the conference for the *American Academy of Ophthalmology*. In 1987, the two American ophthalmologists *Leonard Flom* and *Aron Safir* have patented this idea. The professor of Cambridge University *John*

Daugman comes to help them through the development of the mathematical approach in order to analysis the random motifs of the iris. The collaboration between *Daugman*, *Safir*, and *Flomled* to a functional prototype was patented in 1994. The work of *Daugman* is based on the analysis by the complex non-orthogonal Gabor wavelets (**Daugman,2004**) (**Daugman,2006**).

Some examples of the iris recognition and the iris detection studies are presented in the following table:

Research paper	Methodologies
(Daugman,1993) (Daugman,1994)	Integro-Differential Operator +2D Gabor wavelet + Hamming distance.
(Wildes,1997)	Edge detection and Hough transform + Laplacian of Gaussian filters + Normalized correlation.
(Boles,1998)	Edge detection + Zero Crossing of Wavelet transform + Two Dissimilarity Functions.
(Zhu,2000)	Multi-channel Gabor Filtering and Wavelet transform + Weighted Euclidean distance.
(Lim,2001)	Polar Coordinate transform + 2D Haar Wavelet + Competitive Learning Neural Network LVQ (Uniform distribution of initial vectors) (Multidimensional winner selection).
(Daouk,2002)	Canny Edge Detection and Circular Hough Transform + Haar wavelet + Hamming Distance.
(Ma,2002a)	Hough transform + Gabor filter + Weighted Euclidean distance.
(Tisse,2002)	Hough transform + Integro-Differential Operators + 2D Hilbert transform + Hamming distance.
(Ma,2003)	Gray-level information, Canny edge detection, and Hough transform + Multichannel Spatial filter + Fisher Linear Discriminate + Nearest Center classifier.
(Ma,2004)	Gray-level information, Canny edge detection, and Hough transform + 1D Intensity signal operated on Dyadic wavelet + XOR operation.
(Adjoudj,2005)	Multilevel 2D Wavelet + Neural Networks.
(Avila,2005)	Intensity-based detection + Gabor filter and Multiscale zero crossing of Discrete Dyadic wavelet + Euclidean and Hamming distances.
(Chen,2005a)	Sobel transform and Hough transform + Sobel transform and vertical projection + Wavelet Probabilistic Neural Network (WPNN) and Particle Swarm Optimization (PSO).

(Noh,2005)	Independent Component Analysis ICA method.
(Yuan,2005)	Local intensity minimum algorithm (separable eyelashes) and the template mean and standard deviation (multiple eyelashes) (Eyelash Detection Method).
(Ganeshan,2006)	Gray level variation + LoGau technique (4 levels) + Normalized correlation.
(Daugman,2007)	Active contours and Generalized contours + 2D Gabor wavelet + Weighted Hamming distance.
(Monro,2007)	Heuristic gray-level edge feature and Hough transform + 1D DCT Discrete Cosine Transform + Weighted Hamming distance.
(Poursaberi,2007)	Morphological operators and thresholds + Daubechies wavelet + Complex classifier (joint of Hamming distance and Harmonic mean).
(Chenhong,2008)	Integro-Differential Operator + Laplacian of Gaussian filters + Hamming distance.
(Vatsa,2008a)	Elliptical model and modified Mumford–Shah functional + 1D Log-polar Gabor transform and Euler numbers + SVM.
(Vatsa,2008b)	Intensity-based detection + 1D log-polar Gabor and Euler number + Hamming distance and Directional Difference Matching (DDM).
(Azizi,2009a)	Daugman's method + Contourlet transform + SVM (Support Vector Machine).
(Araghi,2010)	Discrete wavelet + LVQ (Learning Vector Quantization) Competitive Neural Network.
(Hosseini,2010)	Fusion of features Near-InfraRed (NIR) and Visible Light (VL).
(Karthikeyan,2010)	Circular-Mellin and Canny edge detection + Harr wavelet, Embedded-tree zero wavelet and Fuzzy Neural Network + Hamming distance.
(Kekre,2010)	Discrete Cosine Transform (DCT) and Vector Quantization (VQ) with clustering using : Linde-Buzo-Gray(LBG) algorithm, Kekre's Proportionate Error (KPE) algorithm, and Kekre's Fast Codebook Generation Algorithm (KFCGA) + Euclidean distance (no pre-processing and no iris segmentation are used).
(Kong,2010)	IrisCode.
(Gawande,2010)	Hough transform + Zero-crossing 1 D wavelet, Euler number, and Genetic algorithm + Hamming distance.
(Strzelczyk,2010)	Modified Hough transform and energy function (segmentation algorithm for color and noisy eye images).
(Zuo,2010)	Segmentation of nonideal iris.
(Chirchi,2011)	Integro-Differential Operators + Gabor filter and Haar wavelet + Hamming distance and Harmonic mean.
(Dong,2011)	Adaboost cascade and pulling and pushing elastic model + ordinal measures +

	weighted Hamming distance by weight map.
(Costa,2012)	Sobel edge detector and Hough transform+ Dynamic features (DFs) + Euclidean distance.
(Kong,2012)	Iris Code Decompression.
(Si,2012)	New eyelash detection algorithm based on directional filter + 2D Gabor filters and multiscale and multi orientation data fusion method + Hamming distance and iris indexing method.
(Suganthy,2012)	Canny edge detection and circular Hough transform + Local Binary Pattern and histogram approaches + Linear Vector Quantization (LVQ) classifier.
(Tsai,2012)	Fuzzy Greyscale Curve Tracing (FGCT) + Gabor filters + Possibilistic Fuzzy matching.
(Verma,2012)	Hough transform + 1D Log-Gabor + Hamming distance.
(Acar,2013)	Laws Texture Energy Measure (TEM) + k-Nearest Neighbor (k-NN).
(Li,2013)	Figueire do and Jain's Gaussian Mixture Models (FJ-GMMs) + Gabor Filter Bank (GFB) + Simulated Annealing (SA).
(Mesecan,2013)	Scale Invariant Feature Transform (SIFT) + Euclidean distance.
(Sánchez,2013)	Modular Neural Networks (MNNs) and Multi-Objective Hierarchical Genetic Algorithm (MOHGA) (for the selection of the training and the test data).
(Saravanan,2013)	Gabor filters + binary Hamming distance and Euclidean distance.
(Stojmenovic,2013)	Shape based Circularity (iris detection).

Table 4. 2: Examples of the iris recognition methodologies.

4.3.3 IRIS RECOGNITION PROCESS

There are four modules which follow the acquisition of the iris images in the iris recognition system, which are:

- The segmentation.
- The normalization.
- The features extraction.
- The matching.

We will describe these modules in the following sections:

4.3.3.1 IRIS SEGMENTATION

The image acquired of the eye does not only contain the iris information. Therefore, it is necessary to segment and isolate this information from the rest of the image. The iris segmentation is the first step in the recognition process which comes after the capture module. It consists of isolating the iris texture from the rest of the eye image acquired by any sensor.

As illustrated in figure 4.4, the iris area is surrounded by external borders (iris-white of the eye (sclera)) and the internal borders (iris-pupil).

The pupil is the black hole inside the disk of the iris, almost circular. The external border of the iris is the separation between the disc of the iris and the white of the eye (sclera). In addition, this border is largely covered by other regions such as: the eyelashes and the eyelids.

The main goal of this step is to locate the pupil-iris border and the iris-sclera border, also to extract the different elements that are considered to be noise.

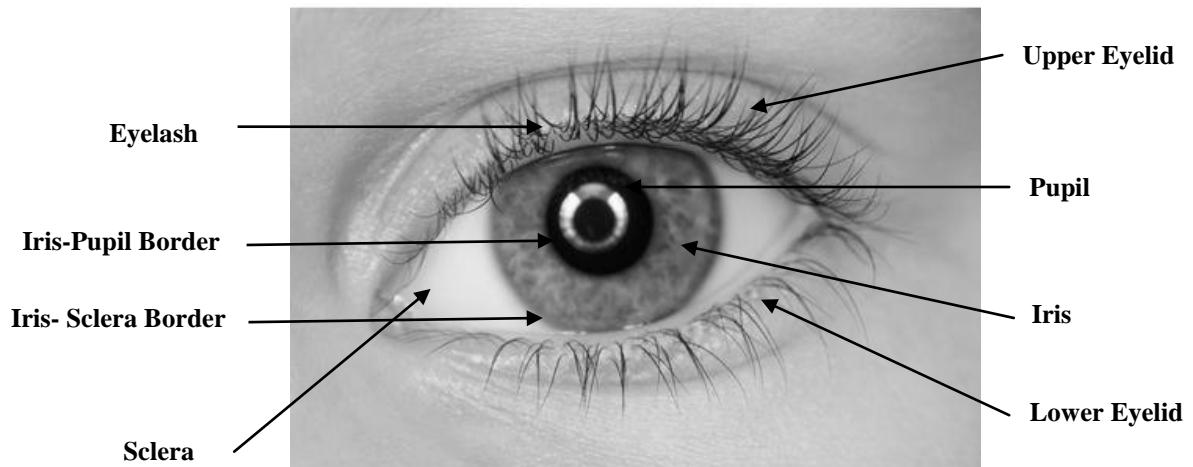


Figure 4. 4: An image of the eye.

The iris segmentation is an important step in the iris recognition process. Therefore, it has attracted the attention of several researches; we cite some of them in the following table:

Research paper	Methodologies
(Daugman,1993); (Nishino,2004)	Integro-Differential Operator.
(Wildes,1997); (Kong,2001); (Ma,2002a); (Ma,2003); (Huang,2004); (Ma,2004); (Smereka,2010).	Hough Transform.
(Blake,1998).	Active contours.
(Mira,2003).	Morphologic operators.
(Liu,2003); (Tian,2004); (He,2006).	Edge detection + Hough transform.
(Cui,2004).	Wavelet transform + integro-Differential Operator.
(Du,20004).	Polar coordinates + Sobel operator.
(Kim,2004).	Expectation-Maximization (EM) algorithm.
(Sung,2004).	One-Dimensional Discrete Fourier Transform 1DDFT + Histogram equalization + High-pass filter.
(Lili,20005).	Edge detection + Curve fitting.
(Teo,2005); (Grabowski,2006).	Black hole search method and Integro-differential Operators.
(Feng,2006b).	Coarse-to-fine strategy.
(Zuo,2010).	Hough circle detector + Contour fitting techniques.

Table 4. 3: Examples of the iris detection methods.

In our work, we used the Hough transform for the iris segmentation step. The Hough transform is used in several studies such as: (Wildes,1994) (Wildes,1997) (Kong,2001) (Ma,2002a) (Tisse,2002) (Liu,2003) (Ma,2003) (Masek,2003) (Huang,2004) (Ma,2004) (Tian,2004) (Chen,2005a) (He,2006) (Monro,2007) (Khiari,2008) (Sudha,2009) (Gawande,2010) (Smereka,2010) (Costa,2012) (Verma,2012).

The Hough transform:

The Hough transform was proposed in 1972 by *Duda* and *Hart* (Duda,1972). It is a geometric technique that used to isolate the simple geometric patterns from the rest of the image such as the lines, the circles, or the ellipses, etc.

One of the great advantages of this technique is that it is tolerant to occlusions in the searched objects, and it remains relatively untouched by the noises. In our work, we are interested to this technique because the objects to be detected in the image of the eye (the iris, the pupil, and the eyelids) are circular or ellipsoid. Wildes was the first who introduce this method in the context of the iris segmentation (Wildes,1997).

The steps of the Hough transform method include:

- The generation of the edges of the image. For example, the method of *John Canny* (**Canny,1986**) can be used in this step. The principle of this method is the transformation of the input image into binary edge map by calculating the first derivative of the intensity value of the eye image, and this is followed by a thresholding operation on the image resultant. This transformation can be done in horizontal or vertical direction or in the both. These are shown in figure 4.5.
- A voting process is applied on the edges image obtained in the previous step. Therefore, each point of the edges vote for a circle which it belongs, and the circle that gets the most votes is the desired circle.

Sometimes, this method becomes heavy when there are many points of edges are detected. For each circle in the desired area, we can count the contours points belonging to this circle when we have a priori knowledge about the location of the desired circle. The circle that has the most points of edges is the desired circle.

This method has attracted the attention of several researchers in the iris segmentation field. However, this method has some limitations, despite its wide use for the iris segmentation step, such as:

- This method is applied to the global image so this makes it intensive in the calculation time.
- This method becomes heavy when there are many points of edges are detected.
- It is possible that the critical points of the object detected may not be considered as edges points, and this is avoided them to intervene in the voting process and the research of the circle.
- This method requires the selection of edges detection method (canny, gradient, threshold, etc.) therefore the number of the edges points won't be the same and this depends by the method used.

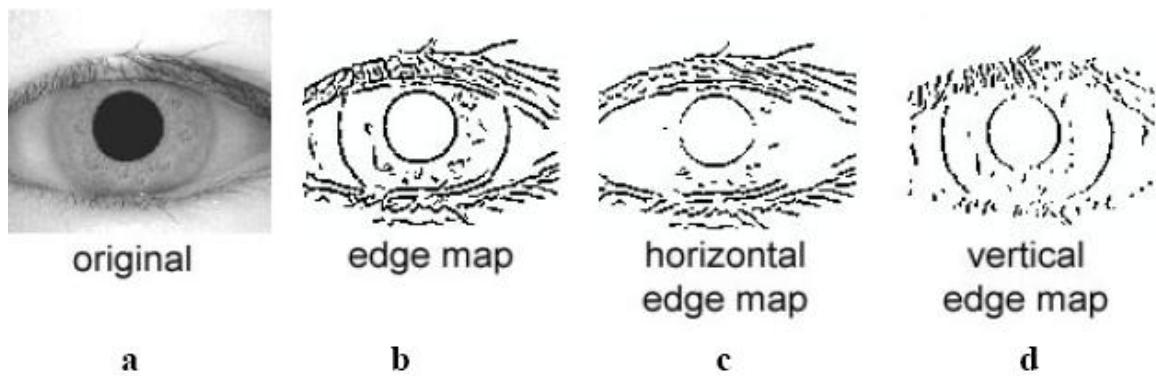


Figure 4. 5: Image of the eye (a), various images of edges by canny method: diagonal edges (b), horizontal edges (c) or vertical edges (d). Figure taken from the thesis of Libor Masek (**Masek,2003**).

The Masek system

The Masek system is an iris recognition system. The steps of the iris segmentation process which are used in the Masek system are (**Masek,2003**):

- **The generation of contour:** The generation of contour is done by the canny detection algorithm in the following manner:
 - The vertical gradients are used to detect the white-iris border.
 - The detection of the pupil border is done by the both gradients vertical and horizontal.
- **The detection of borders:** The detection of the external border (the iris) is done before that of the inner border (the pupil).
- **The detection of the eyelids:** The Hough transform method is used. Therefore, this step is done by searching for the lines on the high and the low of the detected iris. The eyelids is modeled by a horizontal line obtained from the line detected by the Hough transform in the following manner: it search for the points of the intersection between the iris circle and the line detected by the Hough transform, and it draw the horizontal line which passes through the lowest point (if we want to detect the top eyelid), or the most upper point (if we want to detect the lower eyelid).
- **The detection of the eyelashes and the reflections:** they are detected by thresholding the image to grayscale.

In this work, we have proposed a modified method of the method used in the Masek system for the iris segmentation step. We will describe this method in the next chapter.

4.3.3.2 IRIS NORMALIZATION

The result of the iris segmentation process is characterized by:

- The detected iris is a disk perforated inside by another smaller disk (the pupil).
- The size of the iris disk is not always constant due to:
 - The contraction of the iris.
 - The expansion of the iris.
 - The variation of the acquisition distances between the person and the scanner.

In this step, we have used the method proposed by *Daugman* which allows transforming the irregular disc of the iris into a rectangular image of constant size.

The Daugman system is based on several advances (**Daugman,1995**). First, he proposed a method to detect the iris pattern. He also proposed a method for the iris normalization, and a method for the features extraction of the normalized iris. Then, he illustrated a way for the transformation of the features vectors to a constant size code, and a way to make the final decision (**Daugman,2004**).

The iris normalization: Pseudo-polar method

The iris is an irregular disk. These irregularities are due to the expansion and the contraction of the pupil. However, these characteristics have pushed *Daugman* to develop a “Rubber Sheet” method which is a pseudo-polar method in order to normalize the disk of the iris. The process can be explained as follows:

For each pixel of the iris in the Cartesian area assigned a correspondent in the pseudo-polar area according to the distance of the pixel from the centers and the angle that is done with these centers. Specifically, the transformation is done according to the following equation:

$$z(x, \alpha) = (1 - x)z_p(\alpha) + xz_i(\alpha) \quad (1)$$

$$w(x, \alpha) = (1 - x)w_p(\alpha) + xw_i(\alpha) \quad (2)$$

Where $z_p(\alpha)$ represents the abscissa of the point of the pupil border detected whose the segment that passes through this point, and the center of the pupil makes an angle “ α ” with a selected direction.

Similarly, $w_p(\alpha)$ represents the ordered of this same point, then $z_i(\alpha)$ and $w_i(\alpha)$ represent the coordinates of the points obtained by the same principle but on the iris border.

The bottom image of figure 4.6 shows a normalized image obtained by the process described above. As it is shown the normalized image is a rectangular of constant size.

Generally, the selected size is 80*512 pixels. The width of the image represents the variation on the angular axis, and the height represents the variations on the radial axis.

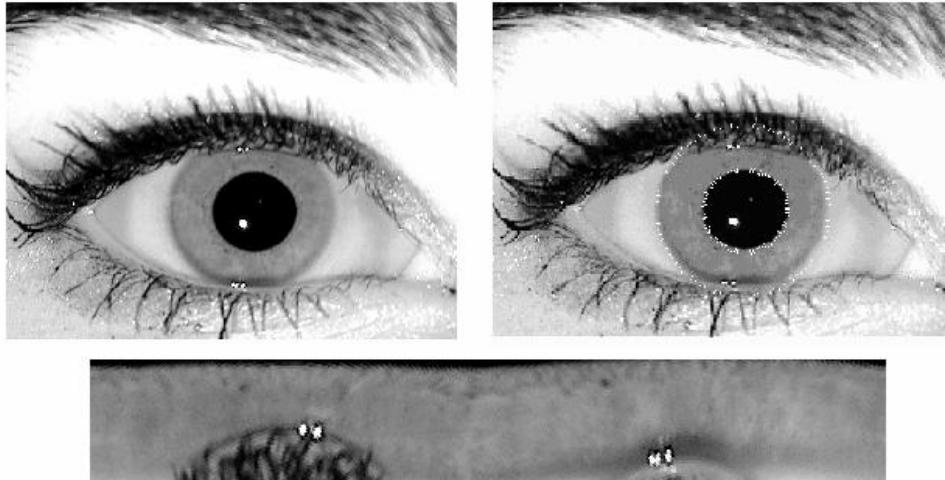


Figure 4. 6: The image of the eye (the top left figure), a segmented iris image (the top right figure), and a normalized iris image (the bottom figure). Figure is taken from the thesis of Libor Masek (**Masek,2003**)

4.3.3.3 FEATURES EXTRACTION

The goal of this step is the extraction of the pertinent characteristics. So, it extracts from the normalized iris images the points, the vectors, or the characteristics coefficients of the iris.

Daugman used the 2D Gabor filter for the features extraction. In our system, we used the wavelets method as a feature extraction method. The type of wavelet used in this work is the Daubechies wavelets.

In the literature, there are several methods for the iris features extraction; we cite some of them in the following table:

Research papers	Methodologies
(Daugman,1993).	Multiscale Quadrature 2D Gabor Wavelets.
(Boles,1998); (Roche,2001); (Avila,2002).	Zero-Crossing of the Dyadic wavelet.
(Wildes,1997).	Laplacian Pyramid with 4 different levels.
(Muron,2001).	Fourrier spectrum.
(Tisse,2002).	Instantaneous Phase.
(Huang,2002); (Bae,2003); (Dorairaj,2005).	ICA Independent Component Analysis.
(Ali,2003); (Ma,2003).	Haar wavelet.
(Ma,2003).	Circularly Symmetric Gabor Filters.
(Du,2004).	Computation of invariant local texture patterns.
(Kim,2004).	Continuous wavelets transform.
(Kim,2004).	Low-pass Filter + 1D Continuous Wavelet Transform.
(Krichen,2004).	Wavelet Packets.
(Nam,2004).	Analysis of the image's second derivatives.
(Son,2004).	2D Discrete Wavelet Transform (DWT) and Direct Linear Discriminant analysis (DLDA).
(Sun,2004).	Gaussian Filter.
(Zhang,2004b); (Yao,2006).	Log-Gabor Filters.
(Miyazawa,2005).	2D Discrete Fourier Transform (DFT).
(Chenhong,2005); (Chou,2006).	Laplacian of Gaussian Filters.
(Park,2006b).	Directional Filter.
(Hosseini,2007).	Shape Analysis Approach (FFT-based Tikhonov Filter with the identity matrix).
(Thornton,2007).	Gabor wavelet.
(Azizi,2009b).	Contourlet Transform.

Table 4. 4: Examples of the iris features extraction methods.

4.3.3.4 MATCHING

The goal of this step is to compare the features of irises between them. There are several methods for the matching step, such as:

- Hamming distance: (Daugman,1993); (Daugman,1994); (Tisse,2002); (Vatsa,2005); (Monro,2007); (Poursaberi,2007); (Gupta,2011); (Chirchi,2011); (Verma,2012).
- Euclidean distance: (Huang,2002); (Avila,2005); (Saravanan,2013).
- Weighted Euclidean: (Zhu,2000).

- Methods based on signal correlation: (**Wildes,1997**).
- Neural Network: (**Lim,2001**); (**Karthikeyan,2010**).
- k- Nearest Neighbour: (**Ma,2003**); (**Acar,2013**).
- SVM: (**Vatsa,2008a**); (**Azizi,2009a**).

4.3.4 DIFFICULTIES OF THE IRIS RECOGNITION PROCESS

The iris of the eye is really described as the ideal part of the human body to release the task of recognition. Despite its advantages, this modality presents multiple difficulties that can affect the recognition process such as:

- **The reflections:** The iris plays the role of the highly reflective mirror. In the acquisition mode, this mirror will involve the reflections on the pupil, the iris, or the both, and these complicate the recognition phase. The iris texture can also suffer from reflections due to wearing glasses or lenses.
- **The occulting noise:** The iris texture can be covered by occulting noise such as the eyelids or the eyelashes.
- **The blurred noise:** such as:
 - *The blur of acquisition:* The responsible of this noise is the distance between the iris and the scanner during the acquisition mode.
 - *The blur of movement:* The creator of this type of noise is the sudden movements of the eye (opening/closing of the eyelids) with those of the contraction or the dilation of the pupil.
- **The richness of the iris texture:** Some textures of iris are not very rich (motifs) so they can cause errors in the recognition phase.
- **The acquisition environment:** The iris is a muscle that expands and contracts, and this is depending on the amount of the light in the acquisition environment.

So, there are several types of noises which affect the iris recognition process, such as:

- Lighting reflections.
 - Specular reflections.
 - Poorly focused images.
 - Partially captured irises.
 - Out-of-iris images.
 - Off-angle iris.
 - Motion blurred images.
 - Iris obstructions by eyelids.
-

- Iris obstructions by eyelashes.
- Pupil wrongly considered as belonging to the iris.
- Sclera wrongly considered as belonging to the iris.

4.3.5 IRIS DATABASES

Before 2000, there were not the public databases for the iris recognition. Today, this situation has changed and several databases are available such as: CASIA ([Web71](#)), UPOL ([Web72](#)), UBATH ([Web73](#)), UBIRIS ([Web74](#)), ICE ([Web75](#)), and MMU ([Web76](#)).

- **CASIA: ([Web71](#))**

The *Chinese Academy of Science Institute of Automation “CASIA”* was the first institute that shared the iris databases. There are four versions in this database which are:

- ✓ **CASIA 1:** This database is characterized by:
 - It is the first public database.
 - It includes 756 images of 108 persons. For each person, 7 images were acquired in two separate sessions of some weeks.
 - The resolution of the images of this database is about 320x280.
 - The images are saved in BMP format.
 - There are several pre-treatment applied to the images of this database before being put to provisions of researchers.
 - The pupil colored in black, and the images were centered.
 - This database is net because the irises are weakly covered of eyelids and eyelashes.
- ✓ **CASIA 2:** This database is characterized by:
 - It includes 2400 images of 120 persons.
 - This database used two different sensors: the OKI sensor and the Pattek sensor.
 - The resolution of images of this database is about 640x480 pixels.
 - The images are saved in BMP format.
 - The limitation of this database is that all the subjects are Chinese.
 - It includes blurred images with different illuminations, and the wearing of glasses is authorized.

- ✓ **CASIA 3:** This database is characterized by:
 - It includes 22,034 images of 700 subjects organized into three groups:
 - CASIA-Iris-Interval: (The resolution of the images is about 320x280).
 - CASIA-Iris-Lamp: (The resolution of the images is about 640x480).
 - CASIA-Iris-Twins: (The resolution of the images is about 640x480).
 - The format of the images is JPG.
- ✓ **CASIA 4:** This database is characterized by:
 - It is an extension of CASIA-Iris3.
 - It contains 54,601 images of iris.
 - The format of the images is JPG.
 - It contains six sub-sets:
 - The three sub-sets of CASIA-Iris3:
 - CASIA-Iris-Interval.
 - CASIA-Iris-Lamp.
 - CASIA-Iris-Twins.
 - The three new sets are:
 - CASIA-Iris-Distance: (The resolution of the images is about 2352x1728).
 - CASIA-Iris-Thousand: (The resolution of the images is about 640x480).
 - CASIA-Iris-Syn: (The resolution of the images is about 640x480).

The following table (table 4.5) presents some characteristics of the four versions of the CASIA database.

	CASIA 1	CASIA 2		CASIA 4						
				CASIA 3			CASIA 4			
				Interval	Lamp	Twins	Distance	Thousand	Syn	
Sensor	CASIA close-up iris Camera.	OKI IRISPASS-h	CASIA-IrisCam V2.	CASIA close-up iris camera.	OKI IRISPASS-h.	OKI IRISPASS-h.	CASIA long-range iris camera.	Irisking IKEMB-100.	CASIA iris image synthesis algo.	
Environment	Indoor	Indoor	Indoor	Indoor	Indoor with lamp on/off	Outdoor	Indoor	Indoor with lamp on/off	N/A	
Session	2	1	1	2	1	1	1	1	N/A	
Attributes of subjects				Most are graduate students of CASIA.	Most are graduate students of CASIA.	Most are children participating Beijing Twins Festival.	Most are graduate students of CASIA.	Students, workers, farmers with wide-range distribution of ages.	The source iris images are from CASIA-Iris 1.	
No. of subjects	108	60	60	249	411	200	142	1000	1000	
No. of images	756	1200	1200	2639	16212	3183	2567	20000	10000	
Resolution	320*280	640*480	640*480	320*280	640*480	640*480	2352*1728	640*480	640*480	
Format	BMP	BMP	BMP	JPG	JPG	JPG	JPG	JPG	JPG	
Total	756	2,400		22,034			32,567			
				54,601						

Table 4. 5: Statistics of CASIA-Iris1, CASIA-Iris2, CASIA-Iris3, and CASIA-Iris4.

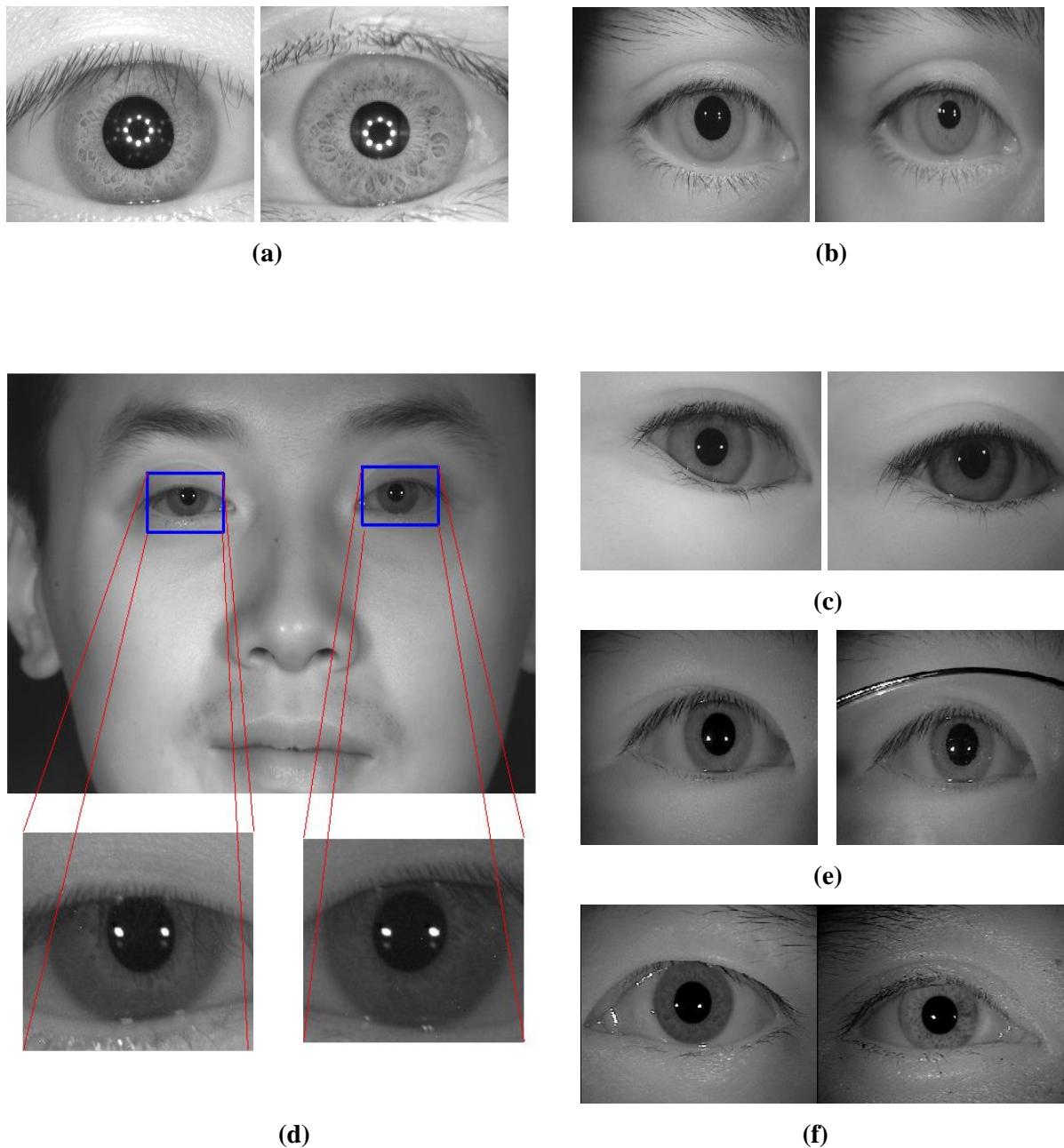


Figure 4.7: Example of iris images (CASIA4):(a) CASIA-Iris-Interval- (b) CASIA-Iris-Lamp- (c) CASIA-Iris-Twins- (d) CASIA-Iris-Distance –(e) CASIA-Iris- Thousand – (f) CASIA-Iris-Syn.

- **UPOL:** This database is characterized by: (**Web72**)
 - It contains 384 images of 64 subjects, and there are 3 images for each subject.
 - The TOPCON TRC50IA sensor connected to SONY DXC-950P3CCD camera is used for the acquisition of the irises.
 - The resolution of the images is about 768x576, saved in PNG format, and the images are in color.

- The images of this database are net, and the quality of these images is very good without any occlusion of eyelids and eyelashes.
 - Europeans subjects are represented in this database.
- **UBATH:** This database is characterized by: ([Web73](#))
 - The University of Bath has developed a system of capture of iris to acquire images with high quality.
 - It contains 2000 images of iris of 50 persons, and it is free to download.
 - The resolution of the images is about 1280x960.
 - The quality of images is very good when the capture was made in very controlled mode.
 - Europeans and Asians are represented in this database.
- **UBIRIS:** This database is characterized by: ([Web74](#))
 - It contains 1877 images of 241 persons captured in two sessions.
 - The resolution of the images is about 400x300.
 - Since the acquisition mode chosen was the visible light, the images are available in color under two resolutions: 800x600 and 200x150.
 - There are several variations of acquisition conditions, and various degradations of images in this database such as the illumination, the contrast, the reflection, and the occlusion.
 - The big weakness of this database is that it cannot be used to evaluate systems developed for the infrared images because it has been acquired in visible light.
- **ICE 2005:** This database is characterized by: ([Web75](#))
 - The ICE 2005 has been making available by the *National Institute of Standards and Technology* (NIST).
 - It contains 2953 images of 132 persons.
 - The camera LG2200 is used for the acquisition mode.
 - This database is a sub-part of a large database of more than 25094 images.
 - In most cases, the both irises (the left and the right) are acquired at the same time.
 - The database contains several intra-class variations and different types of degradation.
 - The images of this database are occulted by the eyelids and the eyelashes.
 - The level of blur and the level of movement blur are larger than those present in other previously mentioned bases.

- **MMU:** This database is characterized by: (**Web76**)
 - It is developed by Multimedia University.
 - It contains two sub-databases:
 - The MMU1 data set of 450 iris images (45 subjects with 5 images for each eye).
 - The MMU2 data set of 995 iris images (100 subjects with 5 for each eye).
 - Every iris image is saved in “BMP” format.

Figure 4.8 illustrates some examples of the images of the databases mentioned above.

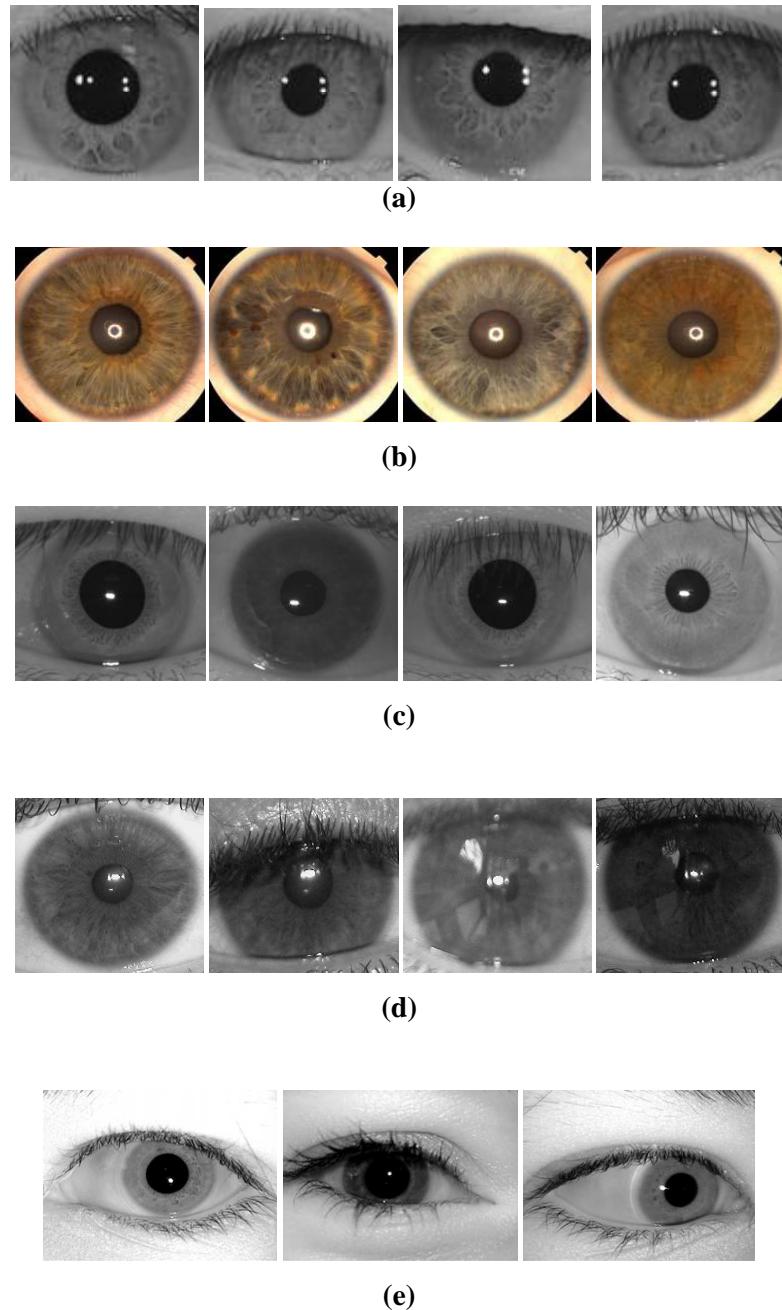


Figure 4.8: Examples of the different iris databases: (a)Casia1, (b)UPOL, (c)Bath, (d)UBIRIS, (e)ICE.

4.4 CONCLUSION

The biometric systems which use one biometric modality have been used in several applications, but they are suitable for a medium level of security. In fact, most the security level is high; more it will tend towards the use of the multi-biometrics systems because these systems are more powerful and more secure.

In this work, we choose to combine the face with the both units of the iris modalities. However, we addressed in this chapter the both biometric modalities that have several advantages listed previously. Indeed, the face and the iris modalities offer significant ease of use. Also, they are not expensive and their processing is fast. In addition, their association is used especially in the high security areas.

In the next chapter, we will present the proposed approach which is used for the integration of the both modalities, and we will highlight the benefits of this multi-biometrics system.

CHAPTER V: THE PROPOSED APPROACH

This chapter details the different steps of the proposed approach which is used for the integration of the face with the both units of the iris modality. This chapter is organized as follows:

Summary:

- 5.1 Introduction
- 5.2 Fusion Level
- 5.3 Related Works
- 5.4 The Proposed Approach
 - 5.4.1 Architecture and Structure of the System
 - 5.4.2 Steps of the Proposed Approach
 - 5.4.2.1 Capture Module
 - 5.4.2.2 Detection Module
 - 5.4.2.2.1 The Face
 - 5.4.2.2.2 The Iris
 - 5.4.2.3 Features Extraction Module
 - 5.4.2.4 Matching Module
 - 5.4.2.4.1 Description of the Support Vector Machines
 - 5.4.2.4.2 Binary Classification
 - 5.4.2.4.3 Multi-Class
 - 5.4.2.5 Scores Normalization
 - 5.4.2.6 Fusion Module
 - 5.4.2.6.1 Fusion Approaches
 - 5.4.2.6.1.1 Combination Approach
 - 5.4.2.6.1.2 Classification Approach
 - 5.4.2.6.2 The Proposed Fusion Approach
 - 5.4.2.7 Decision Module
 - 5.5 Conclusion

5.1 INTRODUCTION

The unimodal biometric systems present multiple advantages compared with the traditional methods of identification. Despite their wide use in various applications, they suffer from several limitations, and this is making them suitable for the application with a medium level of security. In fact, more the need of security is increased; more the use of the multi-biometrics system is desired.

The choice of modalities is a key for the success of the biometric system. Therefore, we have presented the modalities which are chosen to be integrated in our work in the previous chapter. However, the choice was made to combine the modality of the face with the both units of the iris. The challenge that must meet is to improve the performance of the biometric security system by finding an original fusion method such that the recognition rate of the fused modalities is higher than the recognition rate of the modalities taken separately. We'll also take care to analyze the execution time of the application as well as the overall complexity of the calculations that are supposed to be respectively slower and heavier than the unimodal biometric system.

This work addresses the score level fusion for the multi-units and the multi-modal sources of information. For the first category, the both units of the iris modality are fused, while the second is based on the integration of the both modalities the face and the iris.

In this chapter, we will describe the approach used to realize our multi-biometrics system. Therefore, we will express in detail the different steps of our proposed approach.

5.1 FUSION LEVEL

The combination of several biometric systems generates several scenarios. However, the integration of the biometric information can be done at four different levels which are:

- The sensor level.
- The features extraction level.
- The score level.
- The decision level.

The two first levels are relatively little used because they require the homogeneity between the biometric data. The fusion at the decision level is often used for its simplicity but it uses

very little information. Therefore, the fusion at the score level seems to be the best choice for the following reasons:

- It is the most used in the biometric fusion area.
- It can apply to all types of systems.
- It can process more information compared with the decision fusion.
- It is independent of the algorithms that are used for the generation of the similarity scores.
- It offers the best compromise between the ease of implementation and the wealth of information.

These reasons offer great flexibility for the integration into the existing systems that can be updated without interfering with the fusion technique. So, we have used the fusion at this level because it seems to be the best choice.

5.2 RELATED WORKS

The fusion of the face with the iris modality has attracted the attention of several researches. In the following table (table 5.1), we will present some examples of these researches:

Levels	Papers	Fusion Methodologies	Features Extraction	Matching
Feature	(Son,2005).	Reduced Joint Feature Vector Discrete Linear Discriminate Analysis (RJFV DLDA).	2-D Daubechies wavelet.	Euclidean distance.
	(Gan,2008); (Gan,2009).	Kernel Fisher Discriminate Analysis (KFDA).	Two-Dimensional Discrete Cosine Transform (2D-DCT).	Nearest Neighbor classifier.
	(Lin,2009).	Concatenation.	Image pixels.	Consine similarity.
	(Rattani,2009).	Concatenation.	Scale-Invariant Feature Transform (SIFT).	Euclidean distance.
	(Kekre,2011).		<ul style="list-style-type: none"> • Face: Kekre's Wavelets. • Iris: 1 D transform of row and column mean + kekre's wavelet Kekre's Fast Codebook Generation (KFCG) + Kekre's Median Codebook Generation (KMCG) 	K- Nearest Neighborhood (KNN) Classifier.
	(Wang,2011).	Z-score normalization and Serial Rule.	2D Gabor (iris) + Principal Component Analysis PCA (face).	Euclidian distance.
	(Sharma,2012)	Concatenation.	<ul style="list-style-type: none"> • Local Gabor XOR Pattern (LGXP). • Local Binary Pattern (LBP). • Empirical Mode Decomposition (EMD). 	<ul style="list-style-type: none"> • LGXP approach: Weightage based on Irrelevant Pixel + Euclidean distance + Average Matching Score Based on Weightage. • LBP approach: Weightage based on

Levels	Papers	Fusion Methodologies	Features Extraction	Matching
			<ul style="list-style-type: none"> • Principal Component Analysis (PCA) (PCA for face and Gabor filter for iris). 	Irrelevant Pixel + Average Matching Score Based on Weightage. <ul style="list-style-type: none"> • EMD approach: Weightage based on Irrelevant Pixel + Average Matching Score Based on Weightage. • PCA approach: Euclidean distance.
	(Nair,2013).	Principal Component Analysis (PCA).	Discrete Wavelet Transform (DWT) + Discrete Cosine Transform (DCT).	
	(Abuguba,2015).	Concatenation.	2D Gabor filters (iris) + Principal Component Analysis PCA (face).	
	(Wang,2015).	Serial rule.	2D Gabor (iris) + Principal Component Analysis PCA (face).	Fisher Discriminate Analysis.
Score	(Wang,2003).	Weighted sum. Fisher Discriminate Analysis. RBF neural network.	Principal Component Analysis PCA (face) + 1D intensity signal and wavelet (iris).	Principal Component Analysis PCA (face) + Exclusive OR (iris).
	(Chen,2006a).	Unweighted average.	1-D Energy signal.	Wavelet Probabilistic Neural Network (WPNN) + Particle Swarm Optimization (PSO).
	(Vasta,2007).	2v-SVM.	<ul style="list-style-type: none"> • Match scores: 2D Log-Gabor (face) and 1D Log Gabor (Iris). 	Product of the quality score with the corresponding match score represent the quality based match score metric for

Levels	Papers	Fusion Methodologies	Features Extraction	Matching
			<ul style="list-style-type: none"> Quality scores: Redundant Discrete Wavelet Transform (RDWT) 	each modality.
	(Zhang,2007).	Sum rule and Product rule.	Principal Component Analysis PCA (face) and 2D Gabor wavelet (iris).	Hamming distance.
	(Morizet,2009).	WSDSF (Wavelet Score Denoising Statistical Fusion).	Log-Gabor (face) and 2D WPT (Wavelet Packet Transform) (iris).	LG-PCA (Log Gabor Principal Component Analysis) (face) + Cosine combined measure.
	(Wang,2009).	SVM.	Laplacian face algorithm (face) + 2D Log-Gabor filters (iris).	Euclidean distance (face) + XOR with Hamming distance (iris).
	(Zhang,2010).	Sum rule.	Sparse representation (face) + Ordinal representation (iris).	The similarity measure (face) + Hamming distance (iris).
	(Fakhar,2011).	Sum of normalized (Z-score, Min-Max) scores.	Block based Steerable Pyramids.	City-bank distance.
	(Johnson,2011).	Sum rule. Likelihood ratio (LR). Quality based Likelihood ratio (QLR).	FaceIT SDK (face) + Modified Masek system (iris).	FaceIT SDK (face) + Modified Masek system (iris).
	(Liau,2011).	SVM.	Discrete Cosine Transformation (DCT) (face) + Log-Gabor filter (iris).	PSO (Particle Swarm Optimization) (used for the features selection).
	(Eskandari,2012) .	Sum and Product rules.	Local methods: (Subpattern-based Principal Component Analysis (spPCA), Modular Principal Component Analysis (mPCA),	Manhattan distance.

Levels	Papers	Fusion Methodologies	Features Extraction	Matching
<p>(Kim,2012).</p> <p>(Eskandari,2013)</p> <p>(Eskandari,2014)</p> <p>(Wang,2014).</p>			Local Binary Patterns (LBP)). Global methods: (Principal Component Analysis (PCA), subspace LDA (ssLDA))	
	SVM.		Principal Component Analysis PCA (face) + 1D Gabor filter (iris).	Euclidean distance (face) + Hamming distance (iris).
	.	Concatenation (after the fusion of scores, the Nearest Neighbor classifier is used to classify the scores).	Local methods: (Subpattern-based Principal Component Analysis (spPCA), Modular Principal Component Analysis (mPCA), Local Binary Patterns (LBP)). Global methods: (Principal Component Analysis (PCA), subspace LDA (ssLDA)).	Sum rule (sum of scores of the five different features extraction methods for face and iris separately).
	.	Weighted Sum Rule (after the fusion of scores, the Nearest Neighbor classifier is used to classify the scores).	Local Binary Patterns local (face) + subspace Linear Discriminate Analysis global (iris).	Manhattan distance.
		Aczél-Alsina Triangular Norm.	1D Log-Gabor (iris) + Two- Directional Two-Dimensional Fisher Principal Component Analysis (2D) ² FPCA(face).	

Table 5. 1: Examples of multi-biometrics studies based on the integration of the face with the iris.

The studies mentioned in the previous table are based on the integration of the face with the iris at feature and score levels. However, there are other studies which are based on the fusion at other levels such as: In (**Connaughton,2012**) the fusion is performed at the rank level, and the fusion in (**Lee,2007**) is performed at the decision level.

Also, there are other studies which combine the fusion in more than one level like:

- Fusion in the feature level and the score level: (**Eskandari,2015**).
- Fusion in the feature level, the score level, and the decision level: (**Sharifi,2016**).

5.3 THE PROPOSED APPROACH

In this section, we will express the different steps of the approach used to realize our multi-biometrics system which is considered as multi-modal and multi-units system. The multi-modal is based on the combination of the face and the iris biometric traits, while the multi-units fusion combines the left and the right irises.

5.3.1 ARCHITECTURE AND STRUCTURE OF THE SYSTEM

The multi-biometrics system requires the acquisition and the processing of the biometric data. However, the both operations can operate successively (the serial mode) or simultaneously (the parallel mode).

The parallel mode is the most used in the literature because it offers the possibility of use of all available biometric information, and this improves the performance of the fusion.

In this work, the parallel mode is used as shown in Figure 5.1:

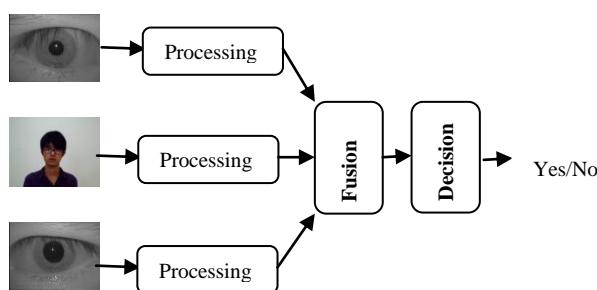


Figure 5. 1: The architecture of the multi-biometrics system.

The combination of several biometric systems generates six scenarios which are detailed in the chapter three (section 3.4), these scenarios are:

- Multi-Sensors system.
- Multi-Algorithms system.
- Multi-Units system.
- Multi-Samples system.
- Multi-Modal system.
- Hybrid system.

A fusion of more than one of the six scenarios can be employed in the same system. However, this work is based on a system that follows the principle of scenario 2 (Multi-algorithms system), scenario 3 (Multi-units system), scenario 4 (Multi-samples system), combined with scenario 5 (Multi-modal system), and scenario 6 (Hybrid system). In fact, the system is interested to recognize persons by their both irises (the principle of Multi-units, scenario 3). It is also attracted to the facial recognition by taking account of the changes in the facial pose such as the front, the left, and the right profile of the face (the principle of multi-samples, scenario 4). In addition, it integrated the both modalities: the face and the iris (the principle of Multi-modals, scenario 5). For this, the SVM was used to obtain the scores, while the fusion is based on the use of two methods: a combination method integrated with a classification method (the principle of multiple algorithms, scenario 2). The system can also be classified as hybrid as follows the principle of scenario 2, scenario 3, combined with that scenario 4, and scenario 5.

Our multi-biometrics system is developed by integrating the face and the both units of the iris modality (the left and the right irises), the structure of this multi-biometrics system is shown in figure 5.2:

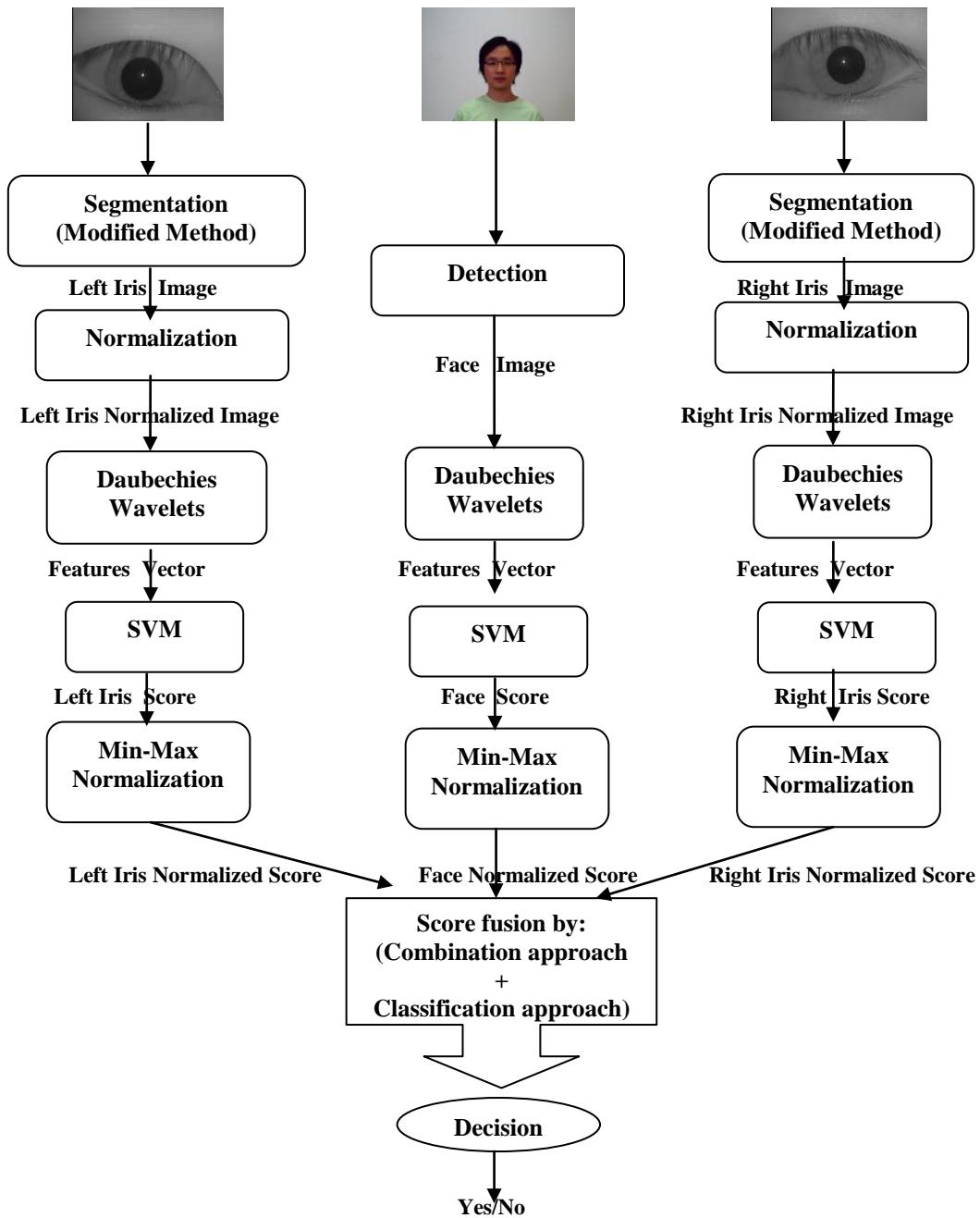


Figure 5. 2: The multi-biometrics system structure.

5.3.2 STEPS OF THE PROPOSED APPROACH

Our multi-biometrics system is based on the integration of the face with the both units of the iris modality. In this work, we have used a standard method that can apply to the both modalities, concerning the features extraction and the matching steps. Therefore, the Daubechies wavelets are used for the features extraction, and the matching score for each modality is calculated by using the SVM method, then the scores are normalized by the Min-

Max method. The final score is generated by using the integration of two methods which are: the combination method and the classification method (**Chikhaoui,2013**), which is then passed to the decision module.

The different steps of our proposed approach are detailed in the following:

5.3.2.1 CAPTURE MODULE

In this module, we have used the public databases in order to test the evaluation of our multi-biometrics system:

- The multi-units (the fusion of the left and the right irises): we are used four databases to test our multi-units biometric system which contains the both irises (the left and the right irises):
 - CASIA 4 (**Web71**).
 - SDUMLA-HMT (**Web77**).
 - MMU1 (**Web76**).
 - MMU2 (**Web76**).

The three databases (CASIA, MMU1, and MMU2) are described in the previous chapter; we will present the characteristics of the SDUMLA-HMT database later.

- The multi-biometrics (the fusion of the face and the both irises): we are used the SDUMLA-HMT database (**Web77**).

5.3.2.2 DETECTION MODULE

5.3.2.2.1 The Face

The images of the database used don't contain only the face data, so it is necessary to segment the image to isolate the face from the rest of the image. However, the database used in this work is created for the facial recognition system, and the detection of the face limits can be done manually.

5.3.2.2.2 The Iris

It is necessary to segment the image to isolate the iris from the rest of the image. Therefore, the detection of the iris is passed by two steps: the segmentation and the normalization.

- ❖ **The segmentation:** The images of the used database don't only include the information of the iris, so it is necessary to segment the image to isolate the iris from the rest of the image. Several studies have been conducted in this area: Daugman (**Daugman,1993**) and (**Daugman,2004**) (Integro-differential operator); Wildes (**Wildes,1997**) (Image intensity gradient and Hough transform); Bole and Boashash (**Boles,1998**) (Edge detection); Masek
-

(**Masek,2003**), Liu et al. (**Liu,2005a**), and Sudha et al. (**Sudha,2009**) (Edge detection, the Canny filter, and the Hough transform); Ma et al. (**Ma,2003**) (Hough transform); Ma et al. (**Ma,2004**) (Gray-level information, Canny edge detection, and Hough transform); Proenca and Alexendre (**Proen ,2007**) (Integro-differential operator); Vatsa et al. (**Vatsa,2008a**) (modified Mumford–Shah functional); He et al. (**He,2009**) (approach to drawing and elastic boost); Liu et al. (**Liu,2005b**) (Modified Hough transform); Schuckers et al. (**Schuckers,2007**) (Integro-differential operator and model of angular deformation); Ross et al. (**Ross,2006b**) (Geodesic active edges); Puhan et al. (**Puhan,2011**) (Fourier spectral density).

In our work, we have proposed a modified method of the method used in the Masek system (**Masek,2003**) to segment the iris pattern. The Masek system (**Masek,2003**) includes a segmentation module based on the Hough transform. This last method allows finding the parameters of simple geometric objects such as circles and lines. However, it is used to localize the pupil, the iris, the eyelids, and the eyelashes. Also, it is used to determine the radius and the coordinates of the center of the pupil and the iris.

The Hough transform is used in several studies such as: (**Wildes,1994**) (**Wildes,1997**) (**Kong,2001**) (**Ma,2002a**) (**Ma,2002b**) (**Tisse,2002**) (**Liu,2003**) (**Ma,2003**) (**Masek,2003**) (**Huang,2004**) (**Ma,2004**) (**Tian,2004**) (**Chen,2005a**) (**He,2006**) (**Monro,2007**) (**Khiari,2008**) (**Sudha,2009**) (**Gawande,2010**) (**Smereka,2010**) (**Costa,2012**) (**Verma,2012**).

In our work, we have used the same steps applied in the Masek system (**Masek,2003**) for the iris segmentation step which are described in the previous chapter, but we have proposed that the coordinates of the center of the pupil and the iris are the same, it isn't like the Masek system (**Masek,2003**).

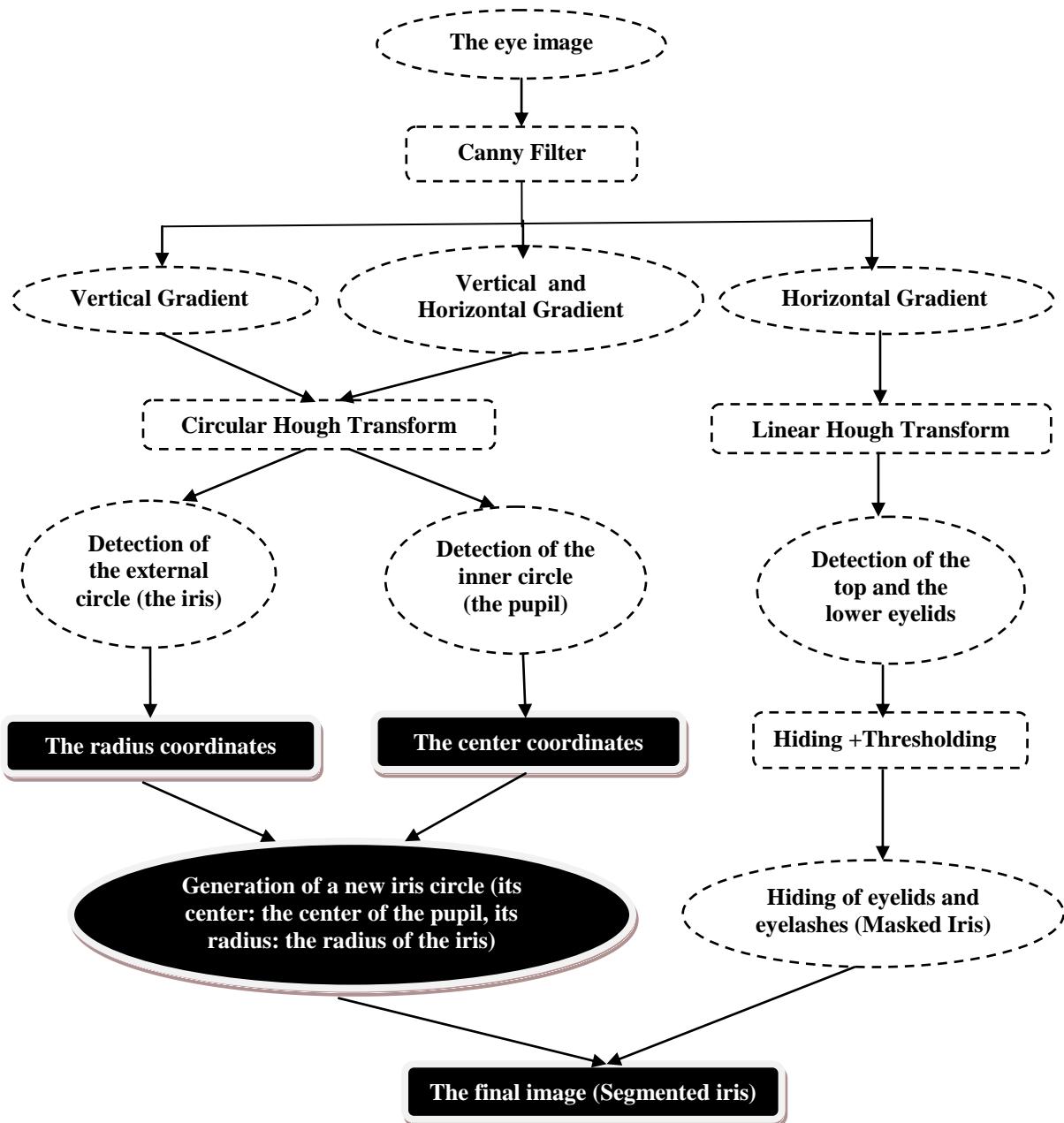
The Masek system segments the iris in the following manner (**Masek,2003**):

- Generation of the contour by the canny detection algorithm in the following manner:
 - The vertical gradients are used to detect the white-iris border.
 - The detection of the pupil border is done by the gradients vertical and horizontal.
- Detection of the external border (the iris) is done before that of the inner border (the pupil).
- In our method, we added a step after this last step of the Masek system: When we applied the Masek system on the databases (**Web71**) (**Web77**) (**Web76**), we found

that there are several examples of incorrect iris segmentation. However, the points of the pupil border are well detected. For this reason, we have proposed that the both circles of the pupil and the iris are concentric. So, we have used the radius of the detected iris circle and the center coordinates of the pupil circle generated by the Masek system for the generation of new iris circle. This new circle has the same radius as the previous detected iris circle and the same center as the pupil circle. By analysing the results of this proposed method on the images of the databases (**Web71**) (**Web77**) (**Web76**), we found that the number of poorly detected iris is reduced.

- The other steps are the same as the Masek system:
 - Detection of the eyelids is done by searching for the lines on the high and the low of the detected iris using the Hough transform.
 - The eyelashes and the reflections are detected by thresholding the image to grayscale.

Figure 5.3 details the different steps of the modified method which is used for the iris segmentation step.



[] : The steps that exist in the Masek method.

[] : The steps added by our modified method.

Figure 5. 3: The diagram of the iris segmentation process (**Zoubida,2017a**).

Figure 5.4 shows the segmentation results of two examples of irises taken from the CASIA database (CASIA 4 interval). Column (a) illustrates the examples that used the Masek system for the iris detection, and column (b) is the same examples but the detection of the irises is done by our modified method.

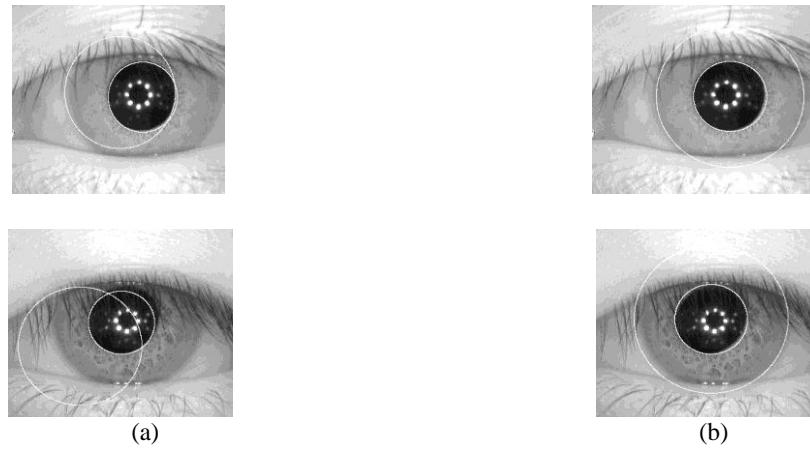


Figure 5.4: Examples of the iris segmentation. (a) examples of incorrect iris segmentation by Masek system; (b) examples of iris segmentation by our modified method.

- ❖ **The Normalization:** This step consists of transforming the irregular disc of the iris into a rectangular image of constant size. In this work, we used the same method as the Masek system (**Masek,2003**). This system includes a normalization module based on the normalization method “pseudo polar”. We have detailed the steps of this method in the previous chapter. For the both steps (the features extraction and the matching), the Masek system (**Masek,2003**) used the Gabor filter for the features extraction and the Hamming distance for the matching step. The methods used in our work will be detailed in the following sections.

5.3.2.3 FEATURES EXTRACTION MODULE

In our system, the single level two-dimensional wavelet decomposition of the signal using the Daubechies wavelet is used to extract the features vectors of the face and the both units of the iris modality.

At this level, we have obtained three features vectors which are: the face features vector, the left iris features vector, and the right iris features vector.

5.3.2.4 MATCHING MODULE

In our work, we have used the SVM method not to provide a decision, but to obtain scores for the fusion.

The Support Vector Machine (SVM) is one of the statistical learning methods (**Vapnik,1995**) (**Vapnik,1998**). They are excellent tools that are used for the classification and the regression. Their goal is to find the optimal separating hyper-plane and the maximal margin.

In our case, the binary classification was chosen. As our system is a verification system, the SVM used is a binary SVM.

During the classification by the SVM method, the choice of the kernel function is a very important step for the effectiveness of the solution found. There are various kernel functions, among these functions we choose the linear function. According to Benyacoub (**Yacoub,1998**) this function gives good results for the data integration.

At this level, we have obtained three scores which are: a score of the face, a score of the left iris, and a score of the right iris.

5.3.2.4.1 Description of the Support Vector Machines

The Support Vector Machine (SVM) is one of the discrimination techniques in the statistical learning theory. This technique has been introduced by *Vapnik* in his book “*The nature of statistical learning theory*” in 1995 (**Vapnik,1995**). The SVM is used for the resolution of several problems such as the regression, the classification, and the fusion, etc.

The support vector machine (SVM) is one of the supervised learning techniques. It is a generalization of linear classifiers. The SVMs have quickly been adapted because:

- They are theoretically well founded and they are formal.
- They have good results in practice.
- They work with data that have large dimensions.
- They have a low number of hyper parameters.
- They give more readable results and geometric interpretation.

5.3.2.4.2 Binary Classification

In our system, we are interested by the case of the binary classification because our system is a verification system, and it has two results (authenticate or non-authenticate).

We suppose that y is the input vector being in a space Y with a scalar product. We can for example take $Y=R^N$.

Now consider n points $\{(y_1, z_1), (y_2, z_2), \dots, (y_n, z_n)\}$; $y_i \in R^N$, with $(i=1, \dots, n)$; and $z_i \in \{\pm 1\}$.

These points can be classified by using a family of linear functions defined by: $w \cdot y + b = 0$, with $w \in R^N$ and $b \in R$, so the decision function is:

$$F(y) = \text{sign}(w \cdot y + b) \quad (3)$$

The goal of the discrimination is to find a hyper-plane that separates two or more vectors.

The linear function of the hyper-plane is:

$$w \cdot y + b = 0 \quad (4)$$

Where y : is the vector of examples.

The two canonical hyper-planes are under the form:

$$w \cdot y + b = \pm 1 \quad (5)$$

The distance between any point and the hyper-plane is defined by:

$$d(y) = \frac{|w \cdot y + b|}{\|w\|} \quad (6)$$

The optimal hyper-plane is the hyper-plane for which the distance to margin is maximal.

This distance is defined by: $\frac{2}{\|w\|}$

Maximize the margin amount to minimize $\|w\|$ or to minimize $\|w\|^2$ under constraints, with: $\|w\|^2 = w^T w$

$$\begin{cases} \text{Min}_{w \in R^N} \frac{1}{2} \|w^2\| \\ (w \cdot y_i + b) - 1 \geq 0, \forall i \in 1 \dots n \end{cases} \quad (7)$$

Where "z" is the label of class, 1 or -1 for example.

The method of Lagrange multipliers is used to achieve the minimization in the presence of constraints. The basic approach involves the definition of new function "L" that combines the original function to minimize and the constraints functions, each proportional have a new variable, called Lagrange multipliers.

We choose to call this multiplier λ_i . The Lagrange multipliers must be all positive.

The Lagrangian that is associated with the previous optimization problem is:

$$L(w, b, \lambda) = \frac{1}{2} \|w\|^2 - \sum_{i=1}^n \lambda_i [(y_i \cdot w + b) z_i - 1] \quad (8)$$

Where n: is the number of examples.

The Lagrangian must be minimized against to “w” and “b”, and maximized against to “ λ ”. It is then assumed that the global minimum is reached when the partial derivatives of L against each of its variables are zero.

$$\frac{\partial L}{\partial w} = 0 \quad (9)$$

$$\frac{\partial L}{\partial b} = 0 \quad (10)$$

and $\lambda_i > 0$. From the both relationships (9) and (10), we can deduce:

$$w = \sum_{i=1}^n \lambda_i z_i y_i \quad (11)$$

$$\sum_{i=1}^n \lambda_i z_i = 0 \quad (12)$$

By substituting the results achieved by the cancellation of the partial derivatives of L in the equation (8), we can express the minimization of L in its dual form (principle of the duality of Wolfe), so we get the maximization given by the following expression in terms of λ_i and examples of learning y_i .

$$\begin{cases} L_D = \sum_{i=1}^n \lambda_i - \frac{1}{2} \sum_{i,j=1}^n \lambda_i \lambda_j z_i z_j y_i \cdot y_j \text{ to maximize U.C} \\ \sum_{i=1}^n \lambda_i z_i = 0 \text{ and } \lambda_i \geq 0, \forall i \in 1 \dots n \end{cases} \quad (13)$$

$$F(u) = \text{sign}(\sum_{i=1}^{ns} \lambda_i z_i y_i \cdot u + b) \quad (14)$$

Where, ns: is the number of support points, u: unknown point to classify.

5.3.2.4.3 Multi-Class

The classification system “*multi-class*” is obtained by the combination of several binary SVM classifiers. The “*one versus all*” also called “*one versus the rest*” and the “*pairwise*” approaches are strategies which solve the classification problems in q classes by the SVM.

In the “*one versus all*” approach, the learning is done by q SVMs which separates each class of all other classes. But in the “*pairwise*” approach, the learning is done by $\frac{q(q-1)}{2}$ SVMs which separate each a pair of classes. These classifiers are arranged as a tree whose nodes are the SVMs.

In the literature, the comparisons between the different multi-classes approaches encourage the use of the approach *one versus all* due to its good performance of classification and its simplicity. However, it is better to have $\frac{q(q-1)}{2}$ SVMs about learning, and the execution time of the two strategies is similar (**Heisele,2003**).

5.3.2.5 SCORES NORMALIZATION

The normalization process is an essential step in the multimodal fusion. Its goal is to transform the monomodal scores in a comparable range. So, it transformed the scores of each signature to make them homogeneous before combining. There are several normalization techniques (**Lum,1999**) (**Bolle,2004**) (**Jain,2005**) such as:

- Min-Max.
- Z-score.
- Hyperbolic tangent Tanh.
- Quadratic-Linear-Quadratic (QLQ).
- Median and Median Absolute Deviation (MAD).
- Double sigmoid function.

In our work, we choose to use the Min-Max normalization. It is one of the simplest methods, and it is used when the minimum and the maximum scores are known. The original distribution of scores is preserved, and the scores are normalized in the interval [0,1].

The normalized score Min-Max for the test S_{ik} is given by:

$$S'_{ik} = \frac{S_{ik} - \text{MIN}(S_i)}{\text{MAX}(S_i) - \text{MIN}(S_i)} \quad (15)$$

Where $\{S_i\} = \{S_{i1}, S_{i2}, \dots, S_{iM}\}$. ($i = 1, 2, \dots, R$; R : The number of modalities; M : The number of match scores).

5.3.2.6 FUSION MODULE

5.3.2.6.1 Fusion Approaches

There are two types of approaches which used to combine the scores obtained by the different systems. The first approach considers the subject as a combination problem, where the scores obtained by each mono-modal system must be normalized before the fusion module (**Jain,2005**). While the second approach treats the problem as a classification problem (**Bolle,2004**). Jain et al. (**Jain,2005**) have shown that the combination approaches are more efficient than the classification methods (**Jain,2005**) (**Ross,2003a**).

The combination methods and the classification methods have advantages and disadvantages depending on the complexity, the parameters to be optimized, or the need for the training data. Therefore, the choice of the appropriate method will depend on the application according to the compromise between the simplicity, the performance, the comfort, and the amount of the available training data.

In this work, an integration technique, combining two approaches, namely combination, and classification, is proposed. The two approaches will be presented and detailed hereinafter.

5.3.2.6.1.1 Combination Approach

In the combination approach, the mono-modal scores are combined to form a single score which is then used to make the final decision. But before this step, the scores must be first converted into a common area by the normalization methods.

There are several methods such as:

Kittler et al. (Kittler,1998) combined the scores obtained by the different systems using: the sum rule, the product rule, the maximum rule, the minimum rule, and the median rule.

In (**Kwak,2004**), *Kwak et al.* realize the integration by the fuzzy of Choquet for the face recognition.

Rasheed et al. (Rasheed,2008) combined the scores of multi-classifiers for the decomposition of an electromyographic (EMG) signal by using the integral of Sugeno fuzzy.

Chia et al. (Chia,2009) combined the scores of two systems which are based on the face authentication and the voice authentication by using a hybrid method of calculation of the minimum, the maximum, or the sum.

Li et al. (Li,2009) combined the scores by using the weighted sum.

Shukla et al. (Shukla,2010) used the combination of fuzzy logic based on the integral of Sugeno and Choquet.

There are other combination methods in the literature. In our work, we use the five combination rules which are:

- The *Sum rule*.
- The *Product rule*.
- The *Min rule*.
- The *Max rule*.
- The *Mean rule*.

5.3.2.6.1.2 Classification Approach

There are several classifiers were used to classify the scores in order to get the final decision.

Wang et al. (Wang,2003) used the fisher discriminate analysis or a classifier neural network combined with a radial basis function (RBFNN) for the classification of scores of the

face recognition and the iris recognition.

Verlinde et al. (Verlinde,1999) used three classifiers which are: the K-Nearest Neighbor algorithm “k-NN”, the decision tree, and a classifier based on a model logistic regression. These classifiers are used to combine the scores of the face recognition with the speech recognition.

Chatzis et al. (Chatzis,1999) used the “fuzzy k-means” with “fuzzy vector quantization” coupled with a median RBF neural network classifier in order to combine the scores of the face recognition with the voice recognition.

Sanderson et al. (Sanderson,2002) used the support vectors machine (SVM) to fuse the scores of the face recognition with the speech recognition.

Among the various classification methods, there is a simple method (*Chikhaoui,2013*) which determines the optimal separating hyper-plane and the maximal margin. This method is interpreted geometrically the norm of a linear mapping. The maximization of a concave quadratic problem is the resulting model of this algorithm (*Chikhaoui,2013*). Then, this quadratic program is resolved by the projection method (*Chikhaoui,2010*). Their important goal is to find the optimal separating hyper-plane and the maximal margin.

5.3.2.6.2 The Proposed Fusion Approach

In our work, the both approaches described above (the combination approach and the classification approach) are used to combine the scores obtained by the monomodal biometric systems. In the combination methods, the combined scores are compared with a threshold to take the final decision, but in our approach, we have considered the problem as a classification problem. Therefore, the combined scores are used as inputs of the classification method *Chikhaoui and Mokhtari (Chikhaoui,2013)* which will be detailed in the next step.

So, we use the five rules (*Sum, Product, Min, Max, and Mean*) to form a single score which isn't compared with a threshold to take the final decision, but it considered as a classification problem.

We suppose that: (S: the final score, S_i : the available scores for $i=1\dots N$ from N systems)

- Sum rule:

$$S = \sum_{i=1}^N S_i \quad (16)$$

- Product rule:

$$S = \prod_{i=1}^N S_i \quad (17)$$

- Min rule:

$$S = \text{Min}(S_i) \quad (18)$$

- Max rule:

$$S = \text{Max}(S_i) \quad (19)$$

- Mean rule:

$$S = \text{Mean}(S_i) \quad (20)$$

Then, the combined scores are classified by the classification method (**Chikhaoui,2013**) which is a separable classification method. This method is based on the supports vector machines (SVM). It is a simple method. Its goal is to determine the optimal separating hyper-plane and the maximal margin. However, the hyper-plane must separate two classes of examples in order to obtain a maximal distance between the both classes. This method constructed differently the optimal hyper-plane and the maximum margin compared to the SVM (**Chikhaoui,2013**). The result of the SVM modeling is a maximization of a concave quadratic program. This concave programming program is solved by the projection method (**Chikhaoui,2010**). Here in briefly, the algorithm of the classification method *Chikhaoui* and *Mokhtari* (**Chikhaoui,2013**) used in this work:

- Suppose that the separating hyper plane with maximum margin be written as:

$$ay + b = 0 \quad (21)$$

Let $Y_+ = \{y : ay + b \geq 1\}$ and $Y_- = \{y : ay + b \leq -1\}$.

Note y_+ an element of Y_+ and y_- an element of Y_- .

- Calculate distances

$$\inf_{\substack{y_+ \in Y_+ \\ y_- \in Y_-}} \|y_+ - y_-\| = \|\bar{y}_+ - \bar{y}_-\| \quad (22)$$

\bar{y}_+ and \bar{y}_- are supports vectors.

- Separation of \bar{y}_+ and \bar{y}_- by the separating hyper-plane of wide margin:

\bar{y}_+ and \bar{y}_- are used to find the parameter of the separating hyper-plane of wide margin (a and b)

$$a = (\bar{y}_+ - \bar{y}_-) \quad (23)$$

$$\begin{cases} ay_+ + b = 1 \\ ay_- + b = -1 \end{cases} \Rightarrow b = -\frac{1}{2}a(\bar{y}_+ + \bar{y}_-) \Rightarrow b = -\frac{1}{2}(\bar{y}_+ - \bar{y}_-)(\bar{y}_+ + \bar{y}_-) = \frac{\|\bar{y}_-\|^2 - \|\bar{y}_+\|^2}{2} \quad (24)$$

- Let:

$$\tilde{Y}_+ = \left\{ y_+ \in Y_+ : (\bar{y}_+ - \bar{y}_-)y_+ + \frac{\|\bar{y}_-\|^2 - \|\bar{y}_+\|^2}{2} \leq 1 \right\} \quad (25)$$

$$\tilde{Y}_- = \left\{ y_- \in Y_- : (\bar{y}_+ - \bar{y}_-)y_- + \frac{\|\bar{y}_-\|^2 - \|\bar{y}_+\|^2}{2} \geq -1 \right\} \quad (26)$$

Note that: $\bar{y}_+ \in \tilde{Y}_+$, $\bar{y}_- \in \tilde{Y}_-$.

- If $\begin{cases} \tilde{Y}_+ = \{\bar{y}_+\} \\ \tilde{Y}_- = \{\bar{y}_-\} \end{cases} \Rightarrow \text{stop}$

(H) is the separating hyper-plane of the wide margin.

- Else,

$$\triangleright \quad \text{If } \text{card}(\tilde{Y}_+) \geq \text{card}(\tilde{Y}_-) \Rightarrow \begin{cases} \text{Max}\{-\|a\|^2\} \\ a(-y_+ + \bar{y}_+) \leq 0 \\ a(y_- - \bar{y}_+) \leq 1 \\ y_+ \in \tilde{Y}_+ \\ y_- \in \tilde{Y}_- \end{cases} \quad (28)$$

$$\triangleright \quad \text{If } \text{card}(\tilde{Y}_+) < \text{card}(\tilde{Y}_-) \Rightarrow \begin{cases} \text{Max}\{-\|a\|^2\} \\ a(y_- - \bar{y}_-) \leq 0 \\ a(\bar{y}_- - y_+) \leq -1 \end{cases} \quad (29)$$

- The result of the SVM modeling is a maximization of a concave quadratic program. This concave programming program is solved by the projection method (**Chikhaoui,2010**).

The projection of the point $0 \in R^n$ on the hyper-plane $a(y_- - \bar{y}_+) = -1$ is given by:

$$P_a(y_- - \bar{y}_+) = -1(0) = 0 - \frac{1}{\|(y_- - \bar{y}_+)\|^2}(y_- - \bar{y}_+) \quad (30)$$

For more details see (**Chikhaoui,2010**).

5.3.2.7 DECISION MODULE

The last module of any biometric system is the decision module. In the decision module, the matching scores are used to verify the user's identity; the authentication decision at this module is based on the similarity or the dissimilarity degree between features. This module is a suite of the fusion module according to the output of the classifier the decision can be taken. The decision function about a point belonging to one of two classes is given by:

$$G(z) = \text{sign}(az + b) \quad (31)$$

Where (z : is an unknown point to classify, and (a and b) are the parameters which are determined by the classification method (**Chikhaoui,2013**)).

If the output of the decision function is positive then the identity proclaimed is accepted. Otherwise, if the output is negative then the claimed identity is rejected.

5.5. CONCLUSION

In this chapter, we have presented the process of our multi-biometrics technique, and we have detailed the different steps of the proposed approach which is used for the integration of the face with the both irises.

In the next chapter, we will present the experimental results of our multi-biometrics system.

CHAPTER VI: EXPERIMENTAL RESULTS

This chapter is the last chapter which is dedicated to the implementation. It presents the experimental results of our multi-biometrics system and their discussions. Also, it compares the results obtained by this work with other results that exist in the literature. The plan of this chapter is articulated as follows:

Summary:

- 1.1 Introduction
 - 1.2 Experimental Results
 - 1.2.1 Multi-Units System (the Left and the Right Irises)
 - 1.2.1.1 Description of Databases
 - 1.2.1.2 Results and Discussions
 - 1.2.2 Multi-Biometrics System (the Face, the Left, and the Right Irises)
 - 1.2.2.1 Description of Database
 - 1.2.2.2 Results and Discussions
 - 1.2.2.2.1 Variations Results
 - 1.2.2.2.2 Settings Results
 - 1.3 Comparison
 - 1.4 Conclusion
-

6.1 INTRODUCTION

After the discussion of the theoretical aspect in the previous chapters, we now turn to the design and the implementation of our application. We are detailed the different steps of our proposed approach in the previous chapter. However, this chapter will present the results obtained in our work.

First, we will present the experimental results obtained by our multi-biometrics system by dividing these results into two sections, the first will present the results obtained by the multi-units system, and the second will dedicate to the multi-biometrics system. However, these experimental results are accompanied by the description of the database used for the test, also the discussions of these results. In addition, we will compare the results obtained with other results that exist in the literature.

6.2 EXPERIMENTAL RESULTS

The experimental results have been achieved on a PC running windows 8.1 with a processor Intel(R) Core(TM) i7-4510U CPU @ 2.00 GHz 2.60 GHz, and the implementation were performed under MATLAB R2013a.

In this section, we will present the results obtained by the both systems: the multi-units and the multi-biometrics systems. The first system is based on the fusion of the both units of the iris modality (the right and the left irises), while the second is based on the integration of the face with the both units of the iris modality.

6.2.1 MULTI-UNITS SYSTEM (THE LEFT AND THE RIGHT IRISES)

6.2.1.1 DESCRIPTION OF DATABASES

In this section, we will describe the databases used for the evaluation of our multi-units system which integrates the left and the right irises.

Therefore, we must use databases that contains N individual having the both units of the iris modality (the left and the right irises).

In this work, we choose to use four databases which are: the CASIA 4 (interval) (**Web71**), the SDUMLA-HMT (**Web77**), the MMU1, and the MMU2 (**Web76**). The characteristics of the both databases CASIA and MMU are detailed in the chapter 4 exactly in section 4.4.5. We will present the characteristics of the SDUMLA-HMT database later.

The table 6.1 describes some characteristics of the databases used for the evaluation of our multi-units system.

Databases	CASIA4-Interval	SDUMLA-HMT	MMU1	MMU2
Example				
Wave length	Near Infrared	Near Infrared	Near Infrared	Near Infrared
Varying distance	No	No	No	No
Acquisition Device	CASIA close-up iris camera	Capture device developed by University of Science and Technology of China.	LG EOU 2200.	Panasonic B - ET100US.
Resolution	320X280	768X576	320X240	320X238
Nb. Subject	249	106	45	100
Train	5	2	2	2
Test	2	3	3	3
Total	4980	1060	450	1000

Table 6. 1: Description of the databases used for the evaluation of the multi-units biometric system.

6.2.1.2 RESULTS AND DISCUSSIONS

There are several indicators to evaluate the biometric authentication systems. In this work, we are attracted to the following indicators:

- FAR is the *False Acceptance Rate*. This rate represents the impostors who can be accepted by error.
- FRR is the *False Rejection Rate*. This rate represents the customers who can be rejected wrongly.
- EER is the *Equal Error Rate*. This rate gives the point where the FAR and the FRR are identical.
- ROC is the *Receiver Operating Curve*. It is the graph which plotted the FRR against the FAR, the FRR (in the X-axis) versus the FAR (in the Y-axis). This curve is used to compare tests.
- AUROCC describes the *Area Under the ROC Curve*. It has a range of 0.5 to 1, so a perfect test is indicated by an area of 1, and an area of 0.5 corresponds to a worthless test. In the tables we use the term AUC instead of AUROCC. The interpretation of the AUROCC is the following:

- Perfect prediction: 1.0
- Excellent prediction: [0.9,0.99]
- Good prediction: [0.8,0.89]
- Mediocre prediction: [0.7,0.79]
- Poor prediction: [0.51,0.69]
- Random prediction: 0.5.

For the evaluation of the performance of our approach, we used: the equal error rate (EER), the ROC curve, and the AUROC.

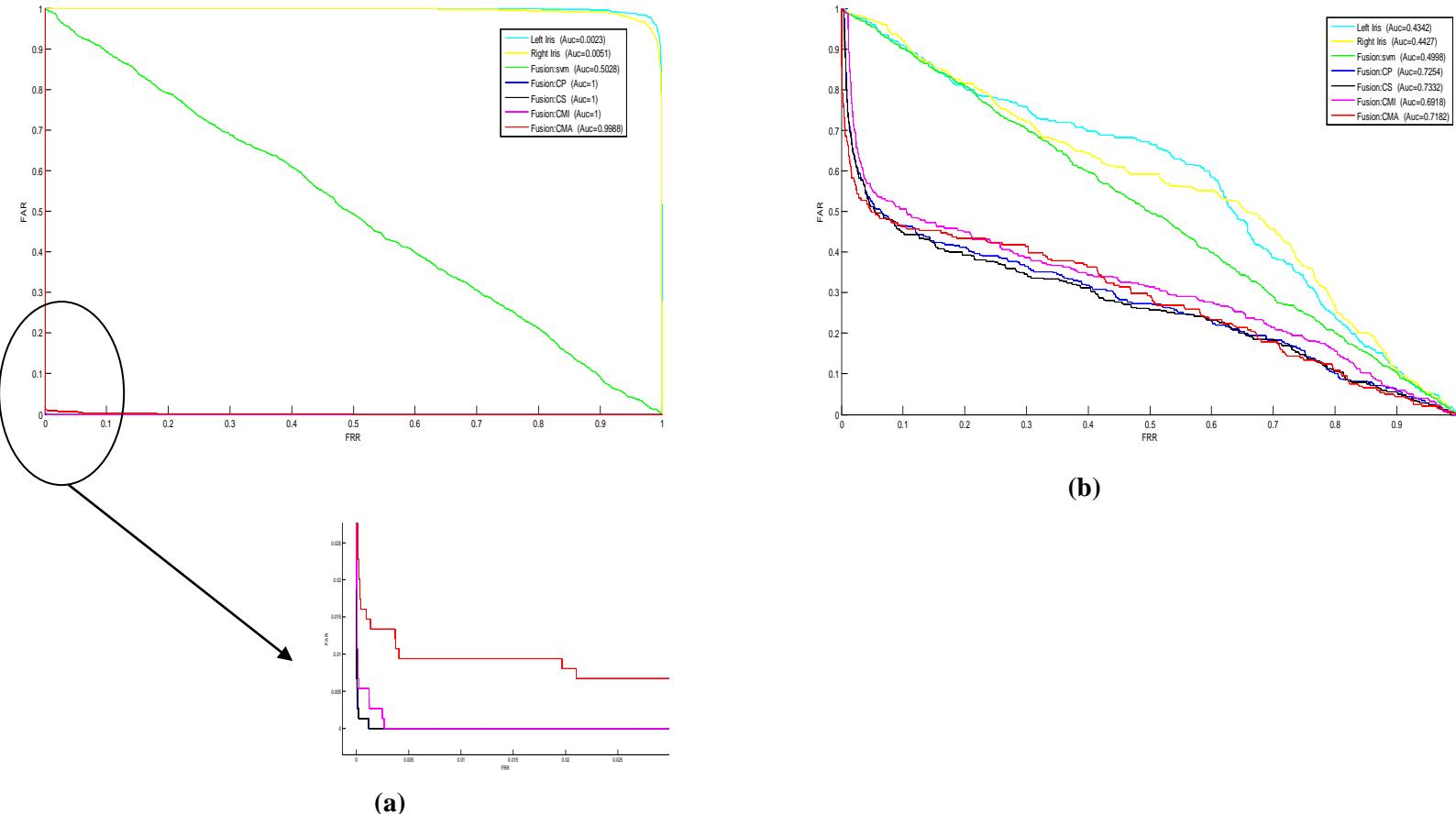
Figure 6.1 presents four curves. The first curve shows the ROC curve for the CASIAV4 (Interval) database. Then, the second illustrates the ROC curve for the SDUMLA-HMT database, while the two last curves are about the MMU1 and the MMU2 databases. However, each curve plots the false acceptance rate FAR in the Y-axis versus the false rejection rate FRR in the X-axis.

Each curve illustrates the performance of the both unimodal biometric systems, the right iris authentication and the left iris authentication system which are tested separately with the SVM classifier.

In addition, each curve shows the performance of the SVM method that is used for the fusion. Also, it illustrates the performance of the four proposed fusion methods which consist to use the combination rules integrated with the classification method (**Chikhaoui,2013**) for the fusion. Therefore, we use the four combination rules (*Product*, *Sum*, *Min*, and *Max*) integrated with the classification method that we talked about earlier. The four proposed methods are namely:

- **CP** is the *product rule* integrated to the classification method *Chikhaoui and Mokhtari (Chikhaoui,2013)*.
- **CS** is the *sum rule* coupled with the classification method (**Chikhaoui,2013**).
- **CMI** is the *min rule* combined with the classification method (**Chikhaoui,2013**).
- **CMA** is the *max rule* added to the classification method (**Chikhaoui,2013**).

Finally, we can conclude that the results illustrated by the figure 6.1 confirm the hypothesis of the superiority of the multi-biometrics especially the multi-units compared to the mono-modal biometric. Also, it illustrates that the use of the four fusion approaches (CP, CS, CMI, and CMA) give results better than the SVM method for all the databases used (**Zoubida,2017b**).



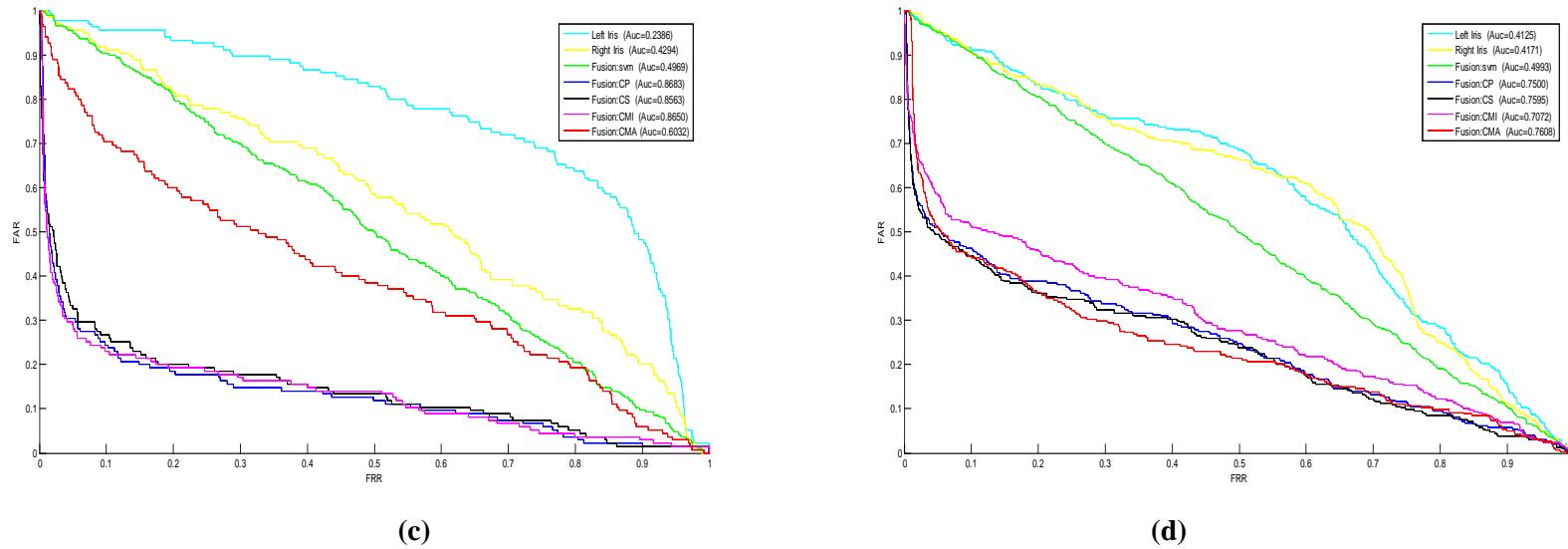


Figure 6.1: ROC plot showing the performance of: the left iris authentication, the right iris authentication, the fusion by (SVM, CP, CS, CMI, and CMA) on (a): CASIA Database; (b): SDUMLA-HMT Database; (c): MMU1 Database; (d): MMU2 Database. Figure taken from ([Zoubida,2017b](#)).

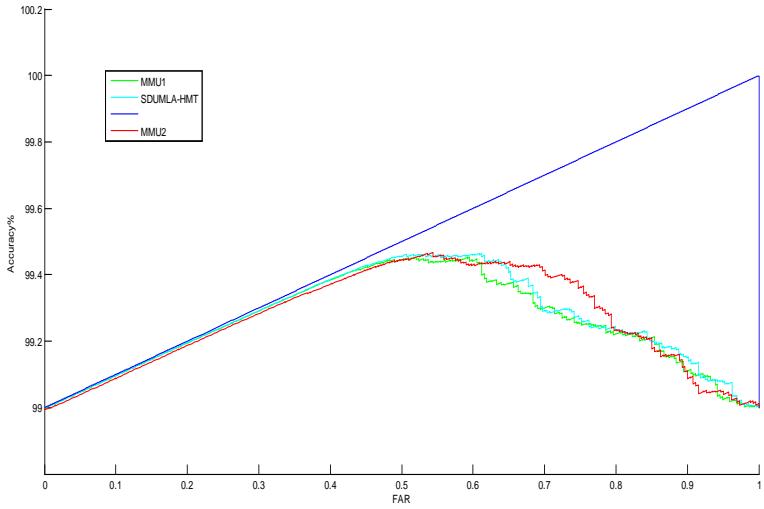
The AUROCC (area under the ROC curve) is one of the criteria that used for evaluating the performance of classification. A perfect test is indicated by an area of 1, and an area of 0.5 corresponds to a worthless test. We can obtain from the ROC curve the AUROCC (area under the ROC curve), and the Equal Error Rate (EER) at which the FAR is equal to the FRR.

Table 6.2 illustrates the results of the performance evaluation. According to the experiments results obtained, we find that the five fusion methods (SVM, CP, CS, CMA, CMI) give an EER and an AUROCC better than the both unimodal systems (the left iris and the right iris authentication systems). Also, the results demonstrate that the four last approaches of fusion (CP, CS, CMA, CMI) are better than the use of the SVM for the fusion for all the databases. According to the EER and the AUROCC obtained, the CS approach (the sum rule coupled with the classification method) is the best for the CASIA and the SDUMLA-HMT databases. The CP approach (the product rule combined with the classification method) is preferable for the MMU1 database, and the CMA approach (the max rule integrated to the classification method) gives the best result for the last database.

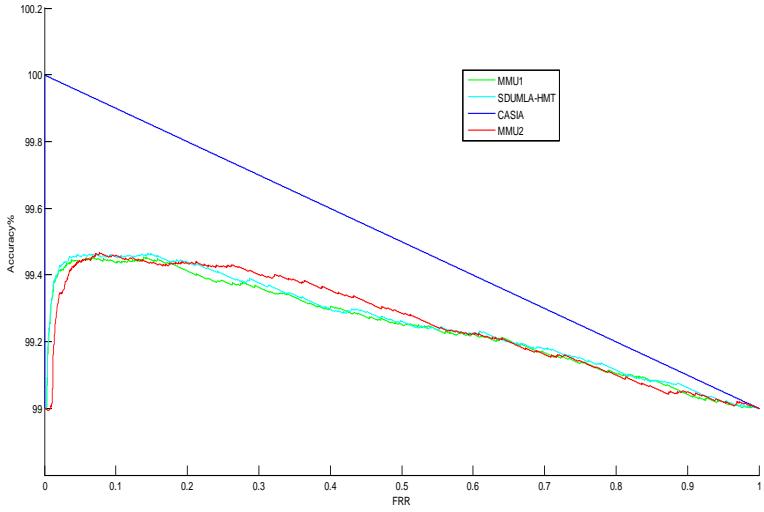
		CASIA		SDUMLA		MMU1		MMU2	
		EER	AUC	EER	AUC	EER	AUC	EER	AUC
Unimodal	Left iris	0.9786	0.0023	0.5975	0.4342	0.7111	0.2386	0.5885	0.4125
	Right iris	0.967	0.0051	0.5597	0.4427	0.5471	0.4294	0.6065	0.4171
Fusion	SVM	0.496	0.5028	0.4992	0.4998	0.5	0.4969	0.4983	0.4993
	CP Approach	0.00117	1	0.3489	0.7254	0.1926	0.8683	0.3281	0.7500
	CS Approach	0.00113	1	0.3333	0.7332	0.2	0.8563	0.3163	0.7595
	CMI Approach	0.002467	1	0.363	0.6918	0.1926	0.8650	0.3657	0.7072
	CMA Approach	0.009371	0.9988	0.377	0.7182	0.4222	0.6032	0.2989	0.7608

Table 6. 2: Evaluation of the performance of the multi-units system using EER and AUROCC criteria.
Table is taken from (**Zoubida,2017b**).

Figure 6. 2 shows the variation of the AUROCC of the best approach for each database according to the two rates the FAR or the FRR.



(a)



(b)

Figure 6. 2: Evaluation using the AUROCC. (a): FAR vs. AUROCC. (b): FRR vs. AUROCC;
Figure taken from ([Zoubida,2017b](#)).

6.2.2 MULTI-BIOMETRICS SYSTEM (THE FACE, THE LEFT, AND THE RIGHT IRISES)

6.2.2.1 DESCRIPTION OF DATABASE

The non chimerical database (SDUMLA-HMT) is used to test our integrated biometric system which is based on the fusion of the face modality with the both units of the iris modality. This database contains the face and the both irises (the left and the right irises).

The SDUMLA-HMT was collected by *Shandong University, Jinan, China* in 2010. This database is characterized by: ([Yin,2011](#))

- The total number of the subjects in this database is 106 subjects, their age is between 17 and 31, and it contains 61 males and 45 females.

- It includes 5 sub-databases which are:
 - The face database.
 - The iris database.
 - The fingerprint database.
 - The finger vein database.
 - The gait database.

However, all the biometric modalities with the same person are captured from the same subject in the five sub-databases (**Yin,2011**). In our work, we use the two sub-databases: the face database and the iris database, which will be detailed herein after:

❖ **Face database:** There are 7 ordinary digital cameras which are used to capture the face modality in this sub-database. There are 4 variations in this database which are: (**Yin,2011**)

- 3 types of poses:
 - Look upward.
 - Forward.
 - Downward.
- 4 types of expressions:
 - Smile.
 - Frown.
 - Surprise.
 - Close eyes.
- 2 types of accessories:
 - Glasses.
 - Hat.
- 3 types of illuminations:
 - Illumination one.
 - Illumination two.
 - Illumination three.

Totally, the face database contains 8904 images ($7 \times (3+4+2+3) \times 106$), and every face image is saved in “BMP” format with 640×480 pixels in size. The total size of the face database is 8.8 G Bytes (**Yin,2011**).

Figure 6.3 illustrates the different variations of the first subject of the SDUMLA-HMT face database.

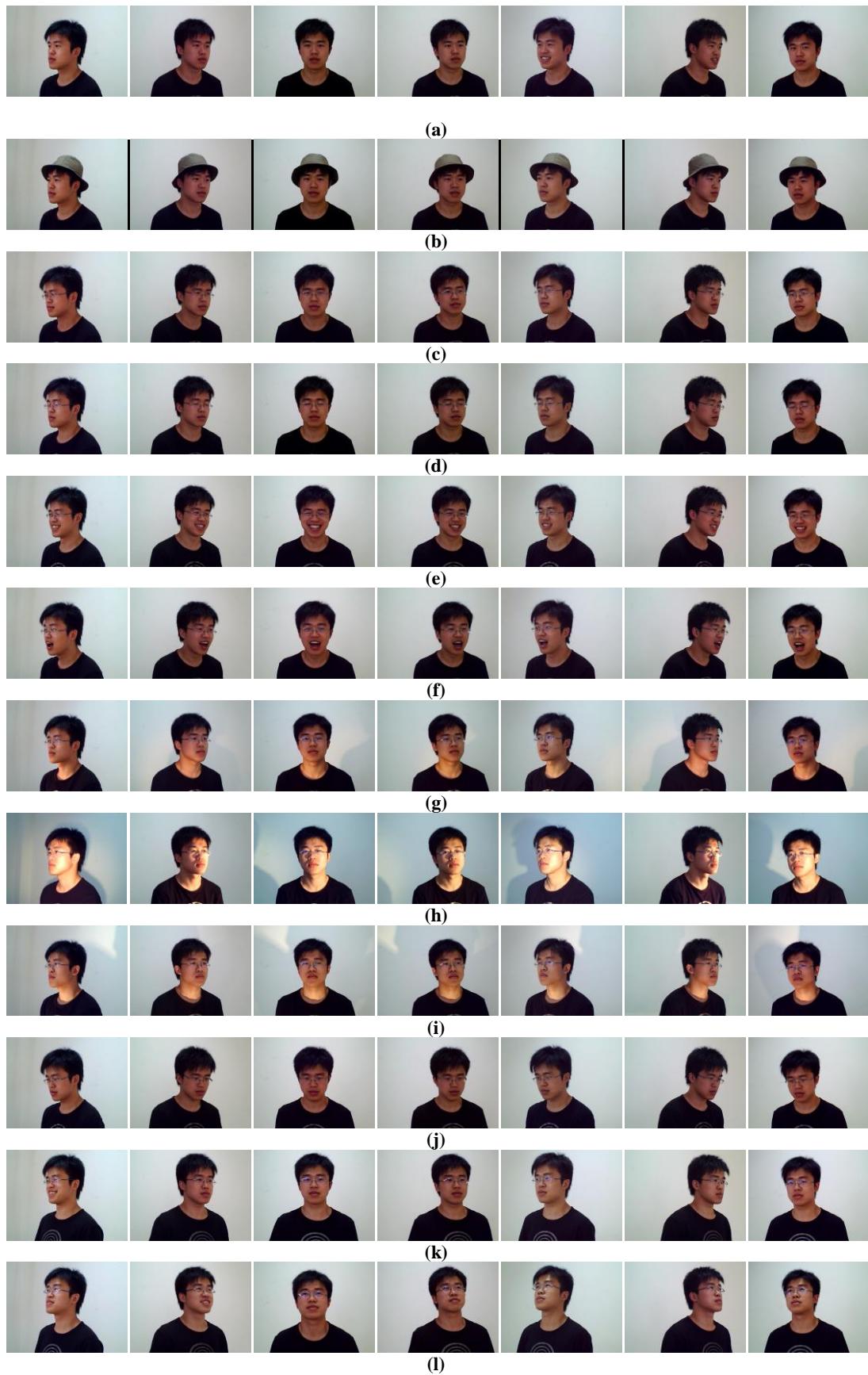


Figure 6.3: The first subject of the face SDUMLA-HMT database with the different variations.(a):accessory eye glass; (b): accessory hat; (c):expression frown; (d): expression pejam; (e): expression smile; (f): expression surprise; (g): illumination one; (h): illumination three; (i): illumination two; (j): pose down; (k): pose normal; (l): pose up.

❖ **Iris database:** The iris database contains 1060 images ($2 \times 5 \times 106$). Every subject provided 5 images for each eye, and every iris image is saved in “BMP” format. The size of each image is 768×576 pixels, and the total size of the iris database is about 0.5 G Bytes (Yin,2011).

Figure 6.4 shows the both units of the iris modality (the left and the right irises) of the first subject from the SDUMLA-HMT iris database.

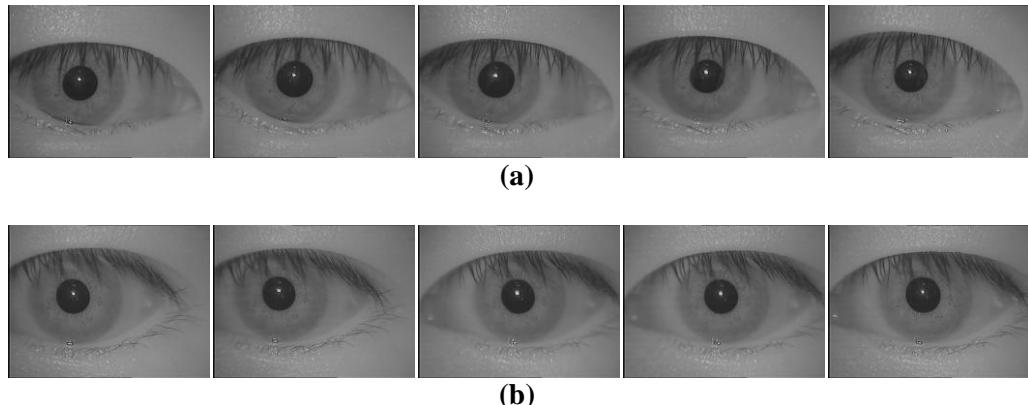


Figure 6. 4: The first subject of the iris SDUMLA-HMT database. (a): Left irises; (b):Right irises.

6.2.2.2 RESULTS AND DISCUSSIONS

In this section, we will present two types of results: The first is based on the different variations of the face modality in the SDUMLA-HMT face database including (the poses, the facial expressions, the illuminations, and the accessories), while the second is based on the different settings of the camera which captures the face modality in the SDUMLA-HMT database. Therefore, we named the first type of results by “*variations results*”, and the second is called “*settings results*”.

6.2.2.2.1 Variations Results

Our integrated system is based on the fusion of the face with the both units of the iris modality. Therefore, we must use a database of N individual having the image of the face and the both instances of the iris modality (the left and the right irises) in order to test the performance of our multi-biometrics system.

In this work, we choose to use the SDUMLA-HMT database detailed above. This database contains the biometric traits with the same person captured from the same subject.

Totally, this database contains 106 subjects, including 7 images of face for each subject, with 5 images for each of his eyes. For each subject and for each modality, the three images are randomly sampled as train samples, and the rest are used for the test.

Table 6.3 illustrates some characteristics of the database used for the test of our multi-biometrics system which is based on the fusion of the face with the both irises.

Modalities	Nb. subject	Nb. total	Size	Format	Nb. Train	Nb. Test
Face	106	8904 $(7*(3+4+2+3)*106)$ 7 cameras. 3 poses. 4 expressions. 2 accessories. 3 illuminations.	640*480	Bmp	3	4
Iris	106	1060 $(2*5*106)$ 5 right. 5 left.	768*756	Bmp	3	2

Table 6. 3: Description of some characteristics of the database used for the test of our multi-biometrics system.

The performance of our approach is evaluated using the following indicators: the equal error rate (EER), the ROC curve, and the AUROCC.

Figure 6.5 shows the ROC (*Receiver Operating Characteristic*) curve for each sub-database extracted from the SDUMLA-HMT database. However, we divide the SDUMLA-HMT database into 12 sub-databases. So each session in the face database (Accessory Eye-Glass, Accessory Hat, Expression Frown, Expression close eyes, Expression Smile, Expression Surprise, Illumination One, Illumination Three, Illumination Two, Pose Down, Pose Normal, Pose Up) was combined with the iris database to form the databases named (BD1, BD2, BD3, BD4, BD5, BD6, BD7, BD8, BD9, BD10, BD11, BD12) respectively. (**Zoubida,2017a**)

- **BD1:** The accessory eye-glass + The iris database.
- **BD2:** The accessory hat + The iris database.
- **BD3:** The expression frown + The iris database.
- **BD4:** The expression close eyes + The iris database.
- **BD5:** The expression smile + The iris database.
- **BD6:** The expression surprise + The iris database.
- **BD7:** The illumination one + The iris database.
- **BD8:** The illumination three + The iris database.
- **BD9:** The illumination two + The iris database.
- **BD10:** The pose down + The iris database.

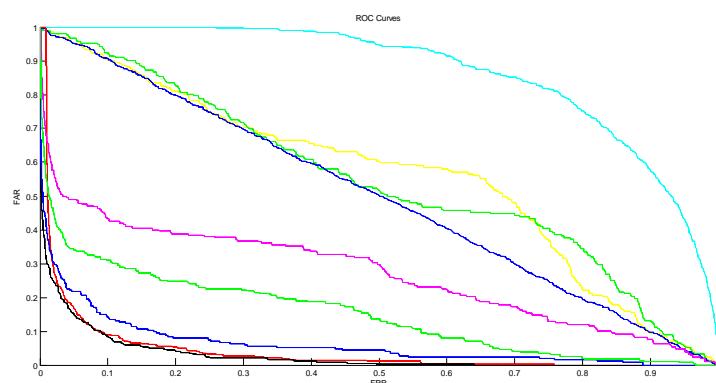
- **BD11:** The pose normal + The iris database.
- **BD12:** The pose up + The iris database.

In the figure 6.5 each curve plots the FAR (*the false acceptance rate*) in the Y-axis versus the FRR (*the false rejection rate*) in the X-axis for each sub databases (BD1, BD2, BD3, BD4, BD5, BD6, BD7, BD8, BD9, BD10, BD11, BD12). In addition, each curve shows the performance of the three mono-modal biometric systems: the face authentication, the left iris authentication, and the right iris authentication. These mono-modal systems are tested separately with the SVM classifier. Also, each curve illustrates the influence of each fusion method on the performance of the proposed approach. However, the first method used for the fusion is the SVM. Our contribution is the use of the combination rules integrated with the classification method (**Chikhaoui,2013**) for the fusion. Therefore, we use the five combination rules (*Product, Somme, Min, Max, and Mean*) coupled with the classification method (**Chikhaoui,2013**) to form the following approaches:(**Zoubida,2017a**)

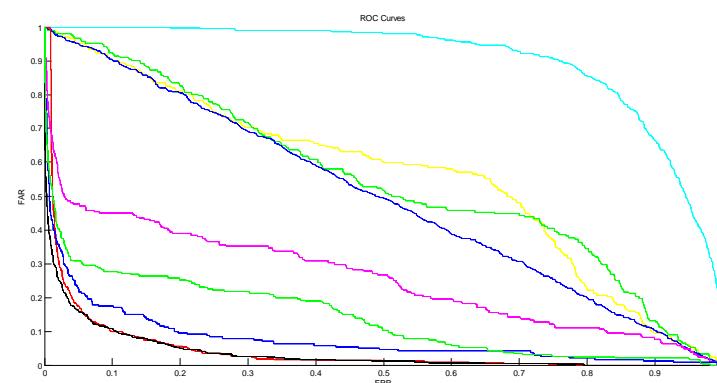
- **CP** is the *product rule* integrated with the classification method *Chikhaoui and Mokhtari* (**Chikhaoui,2013**).
- **CS** is the *sum rule* coupled with the classification method (**Chikhaoui,2013**).
- **CMI** is the *min rule* combined with the classification method (**Chikhaoui,2013**).
- **CMA** is the *max rule* connected to the classification method (**Chikhaoui,2013**).
- **CME** is the *mean rule* added to the classification method (**Chikhaoui,2013**).

By analyzing the curves of the figure 6.5, we can conclude that the hypothesis of the superiority of the multi-biometrics system compared with the mono-modal biometrics is confirmed. In addition, the figure confirms that the iris modality is more performance than the face modality. Also, it validates that the five fusion approaches (CP, CS, CMI, CMA, and CME) which present our contribution give results better than the SVM method used for the fusion for all the sub databases.

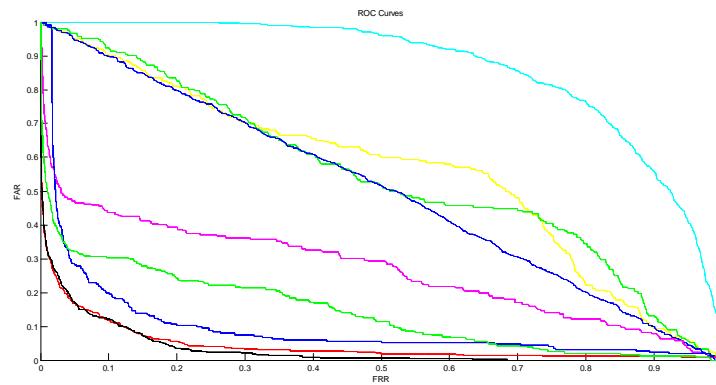
The execution time of each approach (CP, CS, CMI, CMA, and CME) is between 70 sec and 150 sec.



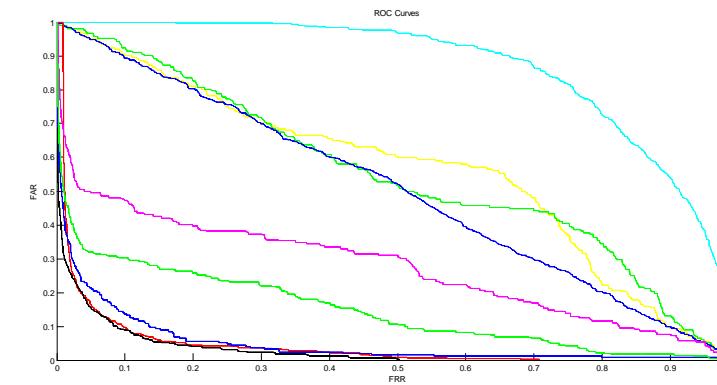
(a)

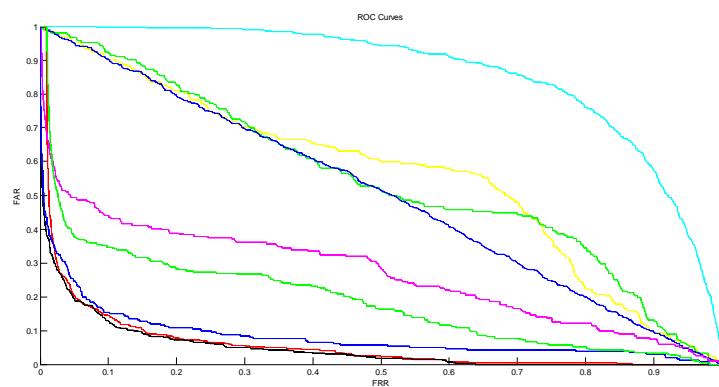


(b)

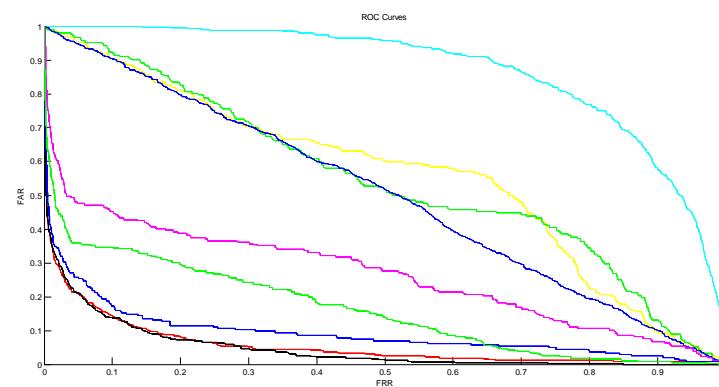


(c)

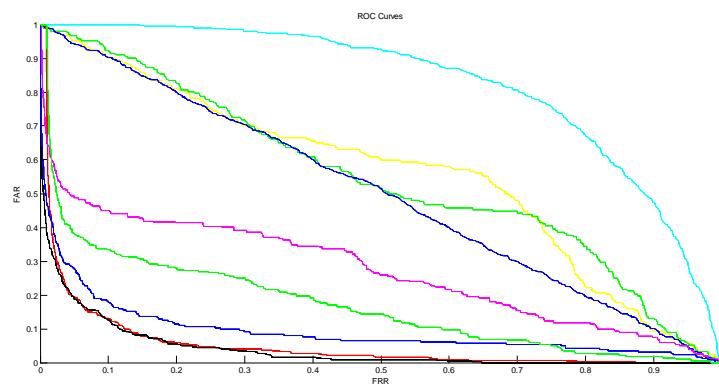
(d)



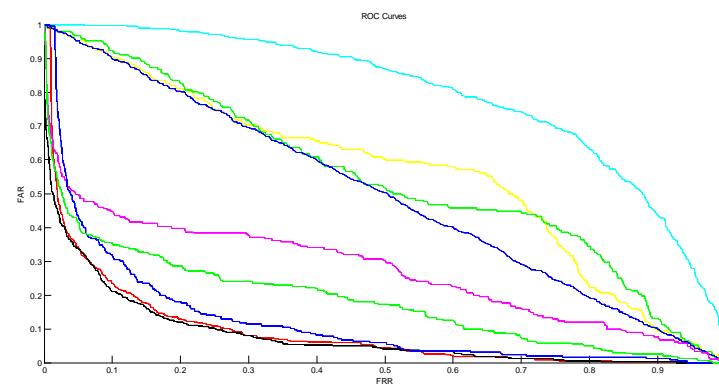
(e)



(f)



(g)

(h)

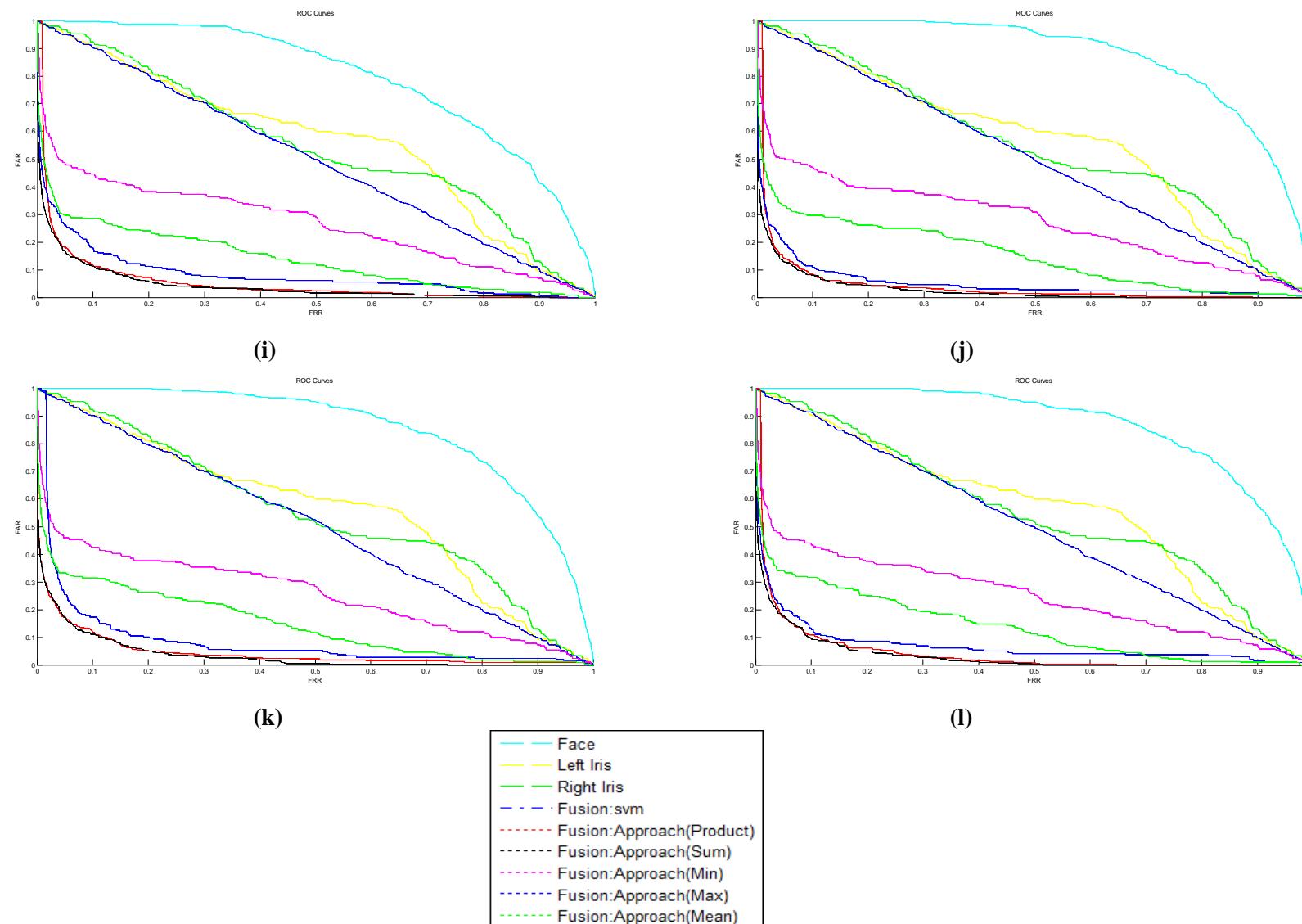


Figure 6.5. ROC plot showing the performance of the authentication by using: the face, the left iris, and the right iris, the fusion by (SVM, CP, CS, CMI, CMA, and CME) on SDUMLA-HMT Database:(a):BD1, (b):BD2,(c):BD3, (d):BD4, (e):BD5, (f):BD6, (g):BD7, (h):BD8, (i):BD9, (j):BD10, (k):BD11, (l):BD12. Figure taken from (**Zoubida,2017a**).

The AUROCC is one of the criteria which can be used to evaluate the performance of classification. The perfect test is indicated by an area of 1, and an area of 0.5 means a worthless test. The both criteria of evaluation (the AUROCC and the EER) can be obtained from the ROC curve.

Table 6.4 presents the performance evaluation results.

		Face	Left iris	Right iris	SVM	CP	CS	CMI	CMA	CME	
Databases	BD1	AUC	0.1338	0.4398	0.4531	0.4999	0.9586	0.9700	0.7291	0.9380	0.8500
		EER	0.7827	0.5849	0.5071	0.5016	0.0946	0.0921	0.3558	0.1266	0.234
	BD2	AUC	0.0964	0.4398	0.4531	0.5021	0.9557	0.9631	0.7421	0.9237	0.8604
		EER	0.8284	0.5849	0.5071	0.4961	0.0991	0.1031	0.3384	0.1459	0.2316
	BD3	AUC	0.1381	0.4398	0.4531	0.4980	0.9573	0.9689	0.7269	0.9499	0.8548
		EER	0.7738	0.5849	0.5071	0.5079	0.0991	0.0927	0.3506	0.1199	0.2376
	BD4	AUC	0.1349	0.4398	0.4531	0.4958	0.9547	0.9659	0.7323	0.9041	0.8587
		EER	0.7807	0.5849	0.5071	0.5072	0.1108	0.1108	0.3519	0.1394	0.2322
	BD5	AUC	0.1383	0.4398	0.4531	0.4970	0.9408	0.9517	0.7308	0.9173	0.8128
		EER	0.7872	0.5849	0.5071	0.5079	0.118	0.111	0.349	0.1346	0.2698
	BD6	AUC	0.1308	0.4398	0.4531	0.4973	0.9443	0.9524	0.7331	0.9079	0.8394
		EER	0.7854	0.5849	0.5071	0.5081	0.1226	0.1227	0.3413	0.1434	0.2628
	BD7	AUC	0.1754	0.4398	0.4531	0.4990	0.9483	0.9593	0.7265	0.9078	0.8313
		EER	0.7524	0.5849	0.5071	0.5047	0.1156	0.1108	0.3639	0.1439	0.2624
	BD8	AUC	0.2076	0.4398	0.4531	0.5015	0.9110	0.9193	0.7272	0.8807	0.8196
		EER	0.7193	0.5849	0.5071	0.5027	0.1604	0.1544	0.3571	0.1875	0.2564
	BD9	AUC	0.2071	0.4398	0.4531	0.5017	0.9466	0.9565	0.7319	0.9175	0.8611
		EER	0.7058	0.5849	0.5071	0.4992	0.1108	0.1061	0.3522	0.1452	0.2242
	BD10	AUC	0.1322	0.4398	0.4531	0.5009	0.9590	0.9714	0.7211	0.9468	0.8477
		EER	0.7854	0.5849	0.5071	0.4989	0.0918	0.0873	0.3549	0.1055	0.25
	BD11	AUC	0.1473	0.4398	0.4531	0.4969	0.9545	0.9635	0.7396	0.9156	0.8537
		EER	0.7736	0.5849	0.5071	0.5118	0.1085	0.1061	0.3398	0.133	0.2448
	BD12	AUC	0.1342	0.4398	0.4531	0.5016	0.9555	0.9652	0.7460	0.9302	0.8617
		EER	0.7791	0.5849	0.5071	0.5	0.1061	0.0991	0.3317	0.1107	0.2396

Table 6.4: Evaluation of the performance of the multi-biometrics (variation) system using EER and AUROCC criteria. Table is taken from (**Zoubida,2017a**).

According to the experiments results obtained in the table 6.4, we can conclude that the iris modality is more performance than the face modality. Also, the results obtained confirm that the fusion gives an EER and an AUROCC better than the three mono-modal biometric systems based on (the face, the left iris, and the right iris). In addition, we find that the five last approaches of fusion that present our contribution give results better than the use of the SVM for the fusion. The CS approach and the CP approach give the best result according to the EER and the AUROCC obtained, then the Max approach, Mean approach, and Min approach respectively with this order.

The results related to the database BD10 are the best results obtained compared with the other databases (**Zoubida,2017a**).

In the literature, there are other means and indicators which are used to visualize the performance of an algorithm such as:

- **TP** is the True Positive (correctly identified).
- **FP** is the False Positive (incorrectly identified).
- **TN** is the True Negative (correctly rejected).
- **FN** is the False Negative (incorrectly rejected).
- **Precision or PPV** is the Positive Predictive Value.

$$\text{PPV} = \frac{\text{TP}}{\text{TP} + \text{FP}} \quad (32)$$

- **NPV** is the Negative Predictive Value.

$$\text{NPV} = \frac{\text{TN}}{\text{TN} + \text{FN}} \quad (33)$$

- **Sensitivity, recall, or TPR** is the True Positive Rate. It determines the proportion of positives that are correctly identified.

$$\text{TPR} = \frac{\text{TP}}{\text{TP} + \text{FN}} \quad (34)$$

- **Specificity or TNR** is the True Negative Rate. It determines the proportion of Negatives that are correctly identified.

$$\text{TNR} = \frac{\text{TN}}{\text{FP} + \text{TN}} \quad (35)$$

- **ACC** is the Accuracy or the recognition rate.

$$\text{ACC} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FN} + \text{TN} + \text{FP}} \quad (36)$$

- The error rate can be calculated from the ACC

$$\text{Error rate} = 1 - \text{ACC} \quad (37)$$

- The false acceptance rate is :

$$\text{FAR} = \frac{\text{FP}}{\text{TP}} \quad (38)$$

- The false rejection rate is:

$$\text{FRR} = \frac{\text{FN}}{\text{TN}} \quad (39)$$

According to the results illustrated in the table 6.4, the CS approach gives the best results on all the sub-databases (according to the AUROCC obtained). Therefore, the table 6.5 present the performance evaluation of the CS approach using (FP, FN, FAR, FRR, Acc, and error rate) for each sub-database.

Database	FP	FN	FAR %	FRR %	Error rate%	Acc %
BD1	2	379	0.47	0.85	0.85	99.15
BD2	0	378	0	0.84	0.85	99.15
BD3	4	362	0.94	0.81	0.82	99.18
BD4	4	354	0.94	0.79	0.8	99.20
BD5	2	371	0.47	0.83	0.83	99.17
BD6	1	371	0.23	0.83	0.83	99.17
BD7	6	371	1.41	0.83	0.84	99.16
BD8	3	400	0.70	0.89	0.9	99.10
BD9	3	359	0.70	0.80	0.81	99.19
BD10	1	357	0.23	0.80	0.8	99.20
BD11	3	364	0.70	0.81	0.82	99.18
BD12	4	359	0.94	0.80	0.81	99.19

Table 6. 5: Evaluation of the performance of the CS approach (variation result) using FAR, FRR, Accuracy. and error rate.

The results of the previous table demonstrate that the maximum accuracy is the accuracy obtained on the sub-database BD10 (Acc=99.20%), and the minimum accuracy is about BD8 (Acc=99.10%). The average accuracy between the 12 sub-databases is: 99.17%.

In the literature, there are other means which are used to visualize the performance of an algorithm such as the confusion matrix. It is also called contingency table or error matrix. It is a table with two rows and two columns that reports the number of FP (the false positives), FN (the false negatives), TP (the true positives), and TN (the true negatives). It is possible to calculate several indicators summarizing the confusion matrix.

According to the results illustrated by the table 6.4 and the table 6.5, the CS approach gives the best results on the sub-database BD10. Therefore, the table 6.6 presents the confusion matrix and some indicators that visualize the performance of the CS approach on the database BD10.

	Condition positive	Condition negative	
Test outcome positive	TP=423	FP=1	PPV=99.76%
Test outcome negative	FN=357	TN=44163	NPV=99.19%
ACC=99.20%	TPR=54.23%	TNR=99.99%	

Table 6. 6: Confusion Matrix (CS Approach on the database BD10).

6.2.2.2.2 Settings Results

The results described in the previous section present the result obtained on the 12 sub-databases according to the four variations including the poses, the facial expressions, the illuminations, and the accessories. However, the results illustrated in this section are obtained on the 7 sub-databases according to the camera settings.

Therefore, we divide the SDUMLA-HMT database into 7 sub-databases. There are 7 ordinary digital cameras that are used symmetrically to capture the both sides of the face as shown in figure6.6. *Yin et al.* mentioned that “all the cameras are fixed in a circle centered at the subject with radius 50 cm and angle interval 22.5°. And the subject was asked to sit towards the center camera C4. The height of the cameras is set to be 110 cm by tripods. All the 7 cameras work simultaneously” (**Yin,2011**).

So, we obtain 7 sub-databases of the face modality according to the camera settings. These sub-databases were combined with the iris database to form the databases named: C1, C2, C3, C4, C5, C6, C7. Totally, each sub-database contains 106 subjects, including 12 images of face for each subject with 5 images for each of his eyes. For each subject and for each modality, the three images are randomly sampled as train samples, and the rest are used for the test. An example of the face modality captured according to the camera settings (the subject number 103 of the face SDUMLA-HMT database) is presented in the figure 6.7.

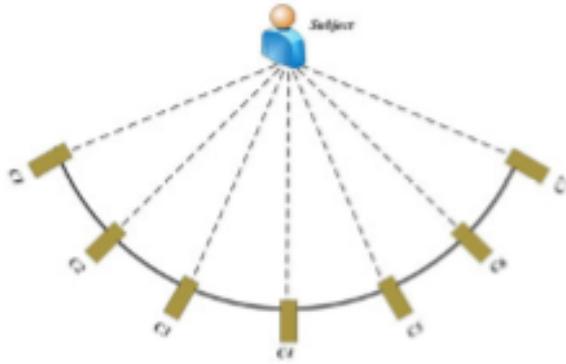
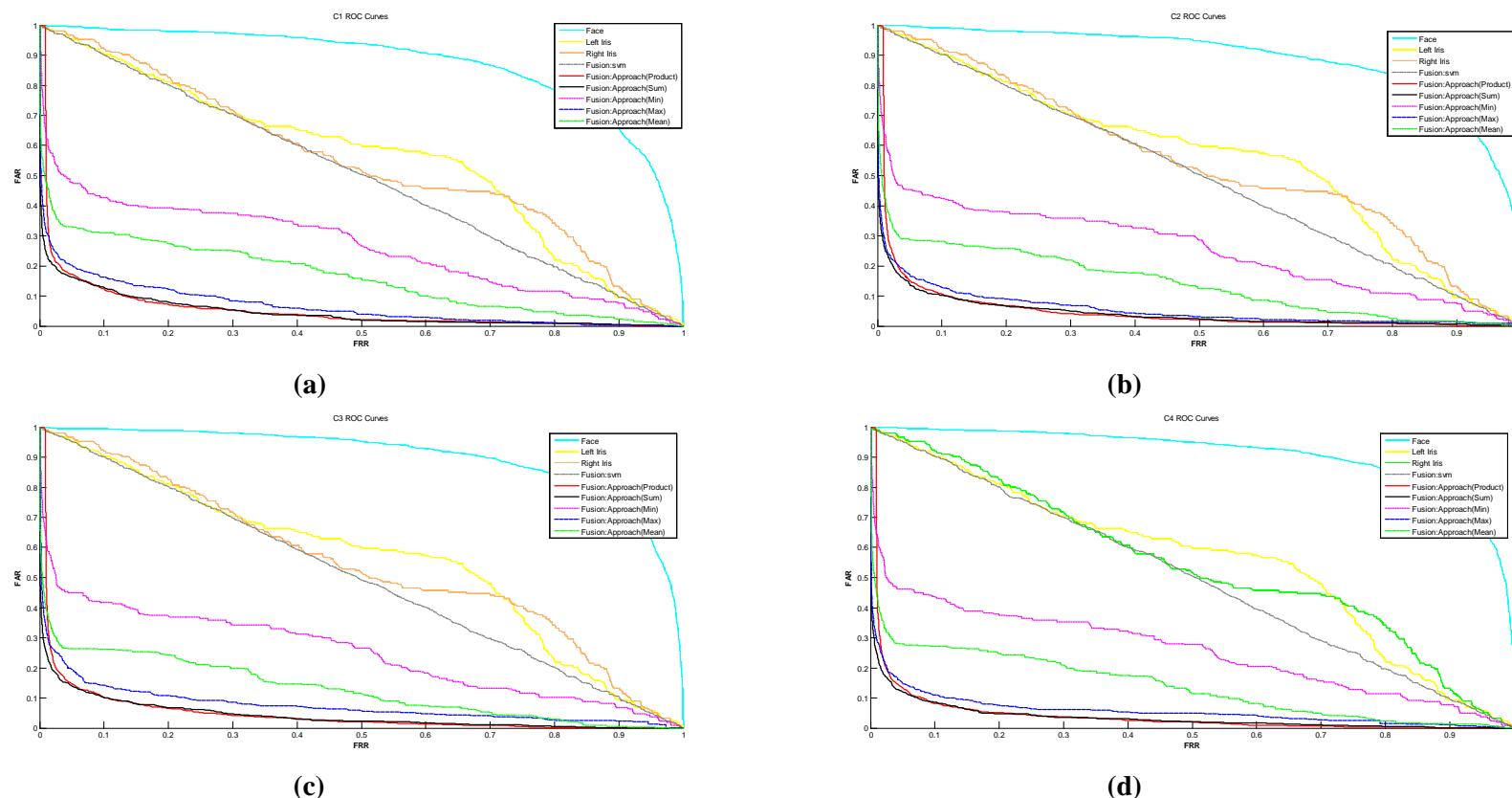


Figure 6. 6: Camera settings, figure taken from (Yin,2011).



Figure 6. 7: The subject (N°103) of the face SDUMLA-HMT database captured according to the camera settings. (a):C1; (b):C2; (c):C3; (d):C4; (e):C5; (f):C6; (g):C7.

Figure 6.8 presents 7 curves and each curve illustrates the ROC (*Receiver Operating Characteristic*) curve for each database extracted from the SDUMLA-HMT database (C1, C2, C3, C4, C5, C6, C7).



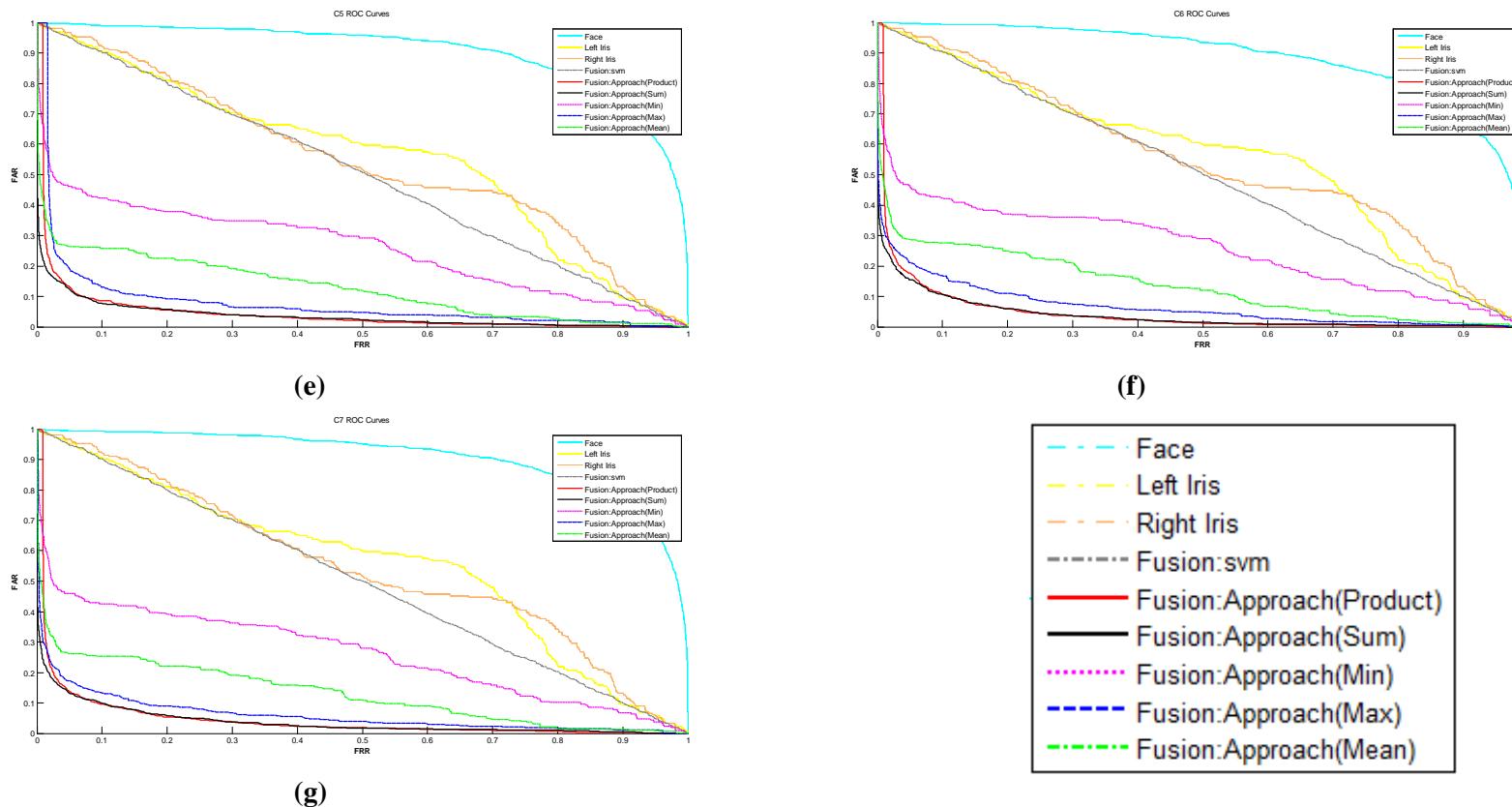


Figure 6.8: ROC plot showing the performance of the authentication by: the face, the left iris, and the right iris, the fusion by (SVM, CP, CS, CMI, CMA, and CME) on SDUMLA-HMT Database: (a):C1, (b):C2,(c):C3, (d):C4, (e):C5, (f):C6, (g):C7.

For each database, each curve plots the FAR (false acceptance rate) in the Y-axis versus the FRR (false rejection rate) in the X-axis. Each curve shows the performance of the three mono-modal systems tested separately with the SVM classifier (the face authentication, the left iris authentication, and the right iris authentication). In addition, it illustrates the influence of each fusion method on the performance of the proposed approach. However, the first method used for the fusion is the SVM. Our contribution is the use of the combination rules integrated to the classification method (**Chikhaoui,2013**), we choose to name this approaches (CP, CS, CMI, CMA, and CME) and these are described above.

Figure 6.8 confirms that the multi-biometrics is more performance than the mono-modal biometrics, also it illustrates that the iris modality is more performance than the face modality. In addition, it shows that the five fusion approaches (CP, CS, CMI, CMA, and CME) give results better than the SVM method used for the fusion for all the databases.

Table 6.7 presents the results of the performance evaluation by using the EER and the AUROCC criteria.

		Mono-modal			Fusion						
		Face	Left iris	Right iris	SVM	CP	CS	CMI	CMA	CME	
Databases	C1	AUC	0.1274	0.4412	0.4536	0.4992	0.9460	0.9530	0.7347	0.9324	0.8365
		EER	0.7925	0.5807	0.507	0.5028	0.1131	0.1168	0.3597	0.1414	0.2544
	C2	AUC	0.1119	0.4412	0.4536	0.4988	0.9502	0.9564	0.7429	0.9435	0.8582
		EER	0.8155	0.5807	0.507	0.5021	0.1029	0.1017	0.3484	0.1167	0.239
	C3	AUC	0.0983	0.4412	0.4536	0.5013	0.9523	0.9579	0.7505	0.9245	0.8716
		EER	0.8228	0.5807	0.507	0.4968	0.1006	0.1014	0.3419	0.1277	0.2245
	C4	AUC	0.0900	0.4412	0.4536	0.5000	0.9579	0.9643	0.7414	0.9427	0.8615
		EER	0.8323	0.5807	0.507	0.5027	0.0896	0.0891	0.3414	0.1075	0.2396
	C5	AUC	0.0962	0.4412	0.4536	0.4980	0.9564	0.9635	0.7392	0.9237	0.8724
		EER	0.8239	0.5807	0.507	0.5045	0.0901	0.086	0.3483	0.1201	0.2188
	C6	AUC	0.1163	0.4412	0.4536	0.4988	0.9545	0.9612	0.7382	0.9328	0.8649
		EER	0.8092	0.5807	0.507	0.5005	0.1048	0.1042	0.3495	0.1418	0.2335
	C7	AUC	0.0926	0.4412	0.4536	0.5003	0.9552	0.9615	0.7370	0.9395	0.8699
		EER	0.8275	0.5807	0.507	0.5004	0.097	0.1006	0.3526	0.1239	0.2222

Table 6. 7: Evaluation of the performance of the multi-biometrics (setting) system using EER and AUROCC criteria.

According to the EER and the AUROCC obtained in the table 6.7, we find that the iris modality is more performance than the face modality. Also, this table confirms the superiority of the multi-biometrics system compared with the unimodal biometric system. In addition, it illustrates that our five proposed approach give result better than the SVM for the fusion. According to the EER and

the AUROCC obtained, the CS approach gives the best result, then the CP approach, the CMA approach, the CME approach, and the CMI approach respectively with this order.

The best result is the result obtained on the sub-database C4. The images of this database are captured by the camera C4 (figure 6.6), and this is logical because the user is located in front to the camera.

According to the results illustrated in the table 6.7, the CS approach gives the best result on all the sub-databases according to the AUROCC obtained. Therefore, the table 6.8 presents the performance evaluation of the CS approach using the FP, the FN, the FAR, the FRR, the accuracy, and the error rate for each sub-database.

Database	FP	FN	FAR %	FRR %	Error rate%	Acc %
C1	6	657	0.62	0.65	0.66	99.34
C2	19	620	1.99	0.61	0.64	99.36
C3	18	629	1.88	0.62	0.64	99.36
C4	10	616	1.04	0.61	0.62	99.38
C5	7	615	0.73	0.61	0.62	99.38
C6	9	622	0.94	0.62	0.63	99.37
C7	5	615	0.52	0.61	0.62	99.38

Table 6. 8: Evaluation of the performance of the CS approach (setting result) using FAR, FRR, Accuracy, and error rate.

The results illustrated in the previous table demonstrate that The maximum accuracy is the accuracy obtained on the sub-database C4 (Acc=99.38%) and the minimum accuracy is about C1 (Acc=99,34%). The average accuracy between the 7 sub-databases is: 99.37%.

We presented in the previous section the confusion matrix which is used to visualize the performance of an algorithm. According to the results illustrated in the table 6.7 and the table 6.8, the CS approach gives the best result on the sub-database C4. Therefore, the table 6.9 presents the confusion matrix and some indicators that visualize the performance of the CS approach on the database C4.

	Condition positive	Condition negative	
Test outcome positive	TP=944	FP=10	PPV=98.95%
Test outcome negative	FN=616	TN=99554	NPV=99.39%
ACC=99.38%	TPR=60.51%	TNR=99.98%	

Table 6. 9 : Confusion Matrix (CS Approach on the database C4)

6.3 COMPARISON

In this section, we will compare the results obtained by our multi-biometrics system with other results that exist in the literature.

Therefore, the table 6.10 presents a summary of some results of the multi-biometrics fusion based on the integration of the face and the iris between 2003 and 2017, including our fusion method. This table compares the different studies according to their: fusion levels, strategies, databases, and results obtained including the EER (equal error rate), and TER (Total Error Rate: is the sum of FAR and FRR, which is equal to twice of the EER value). Among the studies mentioned in this table, we find that our proposed approach gives the best result according to the EER obtained.

Papers	Fusion levels	Strategies	Databases	Results
Wang et al. (Wang,2003)	Score	RBF neural network.	ORL, MIT, Yale, NLPR.	EER=0.24%
Chen and Te Chu (Chen,2006a)	Score	Wavelet Probabilistic Neural Network (WPNN) and Particle Swarm Optimization (PSO).	IIS, ORL/CASIA.	EER=0.33%
Wang and Han (Wang,2009)	Score	SVM.	ORL / UBIRIS.	EER=0.35%
Wang et al. (Wang,2011)	Feature	Serial Rule.	DB1: ORL+ CASIA1. DB2: YALE+ CASIA1.	EER=1,94% EER=1.67%
Liau and Isa (Liau,2011)	Score	SVM.	ORL/CASIA.	TER=1.06±0.39%
Johnson et al. (Johnson,2011)	Score	Quality based Likelihood Ratio (QLR).	Q-fire.	EER=1.9%
Kim et al. (Kim,2012)	Score	SVM.	Internal.	EER=0.131%
Sharma and Kumar (Sharma,2012)	Feature	Concatenation.	ORL/CASIA.	EER=0,5%
Eskandari and Toygar (Eskandari,2012)	Score	Sum and Product rule.	ORL/CASIA.	EER=0.525%
Eskandari et al. (Eskandari,2013)	Score	Concatenation and Nearest Neighbor classifier.	ORL,BANCA/ CASIA,UBIRIS.	EER=1.02%
Eskandari and Toygar (Eskandari,2014)	Score	Weighted Sum Rule and Nearest Neighbor classifier.	ORL, FERET/ CASIA, UBIRIS.	EER=0.5%
Sharifi and Eskandari (Sharifi,2016)	Feature, Score, and Decision	Concatenation, weight Sum, and OR rule.	CASIA-Iris-Distance.	TER=0.27±0.4%
Zoubida and Adjoudj (Zoubida,2017a)	Score	CS Approach.	SDUMLA-HMT.	EER=0.08%

Table 6. 10: Summary of some results of the multi-biometrics systems based on the fusion of the face and the iris between 2003 and 2017, including our proposed approach.

6.4 CONCLUSION

This chapter presented the results obtained by our multi-biometrics system. However, it presented the results of the multi-units system that integrated the both units of the iris modality (the left and the right irises). Also, it illustrated the results of the multi-biometrics system which is based on the fusion of the face with the both units of the iris modality.

The results obtained confirm that the iris modality is more performance than the face modality. In addition, the experiments carried out on the basis of individuals confirm the hypothesis of the superiority of the multi-biometrics compared to the unimodal biometrics. This significant improvement confirms the value of combining the face with the both units of the iris modality. Also, this chapter shows the performance of our proposed approach, and it compares the results obtained with some studies that exist in the literature.

CONCLUSION

In this thesis, we are attracted to one of the most important applications in the pattern recognition field. Therefore, we are interested to study profoundly the biometric in general and the multi-biometrics in particular. Although the biometric techniques are more performance than the use of the traditional means of authentication, but we can't currently guarantee an excellent rate of recognition with the biometric systems which is based on a single biometric modality.

Therefore, the multi-biometrics systems attract the attention of several researches, and it takes an important place in several applications, especially in the recognition of individuals, which is more and more present in the access to the private places.

In this thesis, we have proposed a multi-biometrics technique for the person authentication. This technique integrates the both units of the iris with the face modality. To achieve our goal, we proceeded as follows:

We are presented the pattern recognition field and its applications. Among the most important applications in this field, we find the biometric. Therefore, we have described the biometric in general, and we are presented the different biometric modalities with their advantages and their disadvantages. After these, we found that the performance of the biometric systems depends on several factors and that can vary from one system to another. To overcome all these problems, we concluded that it must combine multiple modalities to get more reliable results. So, we have presented the multi-biometrics and the different types of possible combinations of modalities, also we have described the different architectures, and the fusion levels that can be used in the multi-biometrics systems. Among the modalities described, we are chosen to combine the face and the both units of the iris modality (the left and the right irises).

Our first contribution in this work is a modified method for the iris segmentation which is an important step in the iris recognition process.

Then, the second contribution is the use of a standard method that can be applied for the iris authentication and the face authentication concerning the features extraction and the matching steps.

In addition, other contribution concerns the proposed approach which integrated the face with the both units of the iris modality (the left and the right irises). This multi-biometrics approach is multi-units because it is integrated the both units of the iris modality, it is also multi-samples because it take account of the changes in the facial pose. Therefore, it is multi-modal because it is based on the

fusion of the face with the iris modality. In addition, it is multi-algorithms. These are made this system a hybrid system. The fusion is performed at the score level using the integration between the combination rules and the classification method. However, this classification method is used for the first time in this field.

Our multi-biometrics approach is increase the performance compared with the mono-modality. The results obtained confirm that the iris modality is more performance than the face modality. Also, the experiments carried out on the basis of individuals confirm the hypothesis of the superiority of the multi-biometrics compared to the unimodal biometrics. This significant improvement confirms the value of combining the face with the both units of the iris modality.

In outlook, further improvements may be considered:

- The fusion between the both modalities can be done in the various levels not only at the score level.
- We can add other modalities, and combine different techniques to improve the performance of the verification of the identity of persons.
- The classification method which is used for the fusion can be used to obtain the scores instead of the SVM, or it can be used to realize the unimodal systems.
- The proposed approach can be used for the identification mode.
- We can used the others characteristics biometrics of the SDUMLA-HMT database for the evaluation of our system, such as the veins, the fingerprints, and the gait.

REFERENCES

- (Abate,2007)** A.F. Abate, S. Ricciardi, and G. Sabatino, "3D Face Recognition in a Ambient Intelligence Environment Scenario", *Face Recognition*, by K. Delac and M. Grgic(Ed.), Ch. 1, I-Tech Education and Publishing, pp.1-14, ISBN:978-3-902613-03-5, Vienna, Austria, Jun.2007. **[cited in p.74]**
- (Abdullah,2012)** M. Abdullah, M. Wazzan, and S. Bo-saeed, "Optimizing Face Recognition Using PCA", *International Journal of Artificial Intelligence and Applications (IJAIA)*, Vol.3, No.2, pp.23-31, Mar.2012. DOI:10.5121/ijaia.2012.3203 **[cited in p.74]**
- (Abuguba,2015)** S. Abuguba, M. M. Milosavljević, and N. Maček, "An Efficient Approach to Generating Cryptographic Keys from Face and Iris Biometrics Fused at the Feature Level", *International Journal of Computer Science and Network Security(IJCSNS)*, Vol.15, No.6, pp.6-11, Jun.2015. **[cited in p.102]**
- (Acar,2013)** E. Acar and M. S. Özerdem, "An Iris Recognition System by Laws Texture Energy Measure Based k-NN Classifier", *Signal Processing and Communications Applications Conference (SIU)*, pp. 1-4, Apr.2013. DOI:10.1109/SIU.2013.6531397 **[cited in p.82,90]**
- (Adjoudj,2004)** R. Adjoudj, A. Boukelif, "Detection and recognition of the faces based on the artificial neural networks", *First International Symposium on Control Communications and Signal Processing*, pp.439-442, Mar.2004. DOI:10.1109/ISCCSP.2004.1296323 **[cited in p.73]**
- (Adjoudj,2005)** R. Adjoudj and A. Boukelif, "Artificial Neural Network & Multilevel 2-D Wavelet Decomposition Code-Based Iris Recognition", *RomJist Journal*, Vol. 8, No. 02, pp. 163– 177, 2005. **[cited in p.80]**
- (Adler,1965)** F.H Adler, "Physiology of the Eye", *C.V Mosby*, Saint Louis, Missouri, 1965. **[cited in p.78]**
- (Aguilar,2005a)** J. F. Aguilar, J. O. Garcia, J. G. Rodriguez, and J. Bigun, "Discriminative Multimodal Biometric Authentication based on Quality Measures", *Pattern Recognition*, Vol. 38, No. 5, pp.777-779, May.2005. Doi:10.1016/j.patcog.2004.11.012 **[cited in p.56]**
- (Aguilar,2005b)** J. F. Aguilar, L. Nanni, J. L. Penalba, J. O. Garcia, and D. Maltoni, "An On-line Signature Verification System based on Fusion of Local and Global Information", *The 5th International Conference on Audio- and Video-based Biometric Person Authentication (AVBPA)*, Vol.3546, pp. 523-532, Rye Brook, USA, 2005.

- DOI:10.1007/11527923_54 [cited in p.54]
- (Ali,2003)** J. M. Ali and A. E. Hassanien, "An Iris Recognition System to Enhance E-Security Environment Based on Wavelet Theory", *AMO-Advanced Modeling and Optimization*, Vol. 5, No. 2, pp.93–104, 2003. [cited in p.89]
- (Almahafzah,2012)** H. AlMahafzah and M. Z. AlRwashdeh, "A Survey of Multibiometric Systems", *International Journal of Computer Applications*, Vol. 43, No. 15, pp. 36-43, Apr.2012. Doi:10.5120/6182-8612 [cited in p.30]
- (Antini,2006)** G. Antini, S. Berretti, A. Del Bimbo, P. Pala, "3D Face Identification Based On Arrangement Of Salient Wrinkles", *IEEE International Conference on Multimedia Expo(ICME'06)*, Toronto, Canada, pp.85-88, Jul.2006. DOI:10.1109/ICME.2006.262556 [cited in p.73]
- (Anwar,2009)** F. Anwar, M. A. Rahman, and S. Azad, "Multibiometric Systems Based Verification Technique", *European Journal of Scientific Research*, Vol. 34, No. 2, pp. 260-270, 2009. [cited in p.59]
- (Araghi,2010)** L. F. Araghi, H. Shahhosseini, and F. Setoudeh, "IRIS Recognition Using Neural Network", *Proceedings of the International MultiConference of Engineers and Computer Scientists (IMECS'10)*, Vol.1, pp.338-340, Mar.2010. [cited in p.81]
- (Avila,2002)** C. S. Avila and R. S. Reillo, "Multiscale Analysis for Iris Biometrics", *Proceedings of IEEE 36th Annual International Carnahan Conference on Security Technology*, pp. 35–38, 2002. DOI:10.1109/CCST.2002.1049222 [cited in p.89]
- (Avila,2005)** C. S. Avila and R. S. Reillo, "Two Different Approaches for Iris Recognition Using Gabor Filters and Multiscale Zero-crossing Representation", *Pattern Recognition*, vol. 38, No. 2, pp. 231–240, Feb. 2005. Doi:10.1016/j.patcog.2004.07.004 [cited in p.80,89]
- (Azizi,2009a)** A. Azizi and H. R. Pourreza, "Efficient Iris Recognition Through Improvement of Feature Extraction and subset Selection", *International Journal of Computer Science and Information Security (IJCSIS'09)*, Vol.2, No.1, Jun.2009. [cited in p.81,90]
- (Azizi,2009b)** A. Azizi and H. R. Pourreza, "A Novel Method Using Contourlet to Extract Features for Iris Recognition System", *International Conference on Emerging Intelligent Computing Technology and Applications*, vol.5754, Springer Berlin Heidelberg, pp.544–554, Sep.2009. DOI:10.1007/978-3-642-04070-2_60 [cited in p.89]
- (Bae,2003)** K. Bae, S. Noh, and J. Kim, "Iris Feature Extraction Using Independent Component Analysis", *Proceedings of 4th International Conference on Audio-and Video-Based*

- Biometric Person Authentication (AVBPA '03)*, Springer Berlin Heidelberg, Guildford, UK, Vol. 2688, pp. 838–844, Jun.2003. DOI:10.1007/3-540-44887-X_97 [cited in p.89]
- (Bartlett,1998)** M. S. Bartlett, H. M. Lades, and T. J. Sejnowski, “Independent Component Representations For Face Recognition”, *Proceedings SPIE Symposium on Electronic Imaging: Science and Technology—Conference on Human Vision and Electronic Imaging III*, Vol. 3299, pp. 528–539, 1998. [cited in p.73]
- (Bartlett,2002)** M. S. Bartlett, J. R. Movellan, and T. J. Sejnowski, “Face Recognition by Independent Component Analysis”, *IEEE Transactions on Neural Networks*, Vol.13, No.6, pp.1450-1464, Nov.2002. DOI:10.1109/TNN.2002.804287 [cited in p.73]
- (Belhumeur,1997)** P.N. Belhumeur, J.P. Hespanha, and D.J. Kriegman, “Eigenfaces vs Fisherfaces: Recognition Using Class Specific Linear Projection”, *IEEE Transacations on Pattern Analysis and Machine Intelligence (PAMI)*, Vol.19, No.7, pp.711-720, July 1997. DOI:10.1109/34.598228 [cited in p.73,73]
- (Bertillon,1886)** A. Bertillon, “La couleur de l’iris”, *Revue Scientifique*, 1886. [cited in p.20]
- (Bertillon,1890)** A. Bertillon, “La Photographie Judiciaire, avec un Appendice sur la Classification et L’identification Anthropometriques”, Gauthier-Villars, Paris, 1890. [cited in p.25]
- (Beumier,2001)** C. Beumier and M. Achery, “Face Verification From 3D And Grey Level Cues”, *Pattern Recognition Letters*, Vol.22, No.12, pp.1321–1329, Oct.2001. Doi:10.1016/S0167-8655(01)00077-0 [cited in p.73]
- (Beymer,1995)** D. Beymer and T. Poggio, “Face Recognition from One Model View”, *Proceedings of the 5th International Conference on Computer Vision*, pp.500-507, Jun.1995. DOI:10.1109/ICCV.1995.466898 [cited in p.73]
- (Bezdek,1981)** J.C. Bezdek, “Pattern Recognition with Fuzzy Objective Function Algorithms”, *Plenum Press*, New York, USA, 1981. [cited in p.7,11]
- (Bezdek,2006)** J. C. Bezdek, J. Keller, R. Krisnapuram, and N. Pal, “Fuzzy Models and Algorithms for Pattern Recognition and Image Processing”, *Springer Science and Business Media*, Vol. 4, 2006. [cited in p.6]
- (Bhatnagar,2009)** J. Bhatnagar and A. Kumar, “On Estimating Performance Indices for Biometric Identification”, *Pattern Recognition*, Vol.42, No.9, pp.1803–1815, Sep.2009. Doi:10.1016/j.patcog.2008.10.004 [cited in p.37]
- (Bigün,1997)** E. S. Bigün, J. Bigün, B. Duc, and S. Fischer, “Expert Conciliation for Multi Modal

- Person Authentication Systems by Bayesian Statistics”, *Proceedings of the First International Conference on Audio and Video-Based Biometric Person Authentication (AVBPA '97)*, Vol.1206, pp.291-300, London, UK, Springer-Verlag, 1997. DOI: 10.1007/BFb0016008 [cited in p.56]
- (Billaudel,1999)** P. Billaudel, A. Devillez, and G. V. Lecolier, “Performance Evaluation of Fuzzy Classification Methods Designed for Real Time Application”, *International Journal of Approximate Reasoning*, Vol. 20, No.1, pp. 1–20, Jan.1999. Doi:10.1016/S0888-613X(00)88941-0 [cited in p.11]
- (Blake,1998)** A. Blake and M. Isard, “Active Contours”, Springer-Verlag, 1998. [cited in p.84]
- (Blanz,2003)** V. Blanz and T. Vetter, “Face Recognition Based on Fitting 3D Morphable Model”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.25, No.9, pp.1063-1074, Sep.2003. DOI:10.1109/TPAMI.2003.1227983 [cited in p.73,74]
- (Boles,1998)** W. W. Boles and B. Boashash, “A Human Identification Technique Using Images of the Iris and Wavelet Transform”, *IEEE Transactions on Signal Processing*, Vol.46, No.4, pp.1185–1188,Apr. 1998. DOI:10.1109/78.668573 [cited in p.80,89,108]
- (Bolle,2004)** R. M. Bolle, J. H. Connell, S. Pankanti, N. K. Ratha, and A. W. Senior, “Guide to Biometrics”, Springer-Verlag, New York, 2004. [cited in p.116]
- (Bolle,2005)** R. M. Bolle, J. H. Connell, S. Pankanti, N. K. Ratha, and A. W. Senior, “The Relation between the ROC Curve and the CMC”, *Proceedings of the Fourth IEEE Workshop on Automatic Identification Advanced Technologies*, pp. 15–20, Oct.2005. DOI:10.1109/AUTOID.2005.48 [cited in p.40]
- (Bow,1992)** S. Bow, “Pattern Recognition and Image Processing”, Marcel Dekker Inc. New york, USA, 1992. [cited in p.9]
- (Bowyer,2004)** K. W. Bowyer, K. Chang, and P. Flynn, “A Survey of Approaches to three Dimensional Face Recognition”, *Proceedings of the 17th IEEE International Conference on Pattern Recognition (ICPR'04)*,Vol.1, pp.358-361, Aug.2004. DOI:10.1109/ICPR.2004.1334126 [cited in p.73]
- (Bronstein,2003a)** A. M. Bronstein, M. M. Bronstein, and R. Kimmel, “Expression-invariant 3D face recognition”, *Proceedings of the 4th International Conference on Audio and Video-Based Biometric Person Authentication(AVBPA '03)*, Vol.2688, pp. 62–70, Jun.2003. Doi:10.1007/3-540-44887-X_8 [cited in p.73]
- (Bronstein,2003b)** A.M. Bronstein, M. M. Bronstein, R. Kimmel, and A. Spira , “3D Face Recognition Without Facial Surface Reconstruction”, Technion-Computer Science Department,

- Technical Report, Jan.2003. **[cited in p.74]**
- (Bronstein,2005)** A. M. Bronstein, M. M. Bronstein, R. Kimmel, “Three-Dimensional Face Recognition”, *International Journal of Computer Vision*, Vol.64, no.1, pp.5-30, Aug.2005. DOI: 10.1007/s11263-005-1085-y **[cited in p.73]**
- (Brunelli,1993)** R. Brunelli and T. Poggio, “Face Recognition: Features vs Templates”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.15, No. 10, pp 1042-1052, Oct.1993. DOI:10.1109/34.254061 **[cited in p.73]**
- (Brunelli,1995)** R. Brunelli and D. Falavigna, “Person Identification Using Multiple Cues”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 17, No.10, pp. 955–966, Oct.1995. DOI:10.1109/34.464560 **[cited in p.48,56]**
- (Campbell,2004)** W. M. Campbell, D. A. Reynolds, and J. P. Campbell, “Fusing Discriminative and Generative Methods for Speaker Recognition: Experiments on Switchboard and NFI/TNO Field Data”, *ODYSSEY'04 The Speaker and Language Recognition Workshop*, pp. 41-44, Toledo, Spain, 2004. **[cited in p.54]**
- (Canny,1986)** J. Canny, “A Computational Approach to Edge Detection”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.PAMI-8, No.6, pp.679-698, Nov.1986. DOI:10.1109/TPAMI.1986.4767851 **[cited in p.85]**
- (Cartoux,1989)** J. Y. Cartoux, J. T. Lapreste, and M. Richetin. “Face Authentication or Recognition by Profile Extraction from Range Images”, *Proceedings of the IEEE Workshop on Interpretation of 3D Scenes*, pp.194-199, Nov.1989. DOI:10.1109/TDSCE.1989.68119 **[cited in p.73]**
- (Chang,2003a)** K. I. Chang, K. W. Bowyer, and P. J. Flynn, “Face Recognition Using 2D and 3D Facial Data”, *ACM Workshop on Multimodal User Authentication*, pp. 25–32, Dec.2003. **[cited in p.53]**
- (Chang,2003b)** K. Chang, K. W. Bowyer, S. Sarkar, and B. Victor, “Comparison and Combination of Ear and Face Images in Appearance-based Biometrics”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.25, No.9, pp.1160-1165, Sep.2003. DOI:10.1109/TPAMI.2003.1227990 **[cited in p.56]**
- (Chang,2004)** K. I. Chang, K. W. Bowyer, P. J. Flynn, and X. Chen, “Multibiometrics Using Facial Appearance, Shape and Temperature”, *In 6th IEEE International Conference on Automatic Face and Gesture Recognition*, pp. 43-48, Seoul, Korea, May.2004. DOI:10.1109/AFGR.2004.1301507 **[cited in p.53]**
- (Chang,2005)** K. I. Chang, K. W. Bowyer, and P. J. Flynn, “An Evaluation of Multimodal 2D+3D

- Face Biometrics”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 27, No.4, pp.619- 624, Apr.2005. DOI:10.1109/TPAMI.2005.70 [cited in p.53,57,73]
- (Chang,2006)** K. I. Chang, K. W. Bowyer, and P. J. Flynn, “Multiple Nose Region Matching for 3D Face Recognition under Varying Facial Expression”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.28, No.10, pp. 1695–1700, Oct.2006. DOI:10.1109/TPAMI.2006.210 [cited in p.73]
- (Chatzis,1999)** V. Chatzis, A. G. Bors, and I. Pitas, “Multimodal Decision-Level Fusion for Person Authentication”, *IEEE Transactions on Systems, Man and Cybernetics-Part A : Systems and Humans*, Vol.29, No.6, pp.674–680, Nov.1999. DOI:10.1109/3468.798073 [cited in p.118]
- (Chen,1997)** K. Chen, L. Wang, and H. Chi, “Methods of Combining Multiple Classifiers with Different Features and their Applications to Text-Independent Speaker Identification”, *International Journal of Pattern Recognition and Artificial Intelligence*, Vol. 11, No. 3, pp. 417–445, May.1997. DOI:10.1142/S0218001497000196 [cited in p.60]
- (Chen,2003)** X. Chen, P. Flynn, and K. Bowyer, “Visible-Light and Infrared Face Recognition”, *ACM Workshop on Multimodal User Authentication*, pp. 48–55, Dec.2003. [cited in p.53]
- (Chen,2005a)** C. H. CHEN and C. T. Chu, “Low Complexity Iris Recognition Based on Wavelet Probabilistic Neural Networks”, *Proceedings of International Joint Conference on Neural networks (IJCNN’05)*, Vol. 3, pp.1930-1935, Aug.2005. DOI:10.1109/IJCNN.2005.1556175 [cited in p.80,84,109]
- (Chen,2005b)** X. Chen, P. J. Flynn, and K. W. Bowyer, “IR and Visible Light Face Recognition”, *Computer Vision and Image Understanding*, Vol. 99, No.3, pp.332-358, Sep.2005. Doi:10.1016/j.cviu.2005.03.001 [cited in p.53]
- (Chen,2005c)** Y. Chen, S. Dass, and A. K. Jain, “Fingerprint Quality Indices for Predicting Authentication Performance”, *Proceedings of Fifth International Conference on Audio- and Video-Based Biometric Person Authentication (AVBPA)*, Vol.3546, pp.160–170, New York, NY, USA, Jul.2005. DOI: 10.1007/11527923_17 [cited in p.44,50]
- (Chen,2006a)** C. H. Chen and C. T. Chu, “Fusion of Face and Iris Features for Multimodal Biometrics”, *In International Conference on Biometrics*, Springer Berlin /Heidelberg, Vol. 3832, pp. 571-580, Jan.2006. DOI: 10.1007/11608288_76 [cited in p.56,59,102]

- (Chen,2006b)** Y. Chen, S.C. Dass, and A.K. Jain, “Localized Iris Image Quality Using 2-D Wavelets”, *International Conference on Biometrics (ICB'06)*, pp.373-381, Jan.2006. DOI: 10.1007/11608288_50 [cited in p.44]
- (Cheney,2015)** J. Cheney, B. Klein, A. K. Jain, and B. F. Klare, “Unconstrained Face Detection: State of the Art Baseline and Challenges”, *The 8th IAPR International Conference on Biometrics (ICB)*, Phuket, Thailand, pp.229-236, May.2015. DOI:10.1109/ICB.2015.7139089 [cited in p.74]
- (Chenhong,2005)** L. Chenhong and L. Zhaoyang, “Efficient iris recognition by computing discriminable textons”, *Proceedings of International Conference on Neural Networks and Brain (ICNNB'05)*, Vol.2, pp.1164–1167, Oct.2005. DOI:10.1109/ICNNB.2005.1614822 [cited in p.89]
- (Chenhong,2008)** L. Chenhong and L. Zhaoyang, “Local Feature Extraction for Iris Recognition with Automatic Scale Selection”, *Image and Vision Computing* , Vol. 26, No. 7, pp.935-940, Jul.2008. DOI:10.1016/j.imavis.2007.10.011 [cited in p.81]
- (Cheung,2004)** M. C. Cheung, K. K. Yiu, M. W. Mak, and S. Y. Kung, “Multi-Sample Fusion with Constrained Feature Transformation for Robust Speaker Verification”, *The 8th International Conference on Spoken Language Processing (ICSLP'04)*, pp. 1813-1816, Jeju Island, Korea, Oct.2004. [cited in p.55]
- (Chia,2009)** C. Chia, N. Sherkat, and L. Nolle, “Confidence Partition and Hybrid Fusion in Multimodal Biometric Verification System”, *European Workshop on Biometrics and identity Management*, Vol.5707, Springer Berlin Heidelberg, pp. 212–219, Sep.2009. DOI:10.1007/978-3-642-04391-8_28 [cited in p.117]
- (Chikhaoui,2010)** A. Chikhaoui, B. Djebbar, and R. Mekki, “New Method for Finding an Optimal Solution to Quadratic Programming Problems”, *Journal of Applied Sciences*, Vol.10, No.15, pp.1627-1631, Dec. 2010. Doi:10.3923/jas.2010.1627.1631 [cited in p.118,119,120]
- (Chikhaoui,2013)** A. Chikhaoui and A. Mokhtari, “Classification with Support Vector Machine: New Quadratic Programming Algorithm “, *Journal of Models & Optimisation and Mathematical Analysis*, Vol.2, No.2, pp.1-6, 2013. [cited in p. 108,118, 119,121, 125,134,145]
- (Chirchi,2011)** V. R. E. Chirchi, L. M. Waghmare, and E. R. Chirchi, “Iris Biometric Recognition for Person Identification in security system”, *International Journal of Computer Applications (IJCA'11)*, Vol.24, No.9,pp.1-6, Jun.2011. Doi:10.5120/2986-4002 [cited

in p.81,89]

- (Chorasa,2010)** R. S. Chorasa, "Hybrid Iris and Retina Recognition for Biometrics", *The 3rd International Congress on Image and Signal Processing (CISP)*, vol.5, pp. 2422-2426, Yantai, Oct.2010. DOI:10.1109/CISP.2010.5648281 [cited in p.59]
- (Chou,2006)** C. T. Chou, S. W. Shih, W. S. Chen, and V. W. Cheng, "Iris Recognition with Multi-Scale Edge-Type Matching", *Proceedings of the 18th IEEE International Conference on Pattern Recognition (ICPR'06)*, Vol.4, pp. 545–548, Aug.2006. DOI:10.1109/ICPR.2006.728 [cited in p.89]
- (Colmenarez,1997)** A. J. Colmenarez and T. S. Huang, "Face Detection with Information-Based Maximum Discrimination", *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp.782–787, Jun.1997. DOI:10.1109/CVPR.1997.609415 [cited in p.74]
- (Connaughton,2012)** R. Connaughton, "Fusion of Face and Iris Biometrics Using a Stand-Off Video Sensor", *PhD thesis*, University of Notre Dame, Indiana, Apr.2012. [cited in p.54,55,105]
- (Cootes,2001)** T. F. Cootes, G. J. Edwards, and C. J. Taylor, "Active Appearance Models", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.23, No.6, pp.681–685, Jun.2001. DOI:10.1109/34.927467 [cited in p.74]
- (Costa,2012)** R. M. da Costa and A. Gonzaga, "Dynamic Features for Iris Recognition", *IEEE transactions on systems, man, and cybernetics—part B (cybernetics)*, Vol.42, No.4, pp.1072-1082, Aug.2012. DOI:10.1109/TSMCB.2012.2186125 [cited in p.82,84, 109]
- (Coventry,2003a)** L. Coventry, A. De Angeli, and G. Johnson, "Biometric Verification at a Self Service Interface", *Contemporary Ergonomics*, pp.247–252, 2003. [cited in p.44]
- (Coventry,2003b)** L. Coventry, A. De Angeli, and G. Johnson, "Honest It's Me! Self Service Verification", *ACM Conference on Human Factors in Computing Systems (CHI)*, pp.1–4, Apr.2003. [cited in p.44]
- (Coventry,2003c)** L. Coventry, A. De Angeli, and G. Johnson, "Usability and Biometric Verification at the ATM Interface", *Proceedings of the SIGCHI conference on Human factors in computing systems*, Vol.5, No.1, pp.153–160, Apr.2003. Doi:10.1145/642611.642639 [cited in p.44]
- (Cozman,2003)** F. G. Cozman, I. Cohen, and M.C. Cirelo, "Semi-Supervised Learning of Mixture Models", *The 20th International Conference on Machine Learning (ICML'03)*, pp. 99-

- 106, Washington DC, USA, 2003. [cited in p.11]
- (Craw,1992)** I. Craw, D. Tock, and A. Bennett, “Finding Face Features”, *In European Conference on Computer Vision*, pp. 92–96, May.1992. DOI:10.1007/3-540-55426-2_12 [cited in p.74]
- (Cross,1995)** J. M. Cross and C. L. Smith, “Thermographic Imaging of the Subcutaneous Vascular Network of the Back of the Hand for Biometric Identification”, *International Carnahan Conference on Security Technology*, pp.20-35, Oct.1995. DOI:10.1109/CCST.1995.524729 [cited in p.23]
- (Cui,2004)** J. Cui, Y. Wang, T. Tan, L. Ma, and Z. Sun, “A Fast and Robust Iris Localization Method Based on Texture Segmentation”, *Proceedings of the SPIE Defense and Security Symposium*, Vol.5404, pp.401–408, Aug.2004. Doi:10.1117/12.541921 [cited in p.84]
- (Czyz,2004)** J. Czyz, J. Kittler, and L. Vandendorpe, “Multiple Classifier Combination for Face-based Identity Verification”, *Pattern Recognition*, Vol. 37, No.7, pp.1459-1469, Jul.2004. Doi:10.1016/j.patcog.2004.01.008 [cited in p.54]
- (Dai,2007)** D. Q. Dai and H. Yan, “Wavelets and Face Recognition”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), Ch. 4, I-Tech Education and Publishing, pp.59-74, ISBN:978-3-902613-03-5 , Vienna, Austria,2007. [cited in p.74]
- (Daouk,2002)** C. H. Daouk, L. A. El-Esber, F. D. Kammoun, and M. A. Al Alaoui, “Iris Recognition”, *Proceedings of the IEEE ISSPIT*, Marrakesh, pp.558-562, 2002. [cited in p.80]
- (Daugman,1993)** J. G. Daugman, “High Confidence Visual Recognition of Persons by a Test of Statistical Independence”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 15, No. 11, pp.1148–1161, Nov.1993. DOI:10.1109/34.244676 [cited in p.80,84,89,108]
- (Daugman,1994)** J. G. Daugman, “Biometric Personal Identification System Based on Iris Analysis”, U.S. Patent No. 5 291 560, Mar.1994. [cited in p.80,89]
- (Daugman,1995)** J. Daugman, “High Confidence Recognition of Persons by Rapid Video Analysis of Iris Texture”, *European Convention on Security and Detection*, pp.244-251, May.1995. DOI:10.1049/cp:19950506 [cited in p.87]
- (Daugman,1998)** J. Daugman, “Combining Multiple Biometrics”, 1998. Available at <http://www.cl.cam.ac.uk/~jgd1000/combine/combine.html>. [cited in p.61]

- (Daugman,2004)** J. Daugman, "How Iris Recognition Works", *IEEE Transactions on Circuits and Systems for Video Technology*, Vol.14, No.1, pp.21–30, Jan.2004. DOI:10.1109/TCSVT.2003.818350 [**cited in p.80,87,108**]
- (Daugman,2006)** J. Daugman, "Probing the Uniqueness and Randomness of IrisCodes : Results From 200 Billion Iris Pair Comparisons", *Proceedings of the IEEE*, Vol.94, No.11, pp.1927–1935, Nov.2006. DOI:10.1109/JPROC.2006.884092 [**cited in p.80**]
- (Daugman,2007)** J. Daugman, "New Methods in Iris Recognition", *IEEE Transactions on Systems, Man, and Cybernetics, Part B*, Vol.37, No.5, pp.1167–1175, Oct.2007. DOI:10.1109/TSMCB.2007.903540 [**cited in p.81**]
- (Deane,1995)** F. Deane, K. Barrelle, R. Henderson, and D. Mahar, "Perceived Acceptability of Biometric Security Systems", *Computers & Security*, Vol.14, No.3, pp.225–231, 1995. Doi:10.1016/0167-4048(95)00005-S [**cited in p.44**]
- (Delac,2004)** K. Delac and M. Grgic, "A Survey of Biometric Recognition Methods", *Proceedings Elmar-2004- the 46th International Symposium Electronics in Marine*, Zadar, Croatia, pp.184-193, Jun.2004. [**cited in p.30**]
- (Delac,2005)** K. Delac, M. Grgic, and S. Grgic, "Independent Comparative Study of PCA, ICA, and LDA on the FERET Data Set", *International Journal of Imaging Systems and Technology*, Vol.15, No.5, pp.252-260, Jan.2005. Doi: 10.1002/ima.20059 [**cited in p.73**]
- (Denoeux,1995)** T. Denoeux, "Nearest Neighbor classification rule based on Dempster- Shafer theory", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 25, No.5, pp.804-813, May.1995. DOI:10.1109/21.376493 [**cited in p.11**]
- (Denoeux,2000)** T. Denoeux, "A neural network classifier based on Dempster-Shafer Theory", *IEEE Transactions On Systems, Man, and Cybernetics – Part A: Systems and Humans*, Vol.30, No.2, pp.131-150, Mar.2000. DOI:10.1109/3468.833094 [**cited in p.11**]
- (Devillez,2004)** A. Devillez, "Four Fuzzy Supervised Classification Methods for Discriminating Classes of Non-Convex Shape", *Fuzzy Sets and Systems*, Vol.141, No.2, pp.219- 240, Jan.2004. Doi:10.1016/S0165-0114(03)00265-3 [**cited in p.11**]
- (Dhameliya,2013)** M. D. Dhameliya and P. C. Jitendra, "A Multimodal Biometric Recognition System based on Fusion of Palmprint and Fingerprint", *International Journal of Engineering Trends and Technology (IJETT)*, Vol.4, No.5, pp.1908-1911, May.2013. [**cited in p.56,59**]
- (Dominique,2007)** G. Dominique, Y. Fan, and P. Michel, "Design, Implementation and Evaluation of

- Hardware Vision Systems dedicated to Real-Time Face Recognition”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), pp.123-148, Ch.8, I-Tech Education and Publishing, ISBN:978-3-902613-03-5, Vienna, Austria,2007. [cited in p.74]
- (Dong,2011)** W. Dong, Z. Sun, and T. Tan, “Iris Matching Based on Personalized Weight Map”, *IEEE transactions on pattern analysis and machine intelligence*, Vol. 33, No. 9, pp.1744-1757, Sep.2011. DOI:10.1109/TPAMI.2010.227 [cited in p.81]
- (Dorairaj,2005)** V. Dorairaj, N. A. Schmid, and G. Fahmy, “Performance Evaluation of Non-Ideal Iris Based Recognition System Implementing Global ICA Technique”, *Proceedings of the IEEE International Conference on Image Processing (ICIP’05)*, Vol.3, pp.285–288, Sep.2005. DOI:10.1109/ICIP.2005.1530384 [cited in p.89]
- (Du,20004)** Y. Du, R. Ives, D. Etter, T. Welch, and C. Chang, “A New Approach to Iris Pattern Recognition”, *Proceedings of the SPIE Electro-Optical and Infrared Systems: Technology and Applications*, Vol.5612, pp.104–116, Oct.2004. Doi:10.1117/12.578789 [cited in p.84,89]
- (Duda,1972)** R. O. Duda and P. E. Hart, “Use of the Hough Transformation to Detect Lines and Curves in Pictures”, *Communications of the ACM*, Vol.15, No.1, pp.11–15, Jan.1972. Doi:10.1145/361237.361242 [cited in p.84]
- (Duda,1973)** R.O. Duda and P.E. Hart, “Pattern Classification and Scene Analysis”, Wiley, New York, 1973. [cited in p.6]
- (Duin,2002)** R. P.W. Duin, F. Roli, D. de Ridder , “A Note on Core Research Issues for Statistical Pattern Recognition”, *Pattern Recognition Letters*, Vol.23, No.4, pp.493–499, Feb.2002. Doi:10.1016/S0167-8655(01)00181-7 [cited in p.7]
- (Egan,1975)** J. P. Egan, “Signal Detection Theory and ROC-Analysis”, *Academic Press*, New York, 1975. [cited in p.37]
- (Elliott,2007)** S. J. Elliott, S. A. Massie, and M. J. Sutton, “The Perception of Biometric Technology: A Survey”, *IEEE workshop on Automatic Identification Advanced Technologies*, pp.259–264, Jun.2007. DOI:10.1109/AUTOID.2007.380630 [cited in p.45]
- (Eriksson,2000)** L. Eriksson, E. Johansson, M. Muller, and S. Wold, “On the Selection of the Training Set in Environmental QSAR Analysis When Compounds Are Clustered”, *Journal of Chemometrics*, Vol.14, No.5-6, pp.599-616, Sep.2000. DOI:10.1002/1099-128X(200009/12)14:5/6<599::AID-CEM619>3.0.CO;2-8 [cited in p.41]
- (Eskandari,2012)** M. Eskandari and Ö. Toygar, “Person Identification Using Face and Iris Multimodal Biometric System”, *Proceedings of the International Conference on Image*

- Processing, Computer Vision and Pattern Recognition (IPCV'12)*, 2012. [cited in p.103]
- (Eskandari,2013)** M. Eskandari, Ö. Toygar, and H. Demirel, "A New Approach for Face-Iris Multimodal Biometric Recognition Using Score Fusion", *International Journal of Pattern Recognition and Artificial Intelligence*, Vol.27, No.3, May.2013. Doi:10.1142/S0218001413560041 [cited in p.104]
- (Eskandari,2014)** M. Eskandari and O. Toygar, "Fusion of Face and Iris Biometrics Using Local and Global Feature Extraction Methods", *Signal Image and Video Processing*, Vol.8, No.6, pp.995-1006, Sep.2014. DOI: 10.1007/s11760-012-0411-4 [cited in p.56,104]
- (Eskandari,2015)** M. Eskandari and Ö. Toygar, "Selection of Optimized Features and Weights on Face-Iris Fusion Using Distance Images", *Computer Vision and Image Understanding*, Vol.137, pp.63-75, Aug.2015. Doi:10.1016/j.cviu.2015.02.011 [cited in p.105]
- (Fadzil,1994)** M. H. A. Fadzil and H. Abu Bakar, "Human Face Recognition Using Neural Networks", *International Conference on image Processing (ICIP)*, Vol.3, pp.936-939, Nov.1994. DOI:10.1109/ICIP.1994.413708 [cited in p.73]
- (Fakhar,2011)** K. Fakhar, M. El Aroussi, R. Saadane, M. Wahbi, and D. Aboutajdine, "Fusion of Face and Iris Features Extraction Based on Steerable Pyramid Representation for Multimodal Biometrics", *International Conference on Multimedia Computing and Systems (ICMCS'11)*, pp.1-4, Apr.2011. DOI:10.1109/ICMCS.2011.5945673 [cited in p.103]
- (Fan,2005)** X. Fan and B. Verma, "A Comparative Experimental Analysis of Separate and Combined Facial Features for GA-ANN based Technique", *Proceedings of 6th International Conference on Computational Intelligence and Multimedia Applications (ICCIMA '05)*, pp. 279-284, Aug.2005. DOI:10.1109/ICCIMA.2005.2 [cited in p.73]
- (Fang,2002)** Y. Fang, T. Tan, and Y. Wang, "Fusion of Global and Local Features for Face Verification", *Proceedings of 16th International Conference on Pattern Recognition (ICPR)*, Vol.2, pp.382- 385, Quebec City, Canada, Aug.2002. DOI:10.1109/ICPR.2002.1048319 [cited in p. 54,59]
- (Fathima,2014)** A. A. Fathima, S. Vasuhi, N. N. Babu, V. Vaidehi, and T. M. Treesa, "Fusion Framework for Multimodal Biometric Person Authentication System", *IAENG International Journal of Computer Science IJCS*, Vol.41, No.1, pp.18-31, Feb.2014. [cited in p. 53,56]
- (Feng,2004)** G. Feng, K. Dong, D. Hu, and D. Zhang, "When Faces are Combined with Palmprints:

- A Novel Biometric Fusion Strategy”, *Proceedings of the 1st International Conference on Biometric Authentication (ICBA’04)*, Vol.3072, pp.701-707, Hong Kong, China, 2004. DOI:10.1007/978-3-540-25948-0_95 [**cited in p.56,59**]
- (Feng,2006a)** S. Feng, H. Krim, I. Gu, M. Viberg, “3D Face Recognition Using Affine Integral Invariants”, *Proceedings of the IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP’06)*, Toulouse, Vol.2, pp.189-192, May.2006. DOI:10.1109/ICASSP.2006.1660311 [**cited in p.73**]
- (Feng,2006b)** X. Feng, C. Fang, Z. Ding, and Y. Wu, “Iris Localization with Dual Coarse-to-Fine Strategy”, *Proceedings of the 18th IEEE International Conference on Pattern Recognition (ICPR’06)*, Vol.4, pp.553–556, Aug.2006. DOI:10.1109/ICPR.2006.725 [**cited in p.84**]
- (Fernandez,2007)** F. A. Fernandez, J. Fierrez, J. Ortega-Garcia, J. Gonzalez-Rodriguez, H. Fronthaler, K. Kollreider, and J. Bigun, “A Comparative Study of Fingerprint Image-Quality Estimation Methods”, *IEEE Transactions on Information Forensics and Security*, Vol.2, No.4, pp.734–743, Dec.2007. DOI:10.1109/TIFS.2007.908228 [**cited in p.44**]
- (Fernandez,2008)** F. A. Fernandez, “Biometric Sample Quality and its Application to Multimodal Authentication Systems”, *PhD thesis*, Technical University of Madrid, Sep.2008. [**cited in p.42,43,44**]
- (Frigui,1996)** H. Frigui and R. Krishnapuram, “A Robust Algorithm for Automatic Extraction of an Unknown Number of Clusters From Noisy Data”, *Pattern Recognition Letters*, Vol.17, No.12, pp.1223-1232, Oct.1996. Doi:10.1016/0167-8655(96)00080-3 [**cited in p.11**]
- (Frigui,1997)** H. Frigui and R. Krishnapuram, “Clustering by Competitive Agglomeration”, *Pattern Recognition*, Vol.30, No.7, pp.1109-1119, Jul.1997. Doi:10.1016/S0031-3203(96)00140-9 [**cited in p.11**]
- (Frischholz,2000)** R. W. Frischholz and U. Dieckmann, “BioID: A Multimodal Biometric Identification System”, *IEEE Computer*, Vol.33, No.2, pp.64-68, Feb.2000. DOI:10.1109/2.820041 [**cited in p.56**]
- (Fuentes,2002)** M. Fuentes, S. Garcia-Salicetti, and B. Dorizzi, “On-line Signature Verification: Fusion of a Hidden Markov Model and a Neural Network via a Support Vector Machine”, *The 8th International Workshop on Frontiers in Handwriting Recognition (IWFHR’02)*, pp.253-258, Ontario, Canada, Aug.2002. DOI:10.1109/IWFHR.2002.1030918 [**cited in p.54**]
- (Fukunaga,1972)** K. Fukunaga, “Introduction to Statistical Pattern Recognition”, *Academic Press*, New

- York, Jan.1972. [cited in p.6]
- (Fukunaga,1990)** K. Fukunaga, “Introduction to Statistical Pattern Recognition”, *Academic Press*, Boston, 2nd edition, 1990. [cited in p.7]
- (Gabrys,2000)** B. Gabrys and A. Bargiela, “General Fuzzy Min-Max Neural Network for Clustering and Classification”, *IEEE Transactions on Neural Networks*, Vol.11, No.3, pp.769-783, May.2000. DOI:10.1109/72.846747 [cited in p.11]
- (Gan,2006)** J. Y. Gan and Y. Liang, “A Method for Face and Iris Feature Fusion in Identity Authentication”, *International Journal of Computer Science and Network Security IJCSNS*, Vol. 6, No.2B, pp.135-138, Feb.2006. [cited in p.56,59]
- (Gan,2008)** J. Y. Gan, J. H. Gao, and J. F. Liu, “Research on Face and Iris feature recognition based on 2DDCT and Kernel Fisher Discriminate Analysis”, *Proceedings of International conference on Wavelet analysis and pattern recognition (ICWAPR '08)*, Vol.1, pp.401-405, Hong Kong, Aug.2008. DOI:10.1109/ICWAPR.2008.4635812 [cited in p.101]
- (Gan,2009)** J. Y. Gan and J. F. Liu, “Fusion and Recognition of Face and Iris Feature Based on Wavelet Feature and KFDA”, *Proceedings of the IEEE International conference on Wavelet analysis and pattern recognition (ICWAPR '09)*, Boarding, pp.47-50, Jul.2009. DOI:10.1109/ICWAPR.2009.5207475 [cited in p.101]
- (Gan,2011)** J. Gan and P. Wang, "A Novel Model for Face Recognition", *Proceedings of International Conference on System Science and Engineering (ICSSE)*, pp.482-486, June.2011. DOI:10.1109/ICSSE.2011.5961951 [cited in p.73]
- (Ganesan,2006)** B. Ganeshan, D. Theckedath, R. Young, C. Chatwin, “Biometric Iris Recognition System Using a Fast and Robust Iris Localization and Alignment Procedure”, *Optics and Lasers in Engineering*, Vol.44, No.1, pp.1-24, 2006. DOI:10.1016/j.optlaseng.2005.03.010 [cited in p.81]
- (Garris,2004)** M. D. Garris, C. I. Watson, and C. L. Wilson, “Matching Performance for the US-Visit IDENT System Using Flat Fingerprints”, *National Institute of Standards and Technology (NIST) Internal Report 7110*, May.2004. [cited in p.55]
- (Gascuel,1998)** O. Gascuel, B. Bouchon-Meunier, G. Caraux, P. Gallinari, A. Guenoche, Y. Guermeur, Y. Lechevallier et al., “Twelve Numerical, Symbolic and Hybrid Supervised Classification Methods”, *International Journal of Pattern Recognition and Artificial Intelligence*, Vol.12, No.5, pp. 517–571, Aug.1998. DOI:10.1142/S0218001498000336 [cited in p.11]

- (Gawande,2010)** U. Gawande, M. Zaveri, and A. Kapur, "Improving Iris Recognition Accuracy by Score Based Fusion Method", *International Journal of Advancements in Technology (IJoAT'10)*, Vol.1, No.1, pp.1-12, Jun.2010. [cited in p.81,84,109]
- (Georghiades,2001)** A. S. Georghiades, P. N. Belhumeur, and D. J. Kriegman, "From Few to Many: Illumination Cone Models for Face Recognition under variable lighting and pose", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.23, No.6, pp.643-660, Jun.2001. DOI:10.1109/34.927464 [cited in p.73]
- (Gokberk,2006)** B. Gokberk and L. Akarun, "Comparative Analysis of Decision-Level Fusion Algorithms for 3D Face Recognition", *Proceedings of the 18th International Conference on Pattern Recognition (ICPR'06)*, pp.20–24, 2006. DOI:10.1109/ICPR.2006.387 [cited in p.73]
- (Gonzalez, 1978)** R.C. Gonzalez and M.G Thomas, "Syntactic Pattern Recognition: an Introduction", *Addison Wesley Publishing Company*, Reading, MA, 1978. [cited in p.7]
- (Gordon,1991)** G. G. Gordon, "Face Recognition Based on Depth Maps and Surface Curvature", *Proceedings SPIE 1570 Geometric Methods in Computer Vision*, Vol.1570, pp.234-247, Sep.1991. Doi:10.1117/12.48428 [cited in p.73]
- (Gorman,2003)** L. O'Gorman, "What is Pattern Recognition?", *International Association for Pattern Recognition IAPR Newsletter*, Vol.25, No.1, 2003. [cited in p.10]
- (Grabowski,2006)** K. Grabowski, W. Sankowski, M. Zubert, and M. Napieralska, "Reliable Iris Localization Method with Application to Iris Recognition in Near Infrared Light", *Proceedings of the IEEE International Conference on Mixed Design of Integrated Circuits and System MIXDES 2006*, pp.684-687, Jun.2006. DOI:10.1109/MIXDES.2006.1706671 [cited in p.84]
- (Grewal,2014)** S. K. Grewal, "A Composite Approach for Biometric Template Security", *International Journal and Conference Service Center (IJCSC)*, Vol.5, No.1, pp.170-176, 2014. [cited in p.61]
- (Grother,2007)** P. Grother and E. Tabassi, "Performance of Biometric Quality Measures", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.29, No.4, pp.531–543, Apr.2007. DOI:10.1109/TPAMI.2007.1019 [cited in p.42]
- (Gupta,2011)** R. Gupta and H. Saini, "Generation of Iris Template for Recognition of Iris in Efficient Manner", *International Journal of Computer Science and Technologies (IJCSIT)*, Vol.2, No.4, pp.1753-1755, 2011. [cited in p.89]
- (Haddadnia,2002)** J. Haddadnia, K. Faez, and M. Ahmadi, "N-Feature Neural Network Human Face

- Recognition", *Proceedings of 15th International Conference on Vision Interface*, Calgary, pp.300-307, May.2002. **[cited in p.73]**
- (Harguess,2011)** J. Harguess and J. K. Aggarwal, "Is There a Connection between Face Symmetry and Face Recognition?", *IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, pp.66-73, Jun.2011. DOI:10.1109/CVPRW.2011.5981805 **[cited in p.73]**
- (He,2003)** X. He and P. Niyogi, "Locality Preserving Projections", *Proceedings of Conference on Advances in Neural Information Processing Systems(NIPS'03)*, Vol.16, Dec.2003. **[cited in p.73]**
- (He,2006)** X. He and P. Shi, "A Novel Iris Segmentation Method for Hand-Held Capture Device", *International Conference on Biometrics, Springer Berlin Heidelberg*, pp. 479–485, Jan.2006. DOI: 10.1007/11608288_64 **[cited in p.84,109]**
- (He,2008)** Q. He, Z.A. Sun, T.N. Tan, and Y. Zou, "A Hierarchical Model for the Evaluation of Biometric Sample Quality", *The 19th International Conference on Pattern Recognition (ICPR'08)*, pp.1–4, Dec.2008. DOI:10.1109/ICPR.2008.4761866 **[cited in p.44]**
- (He,2009)** Z. He, T. Tan and Z. Sun, "Toward Accurate and Fast Iris Segmentation for Iris Biometrics", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.31, No.9, pp.1670-1684, Sep.2009. DOI:10.1109/TPAMI.2008.183 **[cited in p.109]**
- (Heckle,2007)** R. R. Heckle, A. S. Patrick, and A. Ozok, "Perception and Acceptance of Fingerprint Biometric Technology", *Proceedings of the 3rd Symposium on Usable Privacy and Security*, pp. 153–154, Jul.2007. Doi:10.1145/1280680.1280704 **[cited in p.45]**
- (Heisele,2003)** B. Heisele, P. Ho, J. Wu, and T. Poggio, "Face Recognition: Component-Based Versus Global Approaches", *Computer Vision and Image Understanding*, Vol.91, No.1, pp.6-21, Jul.2003. Doi:10.1016/S1077-3142(03)00073-0 **[cited in p.115]**
- (Heisele,2004)** B. Heisele and T. Koshizen, "Components for Face Recognition", *Proceedings of the 6th IEEE International Conference on Automatic Face and Gesture Recognition (FGR'04)*, pp.153–158, May.2004. DOI:10.1109/AFGR.2004.1301523 **[cited in p.73]**
- (Heo,2006)** J. Heo, Ma. Savvides, R. Abiantun, Ch. Xie, and B.V.K. Vijayakumar, "Face Recognition with Kernel Correlation Filters on a Large Scale Database", *IEEE International Conference on Acoustics Speech and Signal Processing(ICASSP)*, Toulouse, Vol.2, pp.181-184, May.2006. DOI:10.1109/ICASSP.2006.1660309 **[cited in p.73]**

- (Hesher,2003)** C. Hesher, A. Srivastava, and G. Erlebacher, “A Novel Technique for Face Recognition Using Range Imaging”, *Proceedings of the 7th International Symposium on Signal Processing and its Applications*, Vol.2, pp.201–204, Jul.2003. DOI:10.1109/ISSPA.2003.1224850 [cited in p.73]
- (Hiremath,2007)** P. S. Hiremath, A. Danti, and C. J. Prabhakar , “Modelling Uncertainty in Representation of Facial Features for Face Recognition”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), Ch. 10, I-Tech Education and Publishing, pp.183-218, ISBN:978-3-902613-03-5 ,Vienna, Austria, 2007. [cited in p.74]
- (Ho,1994)** T. K. Ho, J. J. Hull, and S. N. Srihari, “Decision Combination in Multiple Classifier Systems”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.16, No.1, pp.66–75, Jan.1994. DOI:10.1109/34.273716 [cited in p.60]
- (Hong,1998)** L. Hong and A. K. Jain, “Integrating Faces and Fingerprints for Personal Identification”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.20, No.12, pp.1295-1307, Dec.1998. DOI:10.1109/34.735803 [cited in p.56]
- (Hong,1999)** L. Hong, A. Jain, and S. Pankanti, “Can Multibiometrics Improve Performance?”, *Proceedings of the IEEE Workshop on Automatic Identification Advanced Technologies*, Vol.99, pp.59–64, Oct.1999. [cited in p.48]
- (Hosseini,2007)** S. M. Hosseini, B. N. Araabi, and H. S. Zadeh, “Shape Analysis of Stroma for Iris Recognition”, *Springer International Conference on Biometrics*, Springer Berlin Heidelberg, Vol.4642, pp.790–799, Aug.2007. DOI:10.1007/978-3-540-74549-5_83 [cited in p.89]
- (Hosseini,2010)** M. S. Hosseini, B. N. Araabi, and H. Soltanian-Zadeh, “Pigment Melanin: Pattern for Iris Recognition”, *IEEE transactions on instrumentation and measurement*, Vol.59, No.4, pp.792-804, Apr.2010. DOI:10.1109/TIM.2009.2037996 [cited in p.81]
- (Huang,2002)** Y. P. Huang, S. W. Luo, and E. Y. Chen, “An Efficient Iris Recognition System”, *Proceedings of the First International Conference on Machine Learning and Cybernetics*, Vol.1, pp.450–454, China, Nov.2002. DOI:10.1109/ICMLC.2002.1176794 [cited in p. 89]
- (Huang,2004)** J. Huang, Y. Wang, T. Tan, and J. Cui, “A New Iris Segmentation Method for Recognition”, *Proceedings of the 17th International Conference on Pattern Recognition (ICPR’04)*, Vol.3, pp.554–557, Aug.2004. DOI:10.1109/ICPR.2004.1334589 [cited in p.84,109]
- (Huang,2006)** L. L. Huang and A. Shimizu, “Combining Classifiers for Robust Face Detection”,

- International Symposium on Neural Networks*, Vol.3972, pp.116-121, May.2006. DOI: 10.1007/11760023_18 [cited in p.73]
- (Huang,2013)** Z. Huang, Y. Liu, C. Li, M. Yang, and L. Chen, "A Robust Face and Ear Based Multimodal Biometric System Using Sparse Representation", *Pattern Recognition*, Vol.46, No.8, pp.2156-2168, Aug.2013. DOI:10.1016/j.patcog.2013.01.022 [cited in p.59]
- (Iannarelli,1989)** A. Iannarelli, "Ear Identification", *Paramount Publishing Company*, Freemont, California, 1989. [cited in p.25]
- (Ibrahim,2011)** R. Ibrahim and Z. M. Zin, "Study Of Automated Face Recognition System for Office Door Access Control Application", *IEEE 3rd International Conference on Communication Software and Networks (ICCSN)*, pp.132-136, May.2011. DOI:10.1109/ICCSN.2011.6014865 [cited in p.73]
- (Im,2001)** S. K. Im, H. M. Park, Y. W. Kim, S. C. Han, S.W. Kim, and C. H. Kang, "Biometric Identification System by Extracting Hand Vein Patterns", *Journal of the Korean Physical Society*, Vol.38, No.3, pp.268-272, Mar.2001. [cited in p.24]
- (Islam,2013)** S. M. Islam, R. Davies, M. Bennamoun, R. A. Owens, and A. S. Mian, "Multibiometric Human Recognition Using 3D Ear and Face Features", *Pattern Recognition*, Vol.46, No.3, pp.613-627, Mar.2013. DOI:10.1016/j.patcog.2012.09.016 [cited in p.56]
- (Jain,1999)** A. K. Jain, L. Hong, and Y. Kulkarni, "A Multimodal Biometric System Using Fingerprint, Face and Speech", *The 2nd International Conference on Audio and Video based Biometric Person Authentication (AVBPA '99)*, Vol.10, pp.182-187, Washington D.C., USA, Mar.1999. [cited in p.56]
- (Jain,2000)** A. K. Jain, R. P. W. Duin, J. Mao, "Statistical Pattern Recognition: A Review", *IEEE Transactions on pattern analysis and machine intelligence*, Vol.22, No.1, pp.4-37, Jan.2000. DOI:10.1109/34.824819 [cited in p.7]
- (Jain,2002)** A. K. Jain and A. Ross, "Fingerprint Mosaicking", *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP)*, Vol.4, pp.4064-4067, Orlando, USA, May.2002. DOI:10.1109/ICASSP.2002.5745550 [cited in p.55]
- (Jain,2004a)** A. K. Jain and A. Ross, "Multibiometric systems", *Communications of the ACM*, Vol.47, No.1, pp.34–40, Jan.2004. Doi:10.1145/962081.962102 [cited in p.49]
- (Jain,2004b)** A. K. Jain, X. Lu, and D. Colbry, "Three-Dimensional Model Based Face Recognition", *Proceedings of the 17th International Conference on Pattern*

- Recognition (ICPR'04)*, Vol.I, pp.362–366, Aug.2004.
DOI:10.1109/ICPR.2004.1334127 [cited in p.73]
- (Jain,2004c) A. K. Jain, A. Ross, and S. Prabhakar, "An Introduction to Biometric Recognition", *IEEE Transactions on Circuits and Systems for Video Technology*, Vol.14, No.1, pp.4-20, Jan.2004. DOI:10.1109/TCSVT.2003.818349 [cited in p.30]
- (Jain,2005) A. Jain, K. Nandakumar, and A. Ross, "Score Normalization in Multimodal Biometric Systems", *Pattern Recognition*, Vol.38, No.12, pp. 2270–2285, Dec.2005. Doi: 10.1016/j.patcog.2005.01.012 [cited in p.63,64,116]
- (Jain,2006) A. Jain, P. Flynn, and A. Ross, "Handbook of Multibiometrics", Springer,2006. [cited in p.52]
- (Johnson,2011) P. A. Johnson, F. Hua, and S. Schuckers, "Comparison of Quality-Based Fusion of Face and Iris Biometrics", *IEEE International Joint Conference on Biometrics (IJCB)*, pp.1-5, Oct.2011. DOI:10.1109/IJCB.2011.6117481 [cited in p.103]
- (Jones,2007) L. A. Jones, A. I. Anton, and J. B. Earp, "Towards Understanding User Perceptions of Authentication Technologies", *Proceedings of the 2007 ACM Workshop on Privacy in the Electronic Society*, pp.91–98, Oct.2007. DOI:10.1145/1314333.1314352 [cited in p.45]
- (Kale,2004) A. Kale, A. K. RoyChowdhury, and R. Chellappa, "Fusion of Gait and Face for Human Identification", *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP'04)*, Vol.5, pp.901-904, Montreal, Canada, May.2004. DOI:10.1109/ICASSP.2004.1327257 [cited in p.56]
- (Kalka,2006) N. D. Kalka, J. Zuo, N. A. Schmid, and B. Cukic, "Image Quality Assessment for Iris Biometric", *Proceedings of SPIE Biometric Technology for Human Identification III*, Vol.6202, Apr.2006. DOI:10.1117/12.666448 [cited in p.44]
- (Kalra,2014) S. Kalra and A. Lamba, "Improving Performance by Combining Fingerprint and Iris in Multimodal Biometric", *International Journal of Computer Science & Information Technologies (IJCSIT)*, Vol.5, No.3, pp.4522-4525, 2014. [cited in p.59]
- (Kanade,1973) T. Kanade, "Picture Processing System by Computer Complex and Recognition of Human Faces", *PhD thesis*, Department of Information Science, Kyoto University, Nov.1973. [cited in p.73,74]
- (Kanal,1974) L. Kanal, "Patterns in Pattern Recognition", *IEEE Transaction on Information Theory*, Vol. IT-20, No.6, pp. 697–722, Nov.1974. DOI:10.1109/TIT.1974.1055306 [cited in

p.2]

- (Karthikeyan,2010)** T. Karthikeyan, "Efficient Biometric Iris Recognition System Using Fuzzy Neural Network", *International Journal of Advanced Networking and Applications*, Vol.1, No.06, pp.371-376, May.2010. **[cited in p.81,90]**
- (Kekre,2010)** H. B. Kekre, T. K. Sarode, V. A. Bharadi, A. A. Agrawal, R. J. Arora, and M. C. Nair, "Performance Comparison of DCT and VQ Based Techniques for Iris Recognition", *Journal of electronic science and technology*, Vol.8, No.3, pp.223-229, Sep.2010. DOI:10.3969/j.issn.1674-862X.2010.03.005 **[cited in p.81]**
- (Kekre,2011)** H. B. Kekre, V. A. Bharadi, V. I. Singh, V. I. Kaul, and B. Nemade, "Hybrid Multimodal Biometric Recognition using Kekre's Wavelets, 1D Transforms & Kekre's Vector Quantization Algorithms Based Feature Extraction of Face & Iris", *International Journal of Computer Applications(IJCA)*, Vol.3, No.3, pp.29-34, 2011. **[cited in p.101]**
- (Khiari,2008)** N. Khiari, H. Mahersia, and K. Hamrouni, "Iris Recognition Using Steerable Pyramids", *IEEE of the first International Workshops on Image Processing Theory: Tools and Applications(IPTA '08)*, pp.1-7, Sousse, Tunisia, Nov.2008. DOI:10.1109/IPTA.2008.4743737 **[cited in p.84,109]**
- (Kim,2002)** K. I. Kim, K. Jung, and H.J. Kim, "Face Recognition Using Kernel Principal Component Analysis", *IEEE Signal Processing Letters*, Vol.9, No.2, pp.40-42, Feb.2002. DOI:10.1109/97.991133 **[cited in p.73]**
- (Kim,2004)** J. Kim, S. Cho, and J. Choi, "Iris Recognition Using Wavelet Features", *Journal of VLSI Signal Processing Systems for Signal Image and Video Technology*, Vol.38, No.2, pp.147–156, Sep.2004. DOI:10.1023/B:VLSI.0000040426.72253.b1 **[cited in p.84,89]**
- (Kim,2012)** Y. G. Kim, K. Y. Shin, E. C. Lee, and K. R. Park, "Multimodal Biometric System Based on the Recognition of Face and Both Irises", *International Journal of Advanced Robotic Systems*, Vol.9, No.3, pp.1-6, Sep.2012. DOI:10.5772/50869 **[cited in p.104]**
- (Kinnunen,2004)** T. Kinnunen, V. Hautamaki, and P. Franti, "Fusion of Spectral Feature Sets for Accurate Speaker Identification", *The 9th Conference on Speech and Computer*, pp.361-365, Saint-Petersburg, Russia, Aug.2004. **[cited in p.54]**
- (Kittler,1998)** J. Kittler, M. Hatef, R. R. Duin, and J. G. Matas, "On Combining Classifiers", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.20, No.3, pp.226-239, Mar.1998. DOI:10.1109/34.667881 **[cited in p.56,117]**

- (Kittler,2004)** J. Kittler and M. Sadeghi, “Physics-Based Decorrelation of Image Data for Decision Level Fusion in Face Verification”, *In 5th International Workshop on Multiple Classifier Systems*, Vol.3077, pp.354-363, Cagliari, Italy, Jun.2004. DOI:10.1007/978-3-540-25966-4_35 [cited in p.53]
- (Kodate,2007)** K. Kodate and E. Watanabe, “Compact Parallel Optical Correlator for Face Recognition and its Application”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), Ch. 12, I-Tech Education and Publishing, pp.235-260, ISBN:978-3-902613-03-5, Vienna, Austria, 2007. [cited in p.74]
- (Kong,2001)** W. K Kong and D. Zhang, “Accurate Iris Segmentation Method Based on Novel Reflection and Eyelash Detection Model”, *Proceedings of the International Symposium on Intelligent Multimedia, Video and Speech Processing*, pp. 263–266, Hong Kong, May.2001. DOI:10.1109/ISIMP.2001.925384 [cited in p.84,109]
- (Kong,2010)** A. W. Kong, D. Zhang, and M. S. Kamel, “An Analysis of IrisCode”, *IEEE transactions on image processing*, Vol.19, No. 2, pp.522-532, Feb.2010. DOI:10.1109/TIP.2009.2033427 [cited in p.81]
- (Kong,2012)** A. W. Kong, “Iris Code Decompression Based on the Dependence between Its Bit Pairs”, *IEEE transactions on pattern analysis and machine intelligence*, Vol.34, No.3, pp.506-520, Mar.2012. DOI:10.1109/TPAMI.2011.159 [cited in p.82]
- (Kotropoulos,1997)** C. Kotropoulos and I. Pitas, “Rule-Based Face Detection in Frontal Views”, *IEEE International Conference on Acoustics Speech, and Signal Processing (ICASSP’97)*, Vol.4, pp. 2537–2540, Apr.1997. DOI:10.1109/ICASSP.1997.595305 [cited in p.74]
- (Krawczyk,2005)** S. Krawczyk and A. J. Jain, “Securing Electronic Medical Records Using Biometric Authentication”, *Proceedings of 5th International Conference on Audio- and Video-based Biometric Person Authentication (AVBPA’05)*, Vol.3546, pp.1110-1119, Rye Brook, USA, Jul.2005. DOI:10.1007/11527923_115 [cited in p.56]
- (Krichen,2004)** E. Krichen, M. A. Mellakh, S. Garcia-Salicetti, and B. Dorizzi, “Iris Identification Using Wavelet Packets”, *Proceedings of the 17th International Conference on Pattern Recognition (ICPR’04)*, Vol.4, pp. 335–338. Aug.2004. DOI:10.1109/ICPR.2004.1333771 [cited in p.89]
- (Krichen,2007)** E. Krichen, S. G. Salicetti, and B. Dorizzi, “A New Probabilistic Iris Quality Measure for Comprehensive Noise Detection”, *IE6+EE First International Conference on Biometrics: Theory, Applications and Systems (BTAS 2007)*, pp. 1–6, Sep.2007. DOI:10.1109/BTAS.2007.4401906 [cited in p.44]

- (Kshirsagar,2011)** V. P. Kshirsagar, M. R. Baviskar, and M. E. Gaikwad, "Face Recognition Using Eigenfaces", *Proceedings of the 3rd International Conference on Computer Research and Development (ICCRD'11)*, Vol.2, pp.302-306, Mar.2011. DOI:10.1109/ICCRD.2011.5764137 [cited in p.73]
- (Kukula,2009)** E. P. Kukula and R. W. Proctor, "Human-Biometric Sensor Interaction : Impact of Training on Biometric System and User Performance", *Proceedings of the Symposium on Human Interface and the Management of Information. Part II*, Vol.5618, pp.168–177, Jul.2009. DOI:10.1007/978-3-642-02559-4_19 [cited in p.44]
- (Kumar,2003)** A. Kumar, D. C. M. Wong, H. C. Shen, and A. K. Jain, "Personal Verification Using Palmprint and Hand Geometry Biometric", *The 4th International Conference on Audio- and Video-based Biometric Person Authentication (AVBPA'03)*, Vol.2688, pp.668-678, Guildford, UK,Jun.2003. DOI:10.1007/3-540-44887-X_78 [cited in p.54]
- (Kumar,2005)** A. Kumar and D. Zhang, "Personal Authentication using Multiple Palmprint Representation", *Pattern Recognition*, Vol. 38, No.10, pp.1695-1704, Oct.2005. Doi:10.1016/j.patcog.2005.03.012 [cited in p.54]
- (Kumar,2011)** A. Kumar and S. Shekhar, "Personal Identification Using Multibiometrics Rank-Level Fusion", *IEEE Transactions on Systems Man and Cybernetics Part C: Applications and Reviews*, Vol.41, No.5, pp.743-752, Sep.2011. DOI:10.1109/TSMCC.2010.2089516 [cited in p.60]
- (Kumari,2014)** P. A. Kumari and G. J. Suma, "A Novel Mutimodal Biometric Scheme or Personal Authentication", *IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET)*, Vol.2, No.2, pp. 55-66, Feb.2014. [cited in p.59]
- (Kuncheva,1998)** L. I. Kuncheva and J. C. Bezdek, "An Integrated Framework for Generalised Nearest Prototype Classifier Design", *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, Vol.6, No.5, pp.437-457, Oct.1998. DOI:10.1142/S0218488598000355 [cited in p.11]
- (Kwak,2004)** K. C. Kwak and W. Pedrycz , "Face Recognition Using Fuzzy Integral and Wavelet Decomposition Method", *IEEE transactions on systems, man, and cybernetics-part B (Cybernetics)*, Vol.34, No.4, pp.1666-1675, Aug.2004. DOI:10.1109/TSMCB.2004.827609 [cited in p.117]
- (Lades,1993)** M. Lades, J.C. Vorbruggen, J. Buhmann, J. Lange, C. von der Malsburg, R.P. Wurtz, and W. Konen, "Distortion Invariant Object Recognition in the Dynamic Link Architecture", *IEEE Transactions on Computers*, Vol.42, No.3, pp.300-311,Mar.1993.

- DOI:10.1109/12.210173 [cited in p.73]
- (Lagerwall,2016)** B. Lagerwall, S. Viriri, “Increasing Face Recognition Rate”, International Journal of Computers Communications & Control, Vol.11, No.3, pp.381-393, Jun.2016. [cited in p.74]
- (Lam,1995)** L. Lam and C. Suen, “Optimal Combinations of Pattern Classifiers”, *Pattern Recognition Letters*, Vol. 16, No. 9, pp. 945–954, 1995. Doi:10.1016/0167-8655(95)00050-Q [cited in p.61]
- (Lam,1997)** L. Lam and C. Y. Suen, “Application of Majority Voting to Pattern Recognition: An Analysis of its Behavior and Performance”, *IEEE Transactions on Systems Man and Cybernetics- Part A: Systems and Humans*, Vol.27, No.5, pp.553–568, Sep.1997. DOI:10.1109/3468.618255 [cited in p.61]
- (Lanitis,1995)** A. Lanitis, C. J. Taylor, and T. F. Cootes, “Automatic Face Identification System Using Flexible Appearance Models”, *Image and Vision Computing*, Vol.13, No.5, pp.393–401, Jun.1995. Doi:10.1016/0262-8856(95)99726-H [cited in p.74]
- (Lawrence,1997)** S. Lawrence, C. L. Giles, A. C. Tsoi, and A.D. Back, "Face Recognition: A Convolutional Neural-Network Approach", *IEEE Transactions Neural Networks*, Vol.8, No.1, pp.98-113, Jan.1997. DOI:10.1109/72.554195 [cited in p.73]
- (Lee,1990)** J. C. Lee and E. Milios, “Matching Range Images of Human Faces”, *Proceedings of the 3rdIEEE International Conference on Computer Vision*, pp.722-726, Dec.1990. DOI:10.1109/ICCV.1990.139627 [cited in p.73]
- (Lee,2001)** H. C. Lee and R. E. Gaesslen, “Advances in Fingerprint Technology”, *Elsevier Publishing*, New York, 2nd edition, 2001. [cited in p.22]
- (Lee,2006)** S. Lee, C. Lee, and J. Kim, “Model-Based Quality Estimation Of Fingerprint Images”, *IAPR/IEEE International Conference on Biometrics (ICB '06)*, Vol.3832, pp.229-235, Jan.2006. DOI:10.1007/11608288_31 [cited in p.44]
- (Lee,2007)** P. H. Lee, L. J. Chu, Y. P. Hung, S. W. Shih, C. S. Chen, and H. M. Wang, “Cascading Multimodal Verification Using Face, Voice and Iris Information”, *IEEE International Conference on Multimedia and Expo(ICME'07)*, pp. 847-850, Jul.2007. DOI:10.1109/ICME.2007.4284783 [cited in p.105]
- (Leung,1995)** T. K. Leung, M. C. Burl, and P. Perona, “Finding Faces in Cluttered Scenes Using Random Labeled Graph Matching”, *Proceedings of the 5th International Conference on Computer Vision*, pp.637–644, Jun.1995. [cited in p.74]

- (Levin,2002)** A. Levin and A. Shashua, “Principal Component Analysis over Continuous Subspaces and Intersection of Half-Spaces”, *Proceedings of 7th European Conference on Computer Vision*, pp.635-650, May.2002. Doi: 10.1007/3-540-47977-5_42 [cited in p.73]
- (Li,2001)** S. Z. Li, X. W. Hou, H. J. Zhang, and Q. S. Cheng, “Learning Spatially Localized, Parts- Based Representation”, *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'01)*, Vol.1, pp.207-212, 2001. DOI:10.1109/CVPR.2001.990477 [cited in p.73]
- (Li,2003)** Y. Li, S. Gong, and H. Liddell, “Constructing Facial Identity Surfaces for Recognition”, *International Journal of Computer Vision*, Vol.53, No.1, pp.71-92, Jun.2003. DOI:10.1023/A:1023083725143 [cited in p.55]
- (Li,2006)** G. Li, J. Zhang, Y. Wang, and W. J. Freeman, “Face Recognition Using a Neural Network Simulating Olfactory Systems”, *International Symposium on Neural Networks*, Vol.3972, No.1, pp.93-97, May.2006. DOI: 10.1007/11760023_14 [cited in p.73]
- (Li,2009)** Y. Li, J. Yin, E. Zhu, C. Hu, and H. Chen, “Studies of Fingerprint Template Selection and Update”, *Advances in Computational Science and Engineering*, Springer Berlin Heidelberg, Vol.28, pp.150–163, 2009. DOI:10.1007/978-3-642-10238-7_13 [cited in p.117]
- (Li,2013)** Y .H. Li and M. Savvides, “An Automatic Iris Occlusion Estimation Method based on High-Dimensional Density Estimation”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.35, No.4, pp.784-796, Apr.2013. DOI:10.1109/TPAMI.2012.169 [cited in p.82]
- (Liau,2011)** H. F. Liau and D. Isa, “Feature Selection for Support Vector Machine-Based Face-Iris Multimodal Biometric System”, *Expert Systems with Applications*, Vol. 38, No.9, pp.11105–11111, Sep.2011. DOI:10.1016/j.eswa.2011.02.155 [cited in p.103]
- (Lili,20005)** P. Lili and X. Mei, “The Algorithm of Iris Image Processing”, *Proceedings of 4th IEEE Workshop on Automatic Identification Advanced Technologies*, pp.134–138, Oct.2005. DOI:10.1109/AUTOID.2005.47 [cited in p.84]
- (Lim,2001)** S. Lim, K. Lee, O. Byeon, and T. Kim, “Efficient Iris Recognition through Improvement of Feature Vector and Classifier”, *ETRI Journal*, Vol.23, No.2, pp.61–70, Jun.2001. DOI:10.4218/etrij.01.0101.0203 [cited in p.80,90]
- (Lin,1997)** S. H. Lin, S. Y. Kung, and L.J. Lin, “Face Recognition/Detection by Probabilistic

- Decision-Based Neural Network”, *IEEE Transactions on Neural Networks*, Vol.8, No.1, pp.114-132, Jan.1997. DOI:10.1109/72.554196 [**cited in p.73**]
- (Lin,2000)** S. H. Lin, “An Introduction to Face Recognition Technology”, *Informing Science Special Issue on Multimedia Informing Technologies-Part 2*, Vol.3, No.1, pp.1-7, Jan.2000. [**cited in p.74**]
- (Lin,2009)** J. Lin, J. P. Li, H. Lin, and J. Ming, “Robust Person Identification with Face and Iris by Modified PUM Method”, *International Conference on Apperceiving Computing and Intelligence Analysis (ICACIA'09)*, pp.321-324, Oct.2009. DOI:10.1109/ICACIA.2009.5361089 [**cited in p. 56,101**]
- (Linares,2003)** L. R. Linares, C. G. Mateo, and J. L. A. Castro, “On Combining Classifiers for Speaker Authentication”, *Pattern Recognition*, Vol.36, No.2, pp.347-359, Feb.2003. DOI:10.1016/S0031-3203(02)00035-3 [**cited in p.54**]
- (Liu,1999)** C. Liu and H. Wechsler, “Comparative Assessment of Independent Component Analysis (ICA) for Face Recognition”, *The second International Conference on Audio and Video Based Biometric Person Authentication (AVBPA '99)*, Washington D.C. USA, Mar.1999. [**cited in p.73**]
- (Liu,2000)** Q. Liu, S. Levinson, Y. Wu, T. S. Huang, “Interactive and Incremental Learning via a Mixture of Supervised and Unsupervised Learning Strategies”, *Proceedings of the Fifth Joint Conference on Information Sciences (JCIS' 00)*, Vol.1, pp.555-558, NJ, USA, Feb.2000. [**cited in p.11**]
- (Liu,2003)** Y. Liu, S. Yuan, X. Zhu, and Q. Cui, “A Practical Iris Acquisition System and a Fast Edges Locating Algorithm in Iris Recognition”, *Proceedings of the 20th IEEE Conference on Instrumentation and Measurement Technology (IMTC'03)*, Vol.1, pp.166–168, May.2003. DOI:10.1109/IMTC.2003.1208145 [**cited in p.84,109**]
- (Liu,2005a)** X. Liu, K. W. Bowyer and P. J. Flynn, “Experimental Evaluation of Iris Recognition”, *IEEE Conference Computer Vision and Pattern Recognition (CVPR '05)*, pp.158-165, Jun.2005. DOI:10.1109/CVPR.2005.576 [**cited in p.109**]
- (Liu,2005b)** X. Liu, K. W. Bowyer, and P. J. Flynn, “Experiments with An Improved Iris Segmentation Algorithm”, *Fourth IEEE Workshop on Automatic Identification Advanced Technologies (AutoID)*, pp.118-123, New York, Oct.2005. DOI:10.1109/AUTOID.2005.21 [**cited in p.109**]
- (Lorente,1999)** L. Lorente and L. Torres, “Face Recognition of Video Sequences in a MPEG-7 Context Using a Global Eigen Approach”, *International Conference on Image*

- Processing*, Kobe, Japan, Vol.4, pp.187-191, Oct.1999.
DOI:10.1109/ICIP.1999.819576 [cited in p.73]
- (Lu,2003) X. Lu, Y. Wang, and A. K. Jain, "Combining Classifiers for Face Recognition", *IEEE International Conference on Multimedia and Expo (ICME'03)*, Vol.3, pp.13-16, Jul.2003. DOI:10.1109/ICME.2003.1221236 [cited in p.54,73]
- (Lu,2005) X. Lu and A. K. Jain, "Integrating Range and Texture Information for 3D Face Recognition", *IEEE Computer Society Workshop on Application of Computer Vision (WACV)*, Vol.1, pp.156-163, Breckenridge, USA, Jan.2005. DOI:10.1109/ACVMOT.2005.64 [cited in p.53,73]
- (Lu,2006a) K. Lu, X. He, and J. Zhao, "Semi-Supervised Support Vector Learning for Face Recognition", *International Symposium on Neural Networks*, Vol.3972, pp.104-109, May.2006. DOI:10.1007/11760023_16 [cited in p.73,74]
- (Lu,2006b) X. Lu and A. K. Jain, "Automatic Feature Extraction for Multiview 3D Face Recognition", *Proceedings of 7th IEEE International Conference on Automatic Face and Gesture Recognition (FGR'06)*, pp.585–590, Apr.2006. DOI:10.1109/FGR.2006.23 [cited in p.73]
- (Lu,2006c) X. Lu and A. K. Jain, "Deformation Modeling for Robust 3D Face Matching", *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'06)*, pp.1377–1383, 2006. DOI:10.1109/CVPR.2006.96 [cited in p.73]
- (Lu,2006d) X. Lu, A. K. Jain, and D. Colbry, "Matching 2.5D Face Scans to 3D Models", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.28, No.1, pp.31–43, Jan.2006. DOI:10.1109/TPAMI.2006.15 [cited in p.73]
- (Lu,2014) L. Lu and J. Peng, "Finger Multi-Biometric Cryptosystem using Feature Level Fusion", *International Journal of Signal Processing Image Processing and Pattern Recognition*, Vol.7, No.3, pp.223-236, 2014. [cited in p.59]
- (Lum,1999) A. Lum, "Fingerprint Recognition", *Pattern Recognition*, Vol.5, No.2, pp.72–85, Jun.1999. [cited in p.116]
- (Lyengar,1995) S. Lyengar, L. Prasad, and H. Min, "Advances in Distributed Sensor Technology", *IEEE parallel and Distributed Technology Systems and Applications*, Vol.4, No.4, pp.83-84, 1995. DOI:10.1109/MPDT.1996.7102340 [cited in p.58]
- (Ma,2002a) L. Ma, Y. Wang, and T. Tan, "Iris Recognition Based on Multichannel Gabor Filtering", *Proceedings of The 5th Asian Conference on Computer Vision(ACCV'02)*,

- pp.23-25, Melbourne, Australia, Jan.2002. **[cited in p.80,84, 109]**
- (Ma,2002b)** L. Ma, Y. Wang, and T. Tan, "Iris Recognition Using Circular Symmetric Filters", *Proceedings of the 16th International Conference on Pattern Recognition (ICPR'02)*, Vol.2, pp.414–417, Quebec, Aug.2002. DOI:10.1109/ICPR.2002.1048327 **[cited in p.109]**
- (Ma,2003)** L. Ma, T. Tan, Y. Wang, and D. Zhang, "Personal Identification Based on Iris Texture Analysis", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.25, No.12, pp.1519–1533, Dec.2003. DOI:10.1109/TPAMI.2003.1251145 **[cited in p. 80,84,89,90,109]**
- (Ma,2004)** L. Ma, T. Tan, Y. Wang, and D. Zhang, "Efficient Iris Recognition by Characterizing Key Local Variations", *IEEE Transactions on Image Processing*, Vol.13, No.6, pp.739–750, Jun.2004. DOI:10.1109/TIP.2004.827237 **[cited in p.80,84,109]**
- (Makinde,2014)** A. S. Makinde, Y. Nkansah-Gyekye, and L. S. Laizer, "Enhancing the Accuracy of Biometric Feature Extraction Fusion Using Gabor Filter and Mahalanobis Distance Algorithm", *International Journal of Computer Science and Information Security (IJCSIS)*, Vol.12, No.7, pp. 1-8, Jul.2014. DOI:10.13140/2.1.3202.6248 **[cited in p.59]**
- (Marcialis,2004a)** G. L. Marcialis and F. Roli, "Fingerprint Verification by Fusion of Optical and Capacitive Sensors", *Pattern Recognition Letters*, Vol.25, No.11, pp.1315-1322, Aug.2004. DOI:10.1016/j.patrec.2004.05.011 **[cited in p. 53]**
- (Marcialis,2004b)** G. L. Marcialis and F. Roli, "Fusion of Appearance-based Face Recognition Algorithms", *Pattern Analysis and Applications*, Vol.7, No.2, pp.151-163, Jul.2004. DOI:10.1007/s10044-004-0212-7 **[cited in p. 54]**
- (Marcialis,2005)** G. L. Marcialis and F. Roli, "Fusion of Multiple Fingerprint Matchers by Single-layer Perceptron with Class-separation Loss Function", *Pattern Recognition Letters*, Vol.26, No.12, pp.1830-1839, Sep.2005. DOI:10.1016/j.patrec.2005.03.004 **[cited in p. 54]**
- (Martens,1998)** H. A. Martens and P. Dardenne, "Validation and Verification of Regression in Small Data Sets", *Chemometrics and Intelligent Laboratory Systems*, Vol.44, No.1-2, pp. 99-121, Dec.1998. DOI:10.1016/S0169-7439(98)00167-1 **[cited in p.41]**
- (Martin,1997)** A. Martin, G. Doddington, T. Kamm, M. Ordowski, and M. Przybocki, "The DET Curve in Assessment of Detection Task Performance", *The 5th European Conference on Speech Communication and Technology (EUROSPEECH'97)*, pp.1895-1898,1997. **[cited in p.37]**
- (Martinez,2001)** A. M. Martinez and A.C. Kak, "PCA versus LDA", *IEEE Transactions on Pattern*

- Analysis and Machine Intelligence (PAMI)*, Vol.23, No.2, pp.228-233, Feb.2001.
DOI:10.1109/34.908974 [cited in p.73]
- (Martinez,2002)** A. M. Martinez, “Recognizing Imprecisely Localized, Partially Occluded, and Expression Variant Faces from a Single Sample Per Class”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.24, No.6, pp.748–763, Jun.2002.
DOI:10.1109/TPAMI.2002.1008382 [cited in p.73]
- (Masek,2003)** L. Masek, “Recognition of Human Iris Patterns for Biometric Identification”, *PhD thesis*, University of Western Australia, 2003. [cited in p. 84,86,88,109,109,112]
- (Matsumoto,2002)** T. Matsumoto, H. Matsumoto, K. Yamada, and S. Hoshino, “Impact of Artificial Gummy Fingers on Fingerprint Systems”, *Proceedings of SPIE Optical Security and Counterfeit Deterrence Techniques IV*, Vol.4677, pp.275–289, Jan.2002.
DOI:10.1117/12.462719 [cited in p. 36,50]
- (Mesecan,2013)** I. Mesecan, A. Eleyan, B. Karlik, “Sift-based Iris Recognition Using Sub-Segments”, *IEEE International Conference on Technological Advances in Electrical Electronics and Computer Engineering (TAAECE)*, pp.350-353, May.2013.
DOI:10.1109/TAAECE.2013.6557299 [cited in p.82]
- (Mian,2007)** A. S. Mian, M. Bennamoun, and R. Owens, “An Efficient Multimodal 2D-3D Hybrid Approach to Automatic Face Recognition”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.29, No.11, pp.1927–1943, Nov.2007.
DOI:10.1109/TPAMI.2007.1105 [cited in p.73]
- (Mira,2003)** J. Mira and J. Mayer, “Image Feature Extraction for Application of Biometric Identification of Iris -A Morphological Approach”, *Proceedings of the 16th Brazilian Symposium on Computer Graphics and Image Processing (SIBGRAPI'03)*, pp.391–398, Brazil, Oct.2003. DOI:10.1109/SIBGRA.2003.1241035 [cited in p.84]
- (Miura,2004)** N. Miura, A. Nagasaka, and T. Miyatake, “Feature Extraction of FingerVein Patterns Based on Repeated Line Tracking and its Application to Personal Identification”, *Machine Vision and Applications*, Vol.15, No.4, pp.194-203, Oct.2004.
DOI:10.1007/s00138-004-0149-2 [cited in p.24]
- (Miyazawa,2005)** K. Miyazawa, K. Ito, T. Aoki, K. Kobayashi, and H. Nakajima, “An Efficient Iris Recognition Algorithm Using Phase-Based Image Matching”, *Proceedings of IEEE International Conference on Image Processing (ICIP'05)*, Vol.2, pp.49–52, Sep.2005.
DOI:10.1109/ICIP.2005.1529988 [cited in p.89]
- (Moghaddam,2002)** B. Moghaddam, “Principal manifolds and probabilistic subspaces for visual

- recognition”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 24, No. 6, pp.780-788, Jun.2002. DOI:10.1109/TPAMI.2002.1008384 [cited in p.73]
- (Monro,2007)** D. M. Monro, S. Rakshit, and D. Zhang, “DCT-Based Iris Recognition”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.29, No.4, pp.586–595, Apr. 2007. DOI:10.1109/TPAMI.2007.1002 [cited in p.81,84,89,109]
- (Monwar,2009)** M. M. Monwar and M. L. Gavrilova, "Multimodal Biometric System Using Rank-Level Fusion Approach", *IEEE Transactions on Systems Man and Cybernetics Part B: Cybernetics*, Vol.39, No.4, pp.867-878, Aug.2009. DOI:10.1109/TSMCB.2008.2009071 [cited in p.60]
- (Monwar,2010)** M. M. Monwar and M. L. Gavrilova, "Secured Access Control Through Markov Chain Based Rank Level Fusion Method", *Proceedings of the 5th International Conference on Computer Vision Theory and Applications (VISAPP)*, Angres, France, pp.458-463, 2010. [cited in p.60]
- (Monwar,2012)** M. M. Monwar, "A Multimodal Biometric System Based on Rank Level Fusion", *PhD Thesis*, Department of Computer Science University of Calgary, Dec.2012. [cited in p.60]
- (Moody,2004)** J. Moody, “Public Perceptions of Biometric Devices: The Effect of Misinformation on Acceptance and Use”, *Journal of issues in the Informing Science and Information Technology*, Vol.1, pp.753–761, 2004. [cited in p.45]
- (Moon,2001)** H. Moon, P. J. Phillips, “Computational and Performance Aspects of PCA-Based Face Recognition Algorithms”, *Perception*, Vol.30, No.3, pp.303-321, 2001. DOI:10.1068/p2896 [cited in p.73]
- (Moon,2004)** Y. S. Moon, H. W. Yeung, K. C. Chan, and S. O. Chan, “Template Synthesis and Image Mosaicking for Fingerprint Registration: An Experimental Study”, *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP'04)*, Vol.5, pp.409-412, Montreal, Canada, May.2004. DOI:10.1109/ICASSP.2004.1327134 [cited in p.55]
- (Morizet,2009)** N. Morizet, “Reconnaissance Biométrique par Fusion Multimodale du Visage et de L’iris”, *Thèse de doctorat*, l’Ecole Nationale Supérieure des Télécommunications de Paris, Mar.2009. [cited in p.56,103]
- (Moses,1994)** Y. Moses, Y. Adani, and S. Ullman, “Face Recognition: The Problem of Compensating for Changes in Illumination Direction”, *Proceedings European Conference on Computer Vision*, pp.286-296, May.1994. DOI:10.1007/3-540-57956-

- 7_33 [cited in p.73]
- (Murase,1995)** H. Murase and S. K. Nayar, "Visual Learning and Recognition of 3-D Objects from Appearance", *International Journal of Computer Vision*, Vol.14, No.1, pp.5-24, Jan.1995. DOI: 10.1007/BF01421486 [cited in p.73]
- (Muron,2001)** A. Muron, P. Kois, and J. Pospisil, "Identification of Persons by Means of the Fourier Spectra of the Optical Transmission Binary Models of the Human Irises", *Optics Communications*, Vol.192, No.3-6, pp.161–167, Jun.2001. DOI:10.1016/S0030-4018(01)01169-5 [cited in p.89]
- (Naghate,2014)** A. Naghate, M. Sahu, P. Bhange, S. Lonkar, P. Wankhede, and Y. Bute, "Implementation of Multibiometric System Using Iris and Thumb Recognition", *International Journal of Computer Science and Mobile Computing (IJCSMC)*, Vol.3, No.3, pp.932-940, Mar.2014. [cited in p.61]
- (Nair,2013)** S. A. H. Nair, P. Aruna, and M. Vadivukarassi, "PCA Based Image Fusion of Face and Iris Biometric Features", *International Journal on Advanced Computer Theory and Engineering (IJAECTE)*, Vol.1, No.2, pp.106-112, 2013. [cited in p.102]
- (Nam,2004)** K. W. Nam, K. L. Yoon, J. S. Bark, and W. S. Yang, "A Feature Extraction Method for Binary Iris Code Construction", *Proceedings of the 2nd International Conference on Information Technology for Application (ICITA '04)*, pp.284–288, China, Jan.2004. [cited in p.89]
- (Nefian,1996)** A.V. Nefian, "Statistical Approaches to Face Recognition", *Qualifying Examination Report*, Georgia Institute of Technology, Dec. 1996. [cited in p.73]
- (Nishino,2004)** K. Nishino and S. K. Nayar, "Eyes for Relighting", *Proceedings of ACM Transactions on Graphics (TOG)*, Vol.23, No. 3, pp.704–711, Aug.2004. DOI:10.1145/1015706.1015783 [cited in p.84]
- (Niyogi,1994)** S. A. Niyogi and E. H. Adelson, "Analyzing Gait with Spatiotemporal Surfaces", *Proceedings of IEEE Workshop on Non-Rigid Motion and Articulated Objects*, pp.64–69, Nov.1994. DOI:10.1109/MNRAO.1994.346253 [cited in p.25]
- (Noh,2005)** S. Noh, K. Bae, K. R Park, and J. Kim, "A New Iris Recognition Method Using Independent Component Analysis", *IEICE- Transactions on Information and Systems*, Vol.E88-D, No.11, pp.2573–2581, Nov.2005. Doi:10.1093/ietisy/e88-d.11.2573 [cited in p.81]
- (Onofrio,2006)** D. Onofrio, A. Rama, F. Tarres, and S. Tubaro, "P2CA: How Much Information is needed", *IEEE International Conference on Image Processing(ICIP'06)*, Atlanta,

- USA, pp.669-672, Oct.2006. DOI:10.1109/ICIP.2006.312419 **[cited in p.73]**
- (Osuna,1997)** E. Osuna, R. Freund, and F. Girosit, “Training Support Vector Machines: An Application to Face Detection”, *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp.130–136, Jun.1997. DOI:10.1109/CVPR.1997.609310 **[cited in p.74]**
- (Ouamane,2014)** A. Ouamane and M. Belahcene, “New Multiple Classifier Systems For Face Authentication”, *Courrier du Savoir*, Vol.18, pp.53-62, Mar.2014. **[cited in p.54]**
- (Oviatt,2003)** S. Oviatt, “Advances in Robust Multimodal Interface Design”, *IEEE Computer Graphics and Applications*, Vol.23, No.5, pp.62–68, Sep.2003. DOI:10.1109/MCG.2003.1231179 **[cited in p.51]**
- (Padilha,2007)** A. Padilha, J. Silva, and R. Sebastiao, “Improving Face Recognition by Video Spatial Morphing”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), pp.357-376, Ch. 19, Itech Education and Publishing, ISBN:978-3-902613-03-5, Vienna, Austria, 2007. **[cited in p.74]**
- (Palanivel,2003)** S. Palanivel, B. S. Venkatesh and B. Yegnanarayana, “Real Time Face Recognition System Using Auto Associative Neural Network Models”, *IEEE International Conference on Acoustics Speech and Signal Processing(ICASSP'03)*, Hong Kong, Vol.2, pp.833-836, Apr.2003. DOI:10.1109/ICASSP.2003.1202496 **[cited in p.73]**
- (Pang,2005)** S. Pang, D. Kim, S. Y. Bang, “Face Membership Authentication Using SVM Classification Tree Generated by Membership-Based LLE Data Partition”, *IEEE Transactions on Neural Networks*, Vol.16, No.2, pp.436-446, Mar.2005. DOI:10.1109/TNN.2004.841776 **[cited in p.73]**
- (Park,2006a)** C. Park, M. Ki, J. Namkung, and J. K. Paik, “Multimodal Priority Verification of Face and Speech Using Momentum Back-Propagation Neural Network”, *International Symposium on Neural Networks*, Vol.3972, pp.140-149, May.2006. DOI:10.1007/11760023_22 **[cited in p.73]**
- (Park,2006b)** C. Park and J. Lee, “Extracting and Combining Multimodal Directional Iris Features”, *International Conference on Biometrics*, Springer Berlin Heidelberg, Vol.3832, pp.389–396, Jan.2006. DOI:10.1007/11608288_52 **[cited in p.89]**
- (Park,2007)** C. Park and J. Paik, “Face Recognition Using Optimized 3D Information from Stereo Images”, *Face Recognition*, by K. Delac and M. Grgic (Eds.), Ch. 23, I-Tech Education and Publishing, pp.457-466, ISBN:978-3-902613-03-5, Vienna, Austria, 2007. **[cited in p.74]**

- (Pavlidis, 1977)** T. Pavlidis, “Structural Pattern Recognition”, Springer Verlag, Berlin Heidelberg New York, 1977. **[cited in p.6]**
- (Pentland,1994)** A. Pentland, B. Moghaddam, and T. Starner, “View-Based and Modular Eigenspaces for Face Recognition”, *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, Vol.94, pp.84-91, Jun.1994. DOI:10.1109/CVPR.1994.323814 **[cited in p.73]**
- (Perronnin,2002)** F. Perronnin and J. L. Dugelay, “Introduction à la Biométrie Authentification des Individus par Traitement Audio-Vidéo”, *Traitement du signal*, Vol.19, No.4, Dec.2002. **[cited in p. 37,39]**
- (Phillips,2005)** P. J. Phillips, P. J. Flynn, T. Scruggs, K. W. Bowyer, J. Chang, K. Hoffman, J. Marques, J. Min, and W. Worek, “Overview of the Face Recognition Grand Challenge”, *IEEE Computer Society Conference on Computer Vision and Pattern Recognition(CVPR '05)*, Vol.1, pp.947–954, Jun.2005. DOI:10.1109/CVPR.2005.268 **[cited in p.73]**
- (Poinsot,2009)** A. Poinsot, F. Yang, and M. Paindavoine, “Fusion de Biométries sans Contact Paume et Visage”, *Colloque sur le traitement du signal et des images GRETSI*, Sep.2009. **[cited in p.56]**
- (Pons,2008)** A. P. Pons and P. Polak, “Understanding User Perspectives on Biometric Technology”, *Communications of the Association for Computing Machinery (ACM)*, Vol.51, No.9, pp.115–118, Sep.2008. DOI:10.1145/1378727.1389971 **[cited in p.45]**
- (Poursaberi,2007)** A. Poursaberi and B. N. Araabi, “Iris Recognition for Partially Occluded Images: Methodology and Sensitivity Analysis”, *EURASIP Journal on Advances Signal Processing*, Vol.2007, No.1, pp.1-12, Jan.2007. DOI:10.1155/2007/36751 **[cited in p. 81,89]**
- (Prabhakar,2002)** S. Prabhakar and A. K. Jain, “Decision-Level Fusion in Fingerprint Verification”, *Pattern Recognition*, Vol.35, No.4, pp.861-874, Apr.2002. DOI:10.1016/S0031-3203(01)00103-0 **[cited in p. 54,55]**
- (Proença,2007)** H. Proença and L. A. Alexandre, “Toward no Cooperative Iris Recognition: a Classification Approach Using Multiple Signatures”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.29, No.4, pp.607-612, Apr.2007. DOI:10.1109/TPAMI.2007.1016 **[cited in p.109]**
- (Puhan,2011)** N. B. Puhan, N. Sudha and A. S. Kaushalram, “Efficient Segmentation Technique for Noisy Frontal View Iris Images Using Fourier Spectral Density”, *Signal Image and*

- Video Processing (SIViP'11)*, Vol.5, No.1, pp.105-119, Mar.2011.
DOI:10.1007/s11760-009-0146-z [cited in p.109]
- (Putte,2000)** T. Putte and J. Keuning, "Don't Get Your Fingers Burned", *Proceedings of IFIP TC8/WG8.8 Fourth Working Conference on Smart Card Research and Advanced Applications*, pp. 289–303, Sep.2000. Doi:10.1007/978-0-387-35528-3_17 [cited in p. 50]
- (Radha,2011)** N. Radha and A. Kavitha, "Rank Level Fusion Using Fingerprint and Iris Biometrics", *Indian Journal of Computer Science and Engineering (IJCSE)*, Vol.2, No.6, pp.917-923, 2011. [cited in p. 30]
- (Radha,2012)** N. Radha and A. Kavitha, "Rank Level Fusion Using Fingerprint and Iris Biometrics", *Indian Journal of Computer Science and Engineering (IJCSE)*, Vol.2, No.6, pp.917-923, Jan.2012. [cited in p. 60]
- (Rajagopalan,1998)** A. N. Rajagopalan, K. S. Kumar, J. Karlekar, R. Manivasakan, M. M. Patil, U. B. Desai, P. G. Poonacha, and S. Chaudhuri, "Finding Faces in Photographs", *The 6th International Conference on Computer Vision*, pp.640–645, Jan.1998.
DOI:10.1109/ICCV.1998.710785 [cited in p. 74]
- (Rama,2005a)** A. Rama, and F. Tarrés, "P2CA: A New Face Recognition Scheme Combining 2D and 3D Information", *IEEE International Conference on Image Processing (ICIP'05)*, Vol.3, Sep.2005. DOI:10.1109/ICIP.2005.1530507 [cited in p.73]
- (Rama,2005b)** A. Rama, F. Tarrés, D. Onofrio, and S. Tubaro, "Using Partial Information for Face Recognition and Pose Estimation", *IEEE International Conference on Multimedia Expo (ICME'05)*, Amsterdam, Jul.2005. DOI:10.1109/ICME.2005.1521594 [cited in p.73]
- (Rama,2006)** A. Rama, F. Tarres, D. Onofrio, and S. Tubaro, "Mixed 2D-3D Information for Pose Estimation and Face Recognition", *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP'06)*, Vol.2, pp.361-364, Toulouse, May.2006.
DOI:10.1109/ICASSP.2006.1660354 [cited in p.73]
- (Ramli,2009)** D. A. Ramli, S. A. Samad, and A. Hussain, "A Multibiometric Speaker Authentication System with SVM Audio Reliability Indicator", *IAENG International Journal of Computer Science & Information Technologies*, Vol.36, No.4, pp.313-321, Nov.2009.
[cited in p.61]
- (Rasheed,2008)** S. Rasheed, D. W. Stashuk, M. S. Kamel, "Diversity-Based Combination of Non-Parametric Classifiers for EMG Signal Decomposition", *Pattern Analysis and*

- Applications*, Vol.11, No.3, pp. 385–408, Sep.2008. DOI:10.1007/s10044-008-0103-4 [cited in p.117]
- (Ratha,2001)** N. K. Ratha, J. H. Connell, and R. M. Bolle, “Enhancing Security and Privacy in Biometrics-Based Authentication Systems”, *IBM Systems Journal*, Vol.40, No.3, pp.614-634, 2001. DOI:10.1147/sj.403.0614 [cited in p.45]
- (Rattani,2009)** A. Rattani and M. Tistarelli, “Robust Multi-Modal and Multi-Unit Feature Level Fusion of Face and Iris Biometrics”, *International Conference on Biometrics*, Springer Berlin / Heidelberg, Vol.5558, pp.960–969, Jun.2009. DOI:10.1007/978-3-642-01793-3_97 [cited in p. 55,56,59,101]
- (Reynolds,2003)** D. Reynolds, W. Andrews, J. Campbell, J. Navratil, B. Peskin, A. Adami, Q. Jin, D. Klusacek, J. Abramson, R. Mihaescu, J. Godfrey, D. Jones, and B. Xiang, “The SuperSID Project: Exploiting High-level Information for High-Accuracy Speaker Recognition”, *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP'03)*, Vol.4, pp.784-787, Hong Kong, China, Apr.2003. DOI:10.1109/ICASSP.2003.1202760 [cited in p.54]
- (Ripley,1996)** B. Ripley, “Pattern Recognition and Neural Networks”, *Cambridge University Press*, Cambridge, 1996. [cited in p.7]
- (Robert,1965)** L.G. Robert, “Machine Perception of Three-Dimensional Solids”, *Optical and Electro Optical Information Processing*, MIT Press, Tippett, J.T. et al.(Eds), Cambrige, MA, pp.159-197,1965. [cited in p.12]
- (Roche,2001)** D. M. Roche, C. S. Avila, and R.S. Reillo, “Iris Recognition for Biometric Identification Using Dyadic Wavelet Transform Zero-Crossing”, *IEEE 35th International Carnahan Conference on security technology*, pp.272–277, Oct.2001. DOI:10.1109/CCST.2001.962844 [cited in p.89]
- (Ross,2003a)** A. Ross and A. K. Jain, “Information fusion in biometrics”, *Pattern Recognition Letters*, Vol.24, No.13, pp.2115–2125, Sep.2003. DOI:10.1016/S0167-8655(03)00079-5 [cited in p. 52,56,63,116]
- (Ross,2003b)** A. Ross, A. K. Jain, and J. Reisman, “A Hybrid Fingerprint Matcher”, *Pattern Recognition*, Vol.36, No.7, pp.1661-1673, Jul.2003. DOI:10.1016/S0031-3203(02)00349-7 [cited in p.54]
- (Ross,2005)** A. Ross and R. Govindarajan, “Feature Level Fusion Using Hand and Face Biometrics”, *Proceedings of SPIE Conference on Biometric Technology for Human Identification II*, Vol.5779, pp.196-204, Florida, USA, Mar.2005.

- DOI:10.1117/12.606093 [cited in p.54]
- (Ross,2006a)** A. Ross, K. Nandakumar, and A. Jain, “Handbook of Multibiometrics”, Vol.6, Springer- Verlag, New York, 2006. [cited in p.48]
- (Ross,2006b)** A. Ross and S. Shah, “Segmenting Non-Ideal Irises Using Geodesic Active Contours”, *Proceedings of biometrics symposium (BSYM): Special Session on Research at the Biometric Consortium Conference*, Baltimore, USA, Sep.2006. DOI:10.1109/BCC.2006.4341625 [cited in p.109]
- (Ross,2009)** A. Ross and N. Poh ,”Multibiometric Systems: Overview, Case Studies and Open Issues”, *Handbook of Remote Biometrics*, pp.273-292, Springer London, 2009. DOI:10.1007/978-1-84882-385-3_11 [cited in p.52]
- (Roweis,2000)** S. T. Roweis and L. K. Saul, “Nonlinear Dimensionality Reduction by Locally Linear Embedding”, *In Science*, Vol.290, No.5500, pp.2323-2326, Dec.2000. DOI:10.1126/science.290.5500.2323 [cited in p.73]
- (Rowley,1998)** H. A. Rowley, S. Baluja, and T. Kanade, “Neural Network-Based Face Detection”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.20, No.1, pp.23–38, Jan.1998. DOI:10.1109/34.655647 [cited in p.73]
- (Saleh,2014)** I. A. Saleh and L. M. Alzoubiady, "Decision Level Fusion of Iris and Signature Biometrics for Personal Identification using Ant Colony Optimization", *International Journal of Engineering and Innovative Technology (IJEIT)*, Vol.3, No.11, pp.35-42, May.2014. [cited in p.61]
- (Samani,2006)** A. Samani, J. Winkler, and M. Niranjan, “Automatic Face Recognition Using Stereo Images”, *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP'06)*, Vol.5, pp.913-916, Toulouse, May.2006. DOI:10.1109/ICASSP.2006.1661425 [cited in p.73]
- (Samaria,1994a)** F. S. Samaria, “Face Recognition Using Hidden Markov Models”, *PhD thesis*, University of Cambridge, Cambridge, UK, 1994. [cited in p.74]
- (Samaria,1994b)** F. S. Samaria and S. Young, “Hmm-Based Architecture for Face Identification”, *Image and Vision Computing*, Vol.12, No.8, pp.537-543, Oct.1994. DOI:10.1016/0262-8856(94)90007-8 [cited in p.74]
- (Sánchez,2013)** D. Sánchez, P. Melin, O. Castillo, and F. Valdez, “Modular Granular Neural Networks Optimization with Multi-Objective Hierarchical Genetic Algorithm for Human Recognition Based on Iris Biometric”, *IEEE Congress on Evolutionary Computation(CEC)*, pp.772-778, Jun.2013. DOI:10.1109/CEC.2013.6557646 [cited in

p.82]

- (Sanderson,2001)** C. Sanderson and K. K. Paliwal, “Information Fusion for Robust Speaker Verification”, *The 7th European Conference on Speech Communication and Technology*, pp.755-758, Aalborg, Denmark, 2001. [cited in p.54]
- (Sanderson,2002)** C. Sanderson and K. K. Paliwal, “Information Fusion and Person Verification Using Speech and Face Information”, *Research Paper IDIAP-RR*, pp.2-33, Sept.2002. [cited in p. 58,118]
- (Saravanan,2013)** V. Saravanan and R. Sindhuja, “Iris Authentication through Gabor Filter Using DSP Processor”, *Proceedings of IEEE Conference on Information and Communication Technologies (ICT)*, pp.568-571, Apr.2013. DOI:10.1109/CICT.2013.6558159 [cited in p. 82,89]
- (Schalkoff,1992)** R. J. Schalkoff, “Pattern Recognition: Statistical, Structural and Neural Approaches”, *John Wiley & Sons*, 1992. [cited in p.7]
- (Schimke,2004)** S. Schimke, C. Vielhauer, P.K. Dutta, T.K. Basu, A. De Rosa, J. Hansen, J. Dittmann, and B. Yegnanarayana, “Cross Cultural Aspects of Biometrics”, *Workshop Proceedings Biometric Challenges arising from Theory to Practice*, pp.27–30, 2004. [cited in p.45]
- (Schneiderman,1998)** H. Schneiderman and T. Kanade, “Probabilistic Modeling of Local Appearance and Spatial Relationships for Object Recognition”, *Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR’98)*, pp.45–51, Jun.1998. DOI:10.1109/CVPR.1998.698586 [cited in p.74]
- (Schuckers,2007)** S. A. C. Schuckers, N. A. Schmid and A. Abhyankar, V. Dorairaj, C. K. Boyce, and L. A. Hornak, “On Techniques for Angle Compensation in No ideal Iris Recognition”, *IEEE Transactions on Systems Man and Cybernetics-Part B(Cybernetics)*, Vol.37, No.5, pp.1176-1190, Oct.2007. DOI:10.1109/TSMCB.2007.904831 [cited in p.109]
- (Shakhnarovich,2001)** G. Shakhnarovich, L. Lee, and T. J. Darrell, “Integrated Face and Gait Recognition from Multiple Views”, *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR’01)*, Vol.1, pp.439-446, Hawaii, USA, Dec.2001. DOI:10.1109/CVPR.2001.990508 [cited in p.56]
- (Shakhnarovich,2002)** G. Shakhnarovich, P. A. Viola, and B. Moghaddam, “A Unified Learning Framework for Real Time Face Detection and Classification”, *Proceedings of the 5th IEEE International Conference on Automatic Face and Gesture Recognition*, pp.16–23, May.2002. DOI:10.1109/AFGR.2002.1004124 [cited in p.74]

- (Sharifi,2016)** O. Sharifi and M. Eskandari, "Optimal Face-Iris Multimodal Fusion Scheme", *Symmetry*, Vol.8, No.6, pp.48, 2016. DOI:10.3390/sym8060048 [cited in p.105]
- (Sharma,2012)** D. Sharma and A. Kumar, "An Empirical Analysis Over the Four Different Feature-Based Face and Iris Biometric Recognition Techniques", *International Journal of Advanced Computer Science and Applications (IJACSA)*, Vol.3, No.10, pp.76-83, Oct.2012. DOI:10.14569/IJACSA.2012.031013 [cited in p.101]
- (Shen,2001)** L. Shen, A. C. Kot, and W. M. Koo, "Quality Measures of Fingerprint Images", *Proceedings of the 3rd International Conference on Audio- and Video-Based Biometric Person Authentication (AVBPA '01)*, Vol.2091, pp.266–271, Jun.2001. DOI:10.1007/3-540-45344-X_39 [cited in p.44]
- (Shen,2011)** L. Shen, L. Bai, and Z. Ji, "FPCODE: An Efficient Approach for MultiModal Biometrics", *International Journal of Pattern Recognition and Artificial Intelligence*, Vol.25, No.2, pp.273-286, Mar.2011. DOI: 10.1142/S0218001411008555 [cited in p.56]
- (Shimizu,1992)** K. Shimizu, "Optical Trans-body Imaging Feasibility of Optical CT and Functional Imaging of Living Body", *Medicina Philosophica*, Vol.11, pp.620-629, 1992. [cited in p.23]
- (Shukla,2010)** A. Shukla, R. Tiwari, R. Kala, "Multimodal Biometric Systems", *Towards Hybrid and Adaptive Computing*, Springer Berlin Heidelberg, Vol.307, pp.401–418,2010. DOI:10.1007/978-3-642-14344-1_18 [cited in p.117]
- (Si,2012)** Y. Si, J. Mei, H. Gao, "Novel Approaches to Improve Robustness, Accuracy and Rapidity of Iris Recognition System", *IEEE Transactions on Industrial Informatics*, Vol.8, No.1, pp.110-117, Feb.2012. DOI:10.1109/TII.2011.2166791 [cited in p.82]
- (Smereka,2010)** J. M. Smereka, "A New Method of Pupil Identification", *IEEE Potentials*, Vol.29, No.2, pp.15–20, Mar.2010. DOI:10.1109/MPOT.2010.936236 [cited in p. 84,109]
- (Snelick,2005)** R. Snelick, U. Uludag, A. Mink, M. Indovina, and A. K .Jain, "Large Scale Evaluation of Multimodal Biometric Authentication Using State-of-the-Art Systems", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.27, No.3, pp.450-455, Mar.2005. DOI:10.1109/TPAMI.2005.57 [cited in p.56]
- (Socolinsky,2003)** D. A. Socolinsky, A. Selinger, and J. D. Neuheisel, "Face Recognition with Visible and Thermal Infrared Imagery", *Computer Vision and Image Understanding*, Vol.91, No.1-2, pp.72-114, 2003. Doi:10.1016/S1077-3142(03)00075-4 [cited in p.53]
- (Son,2004)** B. Son, H. Won, G. Kee, and Y. Lee, "Discriminate Iris Feature and Support Vector

- Machines for Iris Recognition”, *Proceedings of International Conference on Image Processing (ICIP'04)*, Vol.2, pp.865–868, Oct.2004. DOI:10.1109/ICIP.2004.1419436 [cited in p.89]
- (Son,2005)** B. Son and Y. Lee, “Biometric Authentication System Using Reduced Joint Feature Vector of Iris and Face”, *The 6th International Conference on Audio- and Video-Based Biometric Person Authentication (AVBPA'03)*, Vol.3546, pp.513-522, Springer Berlin / Heidelberg, Jul.2005. DOI:10.1007/11527923_53 [cited in p. 56,59,101]
- (Srihari,1993)** S. N. Srihari and V. Covindaraju, “Pattern Recognition”, *Chapman & Hall*, London, pp. 1034-1041, 1993. [cited in p. 7]
- (Stojmenovic,2013)** M. Stojmenovic, A. Jevremovic, and A. Nayak, “Fast Iris Detection via Shape Based Circularity”, *IEEE 8th Conference on Industrial Electronics and Applications (ICIEA)*, pp.747-752, Jun.2013. DOI:10.1109/ICIEA.2013.6566467 [cited in p. 82]
- (Stone,1977)** M. Stone, “An Asymptotic Equivalence of Choice of Model by Cross-Validation and Akaike’s Criterion”, *Journal of the Royal Statistical Society -Series B(Methodological)*, Vol.39, No.1, pp.44-47,1977. [cited in p.41]
- (Strzelczyk,2010)** P. Strzelczyk, “Robust and Accurate Iris Segmentation Algorithm for Color and Noisy Eye Images”, *Journal of telecommunication & information technology*, Vol.2010, No.4, pp.5-9, Dec.2010. [cited in p.81]
- (Sudha,2009)** N. Sudha, N. B. Puhan, and H .Xia, “Iris Recognition on Edge Maps”, *IET Computer Vision*, Vol.3, No.1, pp.1-7, Mar.2009. DOI:10.1049/iet-cvi:20080015 [cited in p. 84,109,109]
- (Suganthy,2012)** M. Suganthy, P. Ramamoorthy, and R. Krishnamoorthy, “Effective Iris Recognition For Security Enhancement”, *International Journal of Engineering Research and Applications (IJERA)*, Vol.2, No.2, pp.1016-1019, Apr.2012. [cited in p.82]
- (Sun,2004)** Z. Sun, T. Tan, and Y. Wang, “Robust Encoding of Local Ordinal Measures: A General Framework of Iris Recognition”, *Proceedings of International Workshop on Biometric Authentication (BioAW'04)*, pp.270–282, May.2004. DOI:10.1007/978-3-540-25976-3_25 [cited in p.89]
- (Sung,2004)** H. Sung, J. Lim, J. Park, and Y. Lee, “Iris Recognition Using Collarette Boundary Localization”, *Proceedings of the 17th International Conference on Pattern Recognition (ICPR'04)*, Vol.4, pp.857–860, Aug.2004. DOI:10.1109/ICPR.2004.1333907 [cited in p.84]
- (Tabassi,2005)** E. Tabassi and C. L. Wilson, “A Novel Approach to Fingerprint Image Quality”, *IEEE*

- International Conference on Image Processing (ICIP'05)*, pp.37–40, Sep.2005.
DOI:10.1109/ICIP.2005.1529985 [cited in p.44]
- (Tanaka,1998)** H. T. Tanaka, M. Ikeda, and H. Chiaki, “Curvature-Based Face Surface Recognition Using Spherical Correlation Principal Directions for Curved Object Recognition”, *Proceedings of the 3rd IEEE International Conference on Automatic Face and Gesture Recognition*, pp.372-377, Apr.1998. DOI:10.1109/AFGR.1998.670977 [cited in p.73]
- (Teo,2005)** C. C. Teo and H. T. Ewe, “An Efficient One-Dimensional Fractal Analysis for Iris Recognition”, *Proceedings of 13th WSCG International Conference in Central Europe on Computer Graphics*, pp.157–160, 2005. [cited in p.84]
- (Theodoridis,1982)** S. Theodoridis and K. Koutroumbas, “Pattern Recognition”, *Pattern Recognition*, Elsevier(USA), 1982. [cited in p.7]
- (Theofanos,2007)** M. Theofanos, B. Stanton, S. Orandi, R. Micheals, and N.F. Zhang, “Usability Testing of Ten-Print Fingerprint Capture”, *Technical report, National Institute of Standards and Technology (NIST)*, Vol.7403,2007. [cited in p.45]
- (Theofanos,2008)** M. Theofanos, B. Stanton, C. Sheppard, R. Micheals, N. Zhang, J. Wydler, L. Nadel, and W. Rubin, “Usability Testing of Height and Angles of Ten-Print Fingerprint Capture”, *Technical report, National Institute of Standards and Technology (NIST)*, Jun.2008. [cited in p.45]
- (Therrien,1989)** C. W. Therrien, “Decision Estimation and Classification: An Introduction to Pattern Recognition and Related Topics”, *John Wiley & Sons*, New York, Jan.1989. [cited in p.11]
- (Thornton,2007)** J. Thornton, M. Savvides, and B. V. Kumar, “An Evaluation of Iris Pattern Representations”, *The 1st IEEE International Conference on Biometrics: Theory, Applications and Systems (BTAS'07)*, pp.1-6, Sep.2007.
DOI:10.1109/BTAS.2007.4401909 [cited in p.89]
- (Thu,2002)** Q. H. Thu, M. Meguro, and M. Kaneko, “Skin-Color Extraction in Images with Complex Background and Varying Illumination”, *Proceedings of the 6th IEEE Workshop on Applications of Computer Vision (WACV'02)*, pp.280–285, Dec.2002.
DOI:10.1109/ACV.2002.1182195 [cited in p.74]
- (Tian,2004)** Q. C. Tian, Q. Pan, Y. M. Cheng, Q. X. Gao, “Fast Algorithm and Application of Hough Transform in Iris Segmentation”, *Proceedings of the third International Conference on Machine Learning and Cybernetics*, Vol. 7, pp.3977–3980, Aug.2004.
DOI:10.1109/ICMLC.2004.1384533 [cited in p.84,109]

- (Tisse,2002)** C. L. Tisse, L. Martin, L. Torres, and M. Robert, “Person Identification Technique Using Human Iris Recognition”, *Proceedings of the 15th International Conference on Vision Interface*, pp.294–299, Calgary, May.2002. [cited in p.80,84,89,109]
- (Toh,2003)** K. A. Toh, W. Xiong, W. Y. Yau, and X. Jiang, “Combining Fingerprint and Hand Geometry Verification Decisions”, *The 4th International Conference on Audio- and Video based Biometric Person Authentication (AVBPA'03)*, Vol.2688, pp.688-696, Guildford, UK, Jun.2003. DOI:10.1007/3-540-44887-X_80 [cited in p.56]
- (Toh,2004)** K. A. Toh, X. Jiang, and W. Y. Yau, “Exploiting Global and Local Decisions for Multimodal Biometrics Verification”, *IEEE Transactions on Signal Processing*, Vol.52, No.10, pp.3059-3072, Oct.2004. DOI:10.1109/TSP.2004.833862 [cited in p.56]
- (Toh,2005)** K. A. Toh and W. Y Yau, “Fingerprint and Speaker Verification Decisions Fusion Using a Functional Link Network”, *IEEE Transactions on Systems Man and Cybernetics Part C: Applications and Reviews*, Vol.35, No.3, pp.357-370, Aug.2005. DOI:10.1109/TSMCC.2005.848184 [cited in p.56]
- (Tronci,2009)** R. Tronci, G. Giacinto, and F. Roli, “Designing Multiple Biometric Systems: Measures of Ensemble Effectiveness”, *Engineering Applications of Artificial Intelligence*, Vol.22, No.1, pp.66–78, Feb.2009. DOI:10.1016/j.engappai.2008.04.007 [cited in p.41]
- (Tsai,2012)** C. C. Tsai, H. Y. Lin, J. S. Taur, and C. W. Tao, “Iris Recognition Using Possibilistic Fuzzy Matching on Local Features”, *IEEE Transactions on Systems ,Man, and Cybernetics Part B (Cybernetics)*, Vol.42, No.1, pp.150-162, Feb.2012. DOI:10.1109/TSMCB.2011.2163817 [cited in p.82]
- (Tsalakanidou,2004)** F. Tsalakanidou, S. Malassiotis, and M. Strintzis, “Integration of 2D and 3D Images For Enhanced Face Authentication”, *Proceedings of the 6th IEEE International Conference on Automated Face and Gesture Recognition (FGR'04)*, pp.266-271, May.2004. DOI:10.1109/AFGR.2004.1301542 [cited in p.73]
- (Turk,1991)** M. A. Turk and A. P. Pentland, “Face Recognition Using Eigenfaces”, *Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'91)*, pp.586-591, Jun.1991. DOI:10.1109/CVPR.1991.139758 [cited in p.73,73,74]
- (Vachkov,2009)** G. Vachkov, “Online Classification of Machine Operation Modes Based on Information Compression and Fuzzy Similarity Analysis”, *IFSA-EUSFLAT confere 09*,

- Lisbon, Portugal, pp.1456-1461, 2009. [cited in p.11]
- (Vapnik,1995)** V. Vapnik, "The Nature of Statistical Learning Theory", *Springer-Verlag*, New York, 1995. [cited in p.113]
- (Vapnik,1998)** V. Vapnik, "Statistical Learning Theory", *John Wiley and Sons*, New York, 1998. [cited in p.113]
- (Vatsa,2005)** M. Vatsa, R. Singh, and A. Noore, "Reducing the False Rejection Rate of Iris Recognition Using Textural and Topological Features," *International Journal on Signal Processing*, Vol.2, No.1, pp.66–72, 2005. [cited in p.89]
- (Vasta,2007)** M. Vasta, R. Singh, and A. Noore, "Integrating Image Quality in 2v-SVM Biometric Match Score Fusion", *International Journal of Neural Systems*, Vol.17, No.5, pp.343-351, Oct.2007. DOI:10.1142/S0129065707001196 [cited in p.102]
- (Vatsa,2008a)** M. Vatsa, R. Singh, and A. Noore, "Improving Iris Recognition Performance Using Segmentation, Quality Enhancement, Match Score Fusion, and Indexing" ,*IEEE Transaction on Systems, Man, and Cybernetics. Part B, (Cybernetics)*, Vol.38, No.4, pp.1021-1035, Aug.2008. DOI:10.1109/TSMCB.2008.922059 [cited in p. 81,90, 109]
- (Vatsa,2008b)** M. Vatsa, R. Singh, and A. Noore, "Reducing the False Rejection Rate of Iris Recognition Using Textural and Topological Features", *International Journal of Computer Electrical Automation Control and Information Engineering*, Vol.2, No.7, pp.2533–2539, 2008. [cited in p.81]
- (Verlinde,1999)** P. Verlinde, P. Druyts, G. Chollet, and M. Achery, "Applying Bayes Based Classifiers for Decision Fusion in a Multi-Modal Identity Verification System", *Proceedings of International Symposium on Pattern Recognition "InMemoriam Pierre Devijver"*, Brussels, Belgium, Feb.1999. [cited in p.118]
- (Verma,2012)** P. Verma, M. Dubey, S. Basu, and P. Verma, "Hough Transform Method for Iris Recognition-A Biometric Approach", *International Journal of Engineering and Innovative Technology (IJEIT'12)*, Vol.1, No.6, pp.43-48, Jun.2012. [cited in p.82,84,89,109]
- (Wagner,2012)** A. Wagner, J. Wright, A. Ganesh, Z. Zhou, H. Mobahi, and Y. Ma, "Toward a Practical Face Recognition System: Robust Alignment and Illumination by Sparse Representation", *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)*, Vol.34, No.2, pp.372-386, Feb.2012. DOI:10.1109/TPAMI.2011.112 [cited in p.74]
- (Wang,2003)** Y. Wang, T. Tan, and A. K. Jain, "Combining Face and Iris Biometrics for Identity

- Verification”, The 4th International Conference on Audio and Video based Biometric Person Authentication (AVBPA), Vol.2688, pp. 805-813, Guildford, UK, Jun.2003. DOI:10.1007/3-540-44887-X_93 [cited in p.56,102,117]
- (Wang,2006)** J. Wang, K. N. Plataniotis, and A. N. Venetsanopoulos, “Selecting Kernel Eigenfaces For Face Recognition With One Training Sample Per Subject”, *IEEE International Conference on Multimedia Expo(ICME'06)*, Toronto, Canada, pp.1637-1640, Jul.2006. DOI:10.1109/ICME.2006.262861 [cited in p.73]
- (Wang,2009)** F. Wang and J. Han, “Multimodal Biometric Authentication Based on Score Level Fusion Using Support Vector Machine”, *Opto-Electronics Review*, Vol.17, No.1, pp.59-64, Mar.2009. DOI:10.2478/s11772-008-0054-8 [cited in p.103]
- (Wang,2011)** Z. Wang, E. Wang, S. Wang, and Q. Ding, ”Multimodal Biometric System Using Face-Iris Fusion Feature”, *Journal Of Computers(JCP)*, Vol. 6, No. 5, pp.931-938, May.2011. [cited in p.101]
- (Wang,2014)** N. Wang, L. Lu, G. Gao, F. Wang, and S. Li, “Multibiometrics Fusion Using Aczél-Alsina Triangular Norm”, *KSII Transactions on Internet and Information Systems(TIIS)*, Vol.8, No.7, pp.2420-2433, July.2014. DOI:10.3837/tiis.2014.07.012 [cited in p.104]
- (Wang,2015)** Q. Wang, B. Zhu, Y. Liu, L. Xie, and Y. Zheng, ”Iris-Face Fusion and Security Analysis Based on Fisher Discriminant”, *International Journal On Smart Sensing And Intelligent Systems*, Vol.8, No.1, pp.387-407, Mar.2015. [cited in p.102]
- (Watanabe,1985)** S. Watanabe, “Pattern Recognition: Human and Mechanical”, *John Wiley & Sons*, New York, NY, USA, 1985. [cited in p.7]
- (Watanabe,2005)** M. Watanabe, T. Endoh, M. Shiohara, and S. Sasaki, “Palm Vein Authentication Technology and its Applications”, *Proceedings of Biometric Consortium Conference*, pp.19-21, Sep.2005. [cited in p.24]
- (Wildes,1994)** R. P. Wildes, J. C. Asmuth, G. L. Green, S. C. Hsu, R. J. Kolczynski, J. R. Matey, and S. E. McBride, “A System for Automated Iris Recognition”, *Proceedings of the second IEEE Workshop on Applications of Computer Vision*, Sarasota, FL, pp.121-128, Dec.1994. DOI:10.1109/ACV.1994.341298 [cited in p.84,109]
- (Wildes,1997)** R.P. Wildes, “Iris Recognition: An Emerging Biometric Technology”, *Proceedings of the IEEE*, Vol.85, No.9, pp.1348 -1363, U.S.A., Sep.1997. DOI 10.1109/5.628669 [cited in p.80,84,89,90,108,109]
- (Wilson,2004)** C. Wilson, A. R. Hicklin, M. Bone, H. Korves, R. Grother, B. Ulery, R. Micheals, M.

- Zoepfl, S. Otto, and C. Watson, "Fingerprint Vendor Technology Evaluation 2003: Summary of Results and Analysis Report", *NIST Technical Report NISTIR*, Vol.7123, 2004. [cited in p.55]
- (Wiskott,1997)** L. Wiskott, J.M. Fellous, N. Kruger, and C. von der Malsburg, "Face Recognition by Elastic Bunch Graph Matching", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.19, No.7, pp.775-779, Jul.1997. DOI:10.1109/34.598235 [cited in p.73]
- (Wong,2007)** K. C. Wong, W. Y. Lin, Y. H. Hu, N. Boston, and X. Zhang, "Optimal Linear Combination Of Facial Regions For Improving Identification Performance", *IEEE Transactions on Systems Man and Cybernetics Part B: Cybernetics*, Vol.37, No.5, pp.1138-1148, Oct.2007. DOI:10.1109/TSMCB.2007.895325 [cited in p.73]
- (Woods,1997)** K. Woods, W. Kegelmeyer, and K. Bowyer, "Combination of Multiple Classifiers Using Local Accuracy Estimates", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.19, No.4, pp.405–410, Apr.1997. DOI:10.1109/34.588027 [cited in p.60]
- (Woodward,2003)** J. D. Woodward, Jr., C. Horn, J. Gatune, and A. Thomas, "Biometrics: A Look at Facial Recognition", *Technical report*, Rand Corp Santa Monica Ca, 2003. [cited in p.16]
- (Xu,1998)** L. Xu, A. Krzyzak, and C. Suen, "Methods Of Combining Multiple Classifiers and their Applications to Handwriting Recognition", *IEEE Transactions on Systems Man and Cybernetics*, Vol.22, No.3, pp.418–435, May.1992. DOI:10.1109/21.155943 [cited in p.61]
- (Yacoob,2002)** Y. Yacoob and L. Davis, "Smiling Faces Are Better for Face Recognition", *Proceedings of the 5th IEEE. International Conference on Automatic Face and Gesture Recognition (FGR '02)*, pp.59–64, May.2002. DOI:10.1109/AFGR.2002.1004132 [cited in p.73]
- (Yacoub,1998)** S. Ben Yacoub, "Multi-Modal Data Fusion for Person Authentication Using SVM", *IDIAP Research Report*, 1998. [cited in p.113]
- (Yacoub,1999)** S. Ben-Yacoub, Y. Abdeljaoued, and E. Mayoraz, "Fusion of Face and Speech Data for Person Identity Verification", *IEEE Transactions on Neural Networks*, Vol.10, No.5, pp.1065-1074, Sep.1999. DOI:10.1109/72.788647 [cited in p.56]
- (Yang,1994)** G. Yang and T. S. Huang, "Human Face Detection in a Complex Background", *Pattern Recognition*, Vol.27, No.1, pp.53-63, Jan.1994. DOI:10.1016/0031-

- 3203(94)90017-5 [cited in p.74]
- (Yang,2002)** M.H. Yang, “Kernel Eigenfaces vs. Kernel Fisherfaces: Face Recognition Using Kernel Methods”, *Proceedings of the 5th IEEE International Conference on Automatic Face and Gesture Recognition (FG’02)*, Vol.2, pp.215-220, May.2002. [cited in p.73]
- (Yang,2003)** J. Yang, J. Y. Yang, D. Zhang, and J. F. Lu, “Feature Fusion: Parallel Strategy vs. Serial Strategy”, *Pattern Recognition*, Vol.36, No.6, pp.1369-1381, Jun.2003. DOI:10.1016/S0031-3203(02)00262-5 [cited in p.54,59]
- (Yang,2004)** J. Yang, D. Zhang, A.F. Frangi, and J.Yang, “Two-Dimensional PCA: A New Approach to Appearance-based Face Representation and Recognition”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.26, No.1, pp.131-137, Jan.2004. DOI:10.1109/TPAMI.2004.1261097 [cited in p.73]
- (Yao,2006)** P. Yao, J. Li, X. Ye, Z. Zhuang, and B. Li, “Iris Recognition Algorithm Using Modified Log-Gabor Filters”, *Proceedings of the 18th International Conference on Pattern Recognition(ICPR’06)*, Vol.4, pp. 461–464, Aug.2006. DOI:10.1109/ICPR.2006.726 [cited in p.89]
- (Yin,2011)** Y. Yin, L. Liu, and X. Sun, “SDUMLA-HMT: A Multimodal Biometric Database”, *Chenese Conference on Biometrics Recognition (CCBR’11)*, Vol.7098, pp.260–268, Springer Berlin Heidelberg, 2011. DOI:10.1007/978-3-642-25449-9_33 [cited in p.129,130,132,141,142]
- (You,2004)** J. You, W. K. Kong, D. Zhang, and K. H. Cheung, “On Hierarchical Palmprint Coding With Multiple Features for Personal Identification in Large Databases”, *IEEE Transactions on Circuits and Systems for Video Technology*, Vol.14, No.2, pp.234-243, Feb.2004. DOI:10.1109/TCSVT.2003.821978 [cited in p.54,61]
- (Yu,2006)** J. Yu, Q. Tian, “Constructing Descriptive and Discriminant Features for Face Classification”, *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP)*, Toulouse, Vol.2, pp.121-124, May.2006. DOI:10.1109/ICASSP.2006.1660294 [cited in p.73]
- (Yuan,2005)** W. Yuan, W. He, “A Novel Eyelash Detection Method for Iris Recognition”, *Proceedings of the IEEE Engineering in Medicine and Biology 27th Annual Conference*, pp.6536-6539, Sep.2005. DOI:10.1109/IEMBS.2005.1615997 [cited in p.81]
- (Zhang,1997)** J. Zhang, Y. Yan, M. Lades, “Face Recognition: Eigenface, Elastic Matching, and Neural Nets”, *Proceedings of the IEEE*, Vol.85, No.9, pp.1423-1435, Sep.1997.

- DOI:10.1109/5.628712 [cited in p.73]
- (Zhang,2004a)** B. L. Zhang, H. Zhang, and S. S. Ge, "Face Recognition by Applying Wavelet Subband Representation and Kernel Associative Memory", *IEEE Transactions on Neural Networks*, Vol.15, No.1, pp.166-177, Jan.2004.
DOI:10.1109/TNN.2003.820673 [cited in p.73]
- (Zhang,2004b)** P. F. Zhang, D. S. Li, Q. Wang, "A Novel Iris Recognition Method Based on Feature Fusion", *Proceedings of the 3rd International Conference on Machine Learning and Cybernetics*, Shanghai, Vol.6, pp.3661-3665, Aug.2004.
DOI:10.1109/ICMLC.2004.1380440 [cited in p.89]
- (Zhang,2007)** Z. Zhang, R. Wang, K. Pan, S. Z. Li, and P. Zhang, "Fusion Of Near Infrared Face and Iris Biometrics", *International Conference on Biometrics*, Vol.4642, pp.172-180, Springer Berlin / Heidelberg, Aug.2007. DOI:10.1007/978-3-540-74549-5_19 [cited in p.56,103]
- (Zhang,2009)** G. Zhang and Y. Wang, "A Symmetry-Based Quality Assessment of Face Images", *Proceedings of the 5th International Symposium on Advances in Visual Computing (ISVC)*, Springer Berlin Heidberg, Vol.5876, pp.499–508, Nov.2009.
DOI:10.1007/978-3-642-10520-3_47 [cited in p.44]
- (Zhang,2010)** X. Zhang, Z. Sun, and T. Tan, "Hierarchical Fusion of Face and Iris for Personal Identification", *IEEE 20th International Conference on Pattern Recognition (ICPR'10)*, pp.217-220, Aug.2010. DOI:10.1109/ICPR.2010.62 [cited in p.103]
- (Zhang,2011)** L. Zhang, M. Yang, and X. Feng, "Sparse Representation or Collaborative Representation: Which Helps Face Recognition?", *Proceedings of the IEEE International Conference on Computer Vision (ICCV'11)*, pp.471-478, Nov.2011.
DOI:10.1109/ICCV.2011.6126277 [cited in p.74]
- (Zhao,1998)** W. Zhao, R. Chellappa, and A. Krishnaswamy, "Discriminant Analysis of Principal Components for Face Recognition", *Proceedings of the Third IEEE International Conference on Automatic Face and Gesture Recognition*, pp.336-341, April. 1998.
DOI:10.1109/AFGR.1998.670971 [cited in p.74]
- (Zheng,2012)** H. Zheng, J. Xie, and Z. Jin, "Heteroscedastic Sparse Representation Based Classification for Face Recognition", *Neural Processing Letters*, Vol.35, No.3, pp.233-244, 2012. DOI:10.1007/s11063-012-9214-4 [cited in p.74]
- (Zhou,2003)** S. Zhou, V. Krueger, and R. Chellappa, "Probabilistic Recognition of Human Faces from Video", *Computer Vision and Image Understanding*, Vol.91, No.1-2, pp.214-245,

2003. DOI:10.1016/S1077-3142(03)00080-8 [cited in p.55]
- (Zhou,2006)** W. Zhou, X. Pu, and Z. Zheng, "Parts-Based Holistic Face Recognition with RBF Neural Networks", *International Symposium on Neural Networks*, pp.110-115, Vol.3972, May.2006. DOI:10.1007/11760023_17 [cited in p.73]
- (Zhu,2000)** Y. Zhu, T. Tan and Y. Wang, "Biometric Personal Identification Based on Iris Patterns", Proceedings of the *15th IEEE International Conference on Pattern Recognition (ICPR'00)*, Barcelona, Espagne, Vol.2, pp.801-804, Sep.2000. DOI:10.1109/ICPR.2000.906197 [cited in p.80,89]
- (Zoubida,2017a)** L. Zoubida and R. Adjoudj, "Integrating Face and the Both Irises for Personal Authentication", *International Journal of Intelligent Systems and Applications (IJISA)*, Vol.9, No.3, pp.8-17, Mar.2017. DOI:10.5815/ijisa.2017.03.02 [cited in p.111,133,134,137,139,138]
- (Zoubida,2017b)** L. Zoubida and R. Adjoudj, "MultiBiometric Fusion: Left and Right Irises based Authentication Technique", *International Journal of Image, Graphics and Signal Processing (IJIGSP)*, Vol.9, No.4, pp.10-21, Apr.2017. DOI: 10.5815/ijigsp.2017.04.02 [cited in p. 125,127,128,129]
- (Zuo,2010)** J. Zuo and N. A. Schmid, "On a Methodology for Robust Segmentation of Nonideal Iris Images", *IEEE transactions on Systems, Man, and Cybernetics—Part B (Cybernetics)*, Vol.40, No.3, pp.703-718, Jun.2010. DOI:10.1109/TSMCB.2009.2015426 [cited in p.81,84]
- (Web01)** Manfred Bromba. Biometrics FAQ's, 2006. <http://www.bromba.com/faq/> biofaqe.htm [cited in p.15]
- (Web02)** WhatIs Dictionary, IT encyclopedia and learning center, 2005. <http://whatis.techtarget.com/> [cited in p.15]
- (Web03)** Data Core Thecnology. Glossary of terms, 2005. <http://www.data-core.com/glossary-of-terms.htm>. [cited in p.16]
- (Web04)** NIST report to the United States Congress, "Summary of NIST Standards for Biometric Accuracy, Tamper Resistance, and Interoperability", Nov.2002. [cited in p.36]
- (Web05)** National Science & Technology Council's Subcommittee on Biometrics, "Measurement of Performance of Recognition Technologies", Sep.2006. [cited in p.37]
- (Web06)** ISO/IEC 19795-1, Information technology – biometric performance testing and reporting – part

- 1: Principles and framework, 2006. [cited in p.38]
- (Web07) ISO/IEC 29794-1. Information technology – biometric sample quality – part 1 : Framework, 2009. [cited in p.42]
- (Web08) Face Recognition Homepage – Databases: <http://www.face-rec.org/databases/> [cited in p.74]
- (Web09) The Color FERET Database, USA. <https://www.nist.gov/itl/iad/image-group/color-feret-database> [cited in p.74]
- (Web10) The Yale Face Database <http://cvc.cs.yale.edu/cvc/projects/yalefaces/yalefaces.html> [cited in p.74]
- (Web11) The Yale Face Database B <http://cvc.cs.yale.edu/cvc/projects/yalefacesB/yalefacesB.html> [cited in p.74]
- (Web12) PIE Database, CMU. <http://www.cs.cmu.edu/afs/cs/project/PIE/MultiPie/Multi-Pie/Home.html> [cited in p.74]
- (Web13) Project - Face In Action (FIA) Face Video Database, AMP, CMU
<http://www.flintbox.com/public/project/5486/> [cited in p.74]
- (Web14) AT&T "The Database of Faces" (formerly "The ORL Database of Faces")
<http://www.cl.cam.ac.uk/Research/DTG/attarchive/facedatabase.html> [cited in p.74]
- (Web15) Cohn-Kanade AU Coded Facial Expression Database. <http://www.pitt.edu/~emotion/ck-spread.htm> [cited in p.74]
- (Web16) MIT-CBCL Face Recognition Database. <http://cbcl.mit.edu/software-datasets/heisele/facerecognition-database.html> [cited in p.75]
- (Web17) Image Database of Facial Actions and Expressions - Expression Image Database
<http://mambo.ucsc.edu/pls/joehager/images.html> [cited in p.75]
- (Web18) Face Recognition Data, University of Essex, UK
<http://cswww.essex.ac.uk/mv/allfaces/index.html> [cited in p.75]
- (Web19) NIST Mugshot Identification Database <https://www.nist.gov/srd/nist-special-database-18> [cited in p.75]
- (Web20) NLPR Face Database <http://nlpr-web.ia.ac.cn/english/irds/facedatabase.htm> [cited in p.75]
- (Web21) M2VTS Multimodal Face Database (Release 1.00).
<http://www.tele.ucl.ac.be/PROJECTS/M2VTS/m2fdb.html> [cited in p.75]
- (Web22) The Extended M2VTS Database, University of Surrey, UK.

- <http://www.ee.surrey.ac.uk/Research/VSSP/xm2vtsdb/> [cited in p.75]
- (Web23) The AR Face Database, Purdue University, USA. <http://www2.ece.ohio-state.edu/~aleix/ARdatabase.html> [cited in p.75]
- (Web24) The University of Oulu Physics-Based Face Database. <http://www.ee.oulu.fi/research/imag/color/pbfd.html> [cited in p.75]
- (Web25) CAS-PEAL Face Database. <http://www.jdl.ac.cn/peal/index.html> [cited in p.75]
- (Web26) Japanese Female Facial Expression (JAFFE) Database. <http://www.kasrl.org/jaffe.html> [cited in p.75]
- (Web27) BioID Face DB - HumanScan AG, Switzerland. <http://www.humanscan.de/support/downloads/facedb.php> [cited in p.75]
- (Web28) Psychological Image Collection at Stirling (PICS). <http://pics.psych.stir.ac.uk/> [cited in p.75]
- (Web29) The Sheffield Face Database (previously: The UMIST Face Database). <https://www.sheffield.ac.uk/eee/research/iel/research/face> [cited in p.75]
- (Web30) Caltech Faces. <http://www.vision.caltech.edu/html-files/archive.html> [cited in p.75]
- (Web31) EQUINOX HID Face Database. <http://www.equinoxsensors.com/products/HID.html> [cited in p.75]
- (Web32) VALID Database. <http://ee.ucd.ie/validdb/> [cited in p.75]
- (Web33) The UCD Colour Face Image Database for Face Detection. http://blog.sina.com.cn/s/blog_78ca8c520100q2on.html [cited in p.75]
- (Web34) GeorgiaTech Face Database. http://www.anefian.com/face_reco.htm [cited in p.75]
- (Web35) Indian Face Database. <http://cvit.iiit.ac.in/projects/IMFDB/> [cited in p.75]
- (Web36) UPC Face Database. <https://gtav.upc.edu/en/research-areas/face-database> [cited in p.75]
- (Web37) VidTIMIT Database. <http://conradsanderson.id.au/vidtimit/> [cited in p.75]
- (Web38) Labeled Faces in the Wild. <http://vis-www.cs.umass.edu/lfw/> [cited in p.75]
- (Web39) The LFWcrop Database. <http://conradsanderson.id.au/lfwcrop/> [cited in p.75]
- (Web40) Labeled Faces in the Wild-a (LFW-a). <http://www.openu.ac.il/home/hassner/data/lfwa/> [cited in p.75]
- (Web41) The Bosphorus Database. <http://bosphorus.ee.boun.edu.tr/default.aspx> [cited in p.75]
- (Web42) PUT Face Database. <https://biometrics.cie.put.poznan.pl/> [cited in p.75]

- (Web43) Basel Face Model (BFM). <http://faces.cs.unibas.ch/bfm/> [cited in p.75]
- (Web44) Plastic Surgery Face Database. <http://www.iab-rubric.org/resources.html> [cited in p.75]
- (Web45) The Hong Kong Polytechnic University NIR Face Database. http://www4.comp.polyu.edu.hk/~biometrics/polyudb_face.htm [cited in p.75]
- (Web46) MOBIO - Mobile Biometry Face and Speech Database. <https://www.idiap.ch/dataset/mobio> [cited in p.75]
- (Web47) Texas 3D Face Recognition Database (Texas 3DFRD). <http://live.ece.utexas.edu/research/texas3dfr/> [cited in p.75]
- (Web48) Natural Visible and Infrared facial Expression database (USTC-NVIE). <http://nvie.ustc.edu.cn/> [cited in p.75]
- (Web49) FEI Face Database. <http://fei.edu.br/~cet/facedatabase.html> [cited in p.76]
- (Web50) ChokePoint. <http://arma.sourceforge.net/chokepoint/> [cited in p.76]
- (Web51) UMB database of 3D occluded faces. <http://www.ivl.disco.unimib.it/minisites/umbdb/> [cited in p.76]
- (Web52) PhotoFace: Face recognition using photometric stereo. <http://www1.uwe.ac.uk/et/mvl/projects/facerecognition.aspx> [cited in p.76]
- (Web53) EURECOM Kinect Face Dataset (EURECOM KFD). <http://rgb-d.eurecom.fr/> [cited in p.76]
- (Web54) The Adience image set and benchmark of unfiltered faces for age, gender and subject classification. <http://www.openu.ac.il/home/hassner/Adience/data.html> [cited in p.76]
- (Web55) Facial Expression Research Group Database (FERG-DB). <http://grail.cs.washington.edu/projects/deepexpr/ferg-db.html> [cited in p.76]
- (Web56) 3D Mask Attack Database (3DMAD). <https://www.idiap.ch/dataset/3dmad> [cited in p.76]
- (Web57) FaceScrub Databse. <http://vintage.winklerbros.net/facescrub.html> [cited in p.76]
- (Web58) LFW3D and Adience3D sets. <http://www.openu.ac.il/home/hassner/projects/frontalize/> [cited in p.76]
- (Web59) YouTube Faces Database. <http://www.cs.tau.ac.il/~wolf/ytfaces/> [cited in p.76]
- (Web60) YMU (YouTube Makeup) Dataset. <http://www.antitza.com/makeup-datasets.html> [cited in p.76]
- (Web61) Senthilkumar Face Database (Version 1.0). <http://www.geocities.ws/senthilrtt/Senthi%20Face%20Database%20Version1> [cited in p.76]

- (Web62) SiblingsDB Database. <http://areeweb.polito.it/ricerca/cvg/siblingsDB.html> [cited in p.76]
- (Web63) McGill Real-world Face Video Database. <https://sites.google.com/site/meltemdemirkus/mcgill-unconstrained-face-video-database/> [cited in p.76]
- (Web64) Denver Intensity of Spontaneous Facial Action (DISFA) Database. <http://mohammadmahoor.com/databases/denver-intensity-of-spontaneous-facial-action/> [cited in p.76]
- (Web65) BU-3DFE Database. http://www.cs.binghamton.edu/~lijun/Research/3DFE/3DFE_Analysis.html [cited in p.76]
- (Web66) Indian Movie Face database (IMFDB). <http://cvit.iiit.ac.in/projects/IMFDB/> [cited in p.76]
- (Web67) 10k US Adult Faces Database. <http://www.wilmabainbridge.com/facememorability2.html> [cited in p.76]
- (Web68) Senthil IRTT Face Database Version 1.1. <http://www.geocities.ws/senthilrtt/Senthil%20IRTT%20Face%20Database%20Version%201.1> [cited in p.76]
- (Web69) UFI - Unconstrained Facial Images. <http://ufi.kiv.zcu.cz/> [cited in p.76]
- (Web70) IIIT - Cartoon Faces in the Wild. <http://cvit.iiit.ac.in/research/projects/cvit-projects/cartoonfaces> [cited in p.76]
- (Web71) Casia iris database: [http://www.idealtest.org/findDownloadDbByMode.do? mode=Iris](http://www.idealtest.org/findDownloadDbByMode.do?mode=Iris) [cited in p.91,108,109,110,123]
- (Web72) Michal Dobeš and Libor Machala, UPOL Iris Database, <http://www.inf.upol.cz/iris/> [cited in p.91,94]
- (Web73) Bath iris database, <http://www.bath.ac.uk/elec-eng/pages/sipg/irisweb/index.htm> [cited in p.91,95]
- (Web74) Proença, Hugo and Alexandre, Luís A., UBIRIS iris database, 2005. <http://iris.di.ubi.pt/> [cited in p.91,95]
- (Web75) National Institute of Standards and Technology, Iris Challenge Evaluation (ICE) iris database. <http://iris.nist.gov/ice/> [cited in p.91,95]
- (Web76) MMU database: <http://www.mmu.edu.my/~ccteo/> [cited in p.91,96,108,109,110,123]
- (Web77) SDUMLA-HMT Database: <http://mla.sdu.edu.cn/sdumla-hmt.htm> [cited in p.108, 109,110,123]