CONTENTS

PREFACE **xiii**

1 OVERVIEW **1**
1.1 Introduction 1
1.2 Biometric Authentication Methods 2
1.3 Face Recognition: Reality and Challenge 3
1.4 Speaker Recognition: Reality and Challenge 6
1.5 Road Map of the Book 8

2 BIOMETRIC AUTHENTICATION SYSTEMS **11**
2.1 Introduction 11
2.2 Design Tradeoffs 11
2.2.1 Accuracy versus Intrusiveness 12
2.2.2 Recognition versus Verification 14
2.2.3 Centralized versus Distributed Systems 15
2.2.4 Processing Speed 16
2.2.5 Data Storage Requirements 18
2.2.6 Compatibility between Feature Extractor and Classifier 19
2.3 Feature Extraction 20
2.3.1 Criteria of Feature Extraction 20
2.3.2 Projection Methods for Dimension Reduction 21
2.3.3 Feature Selection 24
2.3.4 Clustering Methods: Gaussian Mixture Models 25
2.4 Adaptive Classifiers 26
2.4.1 Neural Networks 27
2.4.2 Training Strategies 28

2.4.3 Criteria on Classifiers 28
2.4.4 Availability of Training Samples 29
2.5 Visual-Based Feature Extraction and Pattern Classification 30
2.5.1 Geometric Features 31
2.5.2 Template Features 32
2.5.3 Texture Features 33
2.5.4 Subspace Projection for Feature Reduction 34
2.5.5 Neural Networks for Feature Selection 34
2.6 Audio-Based Feature Extraction and Pattern Classification 35
2.6.1 Low-Level Features 35
2.6.2 High-Level Features 40
2.6.3 Robustness in Speech Features 41
2.6.4 Classification Schemes for Speech-Based Biometrics 42
2.7 Concluding Remarks 43

3 EXPECTATION-MAXIMIZATION THEORY 50
3.1 Introduction 50
3.1.1 K-Means and VQ algorithms 50
3.1.2 Gaussian Mixture Model 51
3.1.3 Expectation-Maximization Algorithm 52
3.2 Traditional Derivation of EM 54
3.2.1 General Analysis 54
3.2.2 Convergence Property of EM 57
3.2.3 Complete-Data Likelihood 58
3.2.4 EM for GMMs 61
3.3 An Entropy Interpretation 65
3.3.1 Incomplete-Data Likelihood 66
3.3.2 Simulated Annealing 67
3.3.3 EM Iterations 69
3.3.4 Special Case: GMM 71
3.3.5 K-Means versus EM 71
3.4 Doubly-Stochastic EM 72
3.4.1 Singly-Stochastic Single-Cluster with Partial Data 74
3.4.2 Doubly-Stochastic (Partial-Data and Hidden-State) Problem 75
3.5 Concluding Remarks 78

4 SUPPORT VECTOR MACHINES 85
4.1 Introduction 85

4.2 Fisher's Linear Discriminant Analysis 85
4.2.1 A Two-Class Classifier 87
4.2.2 Fisher's Discriminant Analysis 87
4.2.3 The Bayes Optimality Property 89
4.2.4 Fisher's Discriminant versus Least-Squares Classifiers 89
4.3 Linear SVMs: Separable Case 90
4.3.1 Margin of Separation 91
4.3.2 Wolfe Dual Optimization 92
4.3.3 Support Vectors 93
4.3.4 Decision Boundary 93
4.4 Linear SVMs: Fuzzy Separation 97
4.4.1 Why Fuzzy Separation? 97
4.4.2 Wolfe Dual Optimization 98
4.4.3 Support Vectors in the Fuzzy Region 101
4.4.4 Decision Boundary 103
4.4.5 Probabilistic Function for Decision Confidence 107
4.4.6 Invariance Properties of Linear SVMs 107
4.5 Nonlinear SVMs 108
4.5.1 Two-Layer SVM Network Architectures 109
4.5.2 Hidden Nodes and Retrieving Speed 112
4.5.3 Training Criteria and Running Time 116
4.5.4 Generalization Performance of Nonlinear SVMs 118
4.5.5 Effects of Scaling and Shifting 124
4.6 Biometric Authentication Application Examples 131

5 MULTI-LAYER NEURAL NETWORKS 139
5.1 Introduction 139
5.2 Neuron Models 140
5.2.1 Basis Functions (Net Functions) 140
5.2.2 Activation Functions (Neuron Functions) 141
5.2.3 Discriminant Functions (Output Functions) 141
5.3 Multi-Layer Neural Networks 142
5.3.1 Multi-Layer Neural Models 143
5.3.2 The Classic XOR Problem 144
5.4 The Back-Propagation Algorithms 144
5.4.1 BP Algorithm for Multi-Layer LBF Networks 148
5.4.2 BP Algorithm for Multi-Layer RBF Networks 148

5.5 Two-Stage Training Algorithms 151
5.5.1 Two-Stage Training for RBF Networks 151
5.5.2 Two-Stage Training for LBF Networks 157
5.6 Genetic Algorithm for Multi-Layer Networks 158
5.6.1 Basic Elements of GAs 159
5.6.2 Operation of GAs 159
5.6.3 Applications of GAs to Evolve Neural Networks 160
5.7 Biometric Authentication Application Examples 170

6 MODULAR AND HIERARCHICAL NETWORKS 185
6.1 Introduction 185
6.2 Class-Based Modular Networks 186
6.2.1 Class-Based OCON Structure 188
6.2.2 ACON versus OCON Networks 189
6.3 Mixture-of-Experts Modular Networks 190
6.3.1 Local Experts and Gating Network 191
6.3.2 LBF MOE Networks 192
6.3.3 RBF MOE Networks 193
6.3.4 Comparison of MLP and MOE 195
6.4 Hierarchical Machine Learning Models 195
6.4.1 Hierarchical Mixture-of-Experts 196
6.4.2 Experts-in-Class and Classes-in-Expert Structures 202
6.5 Biometric Authentication Application Examples 205

7 DECISION-BASED NEURAL NETWORKS 209
7.1 Introduction 209
7.2 Basic Decision-Based Neural Networks 209
7.2.1 Decision-Based Learning Rule 210
7.2.2 Comparison of MOE and DBNNs 214
7.3 Hierarchical Design of Decision-Based Learning Models 216
7.3.1 Hybrid Supervised/Unsupervised Learning Scheme 216
7.3.2 Local Winners: Minimal Side-Effect Learning Rule 218
7.4 Two-Class Probabilistic DBNNs 221
7.4.1 Discriminant Functions of PDBNNs 224
7.4.2 Learning Rules for PDBNNs 226
7.4.3 Threshold Updating 228
7.5 Multiclass Probabilistic DBNNs 228
7.5.1 Structure of Multiclass PDBNNs 229

7.5.2 False Acceptance and False Rejection 230
7.5.3 Learning Rules for Multiple Subnet PDBNNs 233
7.6 Biometric Authentication Application Examples 237

8 BIOMETRIC AUTHENTICATION BY FACE RECOGNITION 241
8.1 Introduction 241
8.2 Facial Feature Extraction Techniques 243
8.2.1 Feature-Invariant Approaches 243
8.2.2 Template-Based Approaches 244
8.3 Facial Pattern Classification Techniques 249
8.4 Face Detection and Eye Localization 250
8.4.1 Face Detection 251
8.4.2 Eye Localization 255
8.4.3 Assisting Realtime Face Recognition 256
8.5 PDBNN Face Recognition System Case Study 258
8.5.1 Face Detection and Eye Localization 260
8.5.2 Facial Region 260
8.5.3 Frontal View Faces 261
8.5.4 Presence of Intruder Patterns 263
8.5.5 Invariance Assurance 264
8.5.6 Training Pattern Generation 266
8.5.7 Hierarchical Face Recognition System 266
8.6 Application Examples for Face Recognition Systems 268
8.6.1 Network Security and Access Control 269
8.6.2 Video Indexing and Retrieval 269
8.6.3 Airport Security Application 272
8.6.4 Face Recognition Based on a Three-Dimensional CG Model 274
8.6.5 Opportunities for Commercial Applications 274
8.7 Concluding Remarks 276

9 BIOMETRIC AUTHENTICATION BY VOICE RECOGNITION 280
9.1 Introduction 280
9.2 Speaker Recognition 281
9.2.1 Components of Speaker Verification Systems 281
9.2.2 Speaker-Specific Features 281
9.2.3 Speaker Modeling 282

9.2.4 Threshold Determination 284
9.2.5 Performance Evaluation 285
9.2.6 Speaker Recognition in Adverse Environments 286
9.3 Kernel-Based Probabilistic Speaker Models 286
9.3.1 Gaussian Mixture Models 287
9.3.2 Elliptical Basis Function Networks 287
9.3.3 Probabilistic Decision-Based Neural Networks 289
9.3.4 Comparison of Probabilistic Speaker Models 290
9.4 Handset and Channel Distortion 301
9.4.1 Handset and Channel Compensation Techniques 303
9.4.2 Stochastic Feature Transformation 305
9.4.3 Stochastic Model Transformation 318
9.4.4 Out-of-Handset Rejection 332
9.5 Blind Handset-Distortion Compensation 345
9.5.1 Blind Stochastic Feature Transformation 346
9.5.2 Integration of Blind and Supervised Compensation 352
9.6 Speaker Verification Based on Articulatory Features 353
9.6.1 Articulatory Feature Extraction 354
9.6.2 AF-Based Speaker Verification 356
9.6.3 Fusion of Spectral and Articulatory Features 358
9.7 Concluding Remarks 361

10 MULTICUE DATA FUSION 368
10.1 Introduction 368
10.2 Sensor Fusion for Biometrics 369
10.2.1 Feature-Level Fusion 370
10.2.2 Decision-Level Fusion 370
10.3 Hierarchical Neural Networks for Sensor Fusion 373
10.3.1 PDBNNs for Multichannel Fusion 374
10.3.2 Class-Dependent Channel Fusion 375
10.3.3 Data-Dependent Channel Fusion 376
10.4 Multisample Fusion 378
10.4.1 Data-Dependent Decision Fusion Model 380
10.4.2 Fusion of Sorted Scores 385
10.4.3 Adaptation of Prior Scores 389
10.4.4 Experiments and Results 393
10.5 Audio and Visual Biometric Authentication 404

10.5.1 AV Feature Extraction 405
10.5.2 AV Multisample Fusion 406
10.6 Concluding Remarks 408

APPENDIX A CONVERGENCE PROPERTIES OF EM 414

APPENDIX B AVERAGE DET CURVES 416

APPENDIX C MATLAB PROJECTS 418
C.1 Matlab Project 1: GMMs and RBF Networks for Speech Pattern Recognition 418
C.1.1 Introduction 418
C.1.2 Objectives 418
C.1.3 Procedures 418
C.2 Matlab Project 2: SVMs for Pattern Classification 421
C.2.1 Objectives 421
C.2.2 Procedures 421

BIBLIOGRAPHY 427

INDEX 457

PREFACE

Biometrics has long been an active research field, particularly because of all the attention focused on public and private security systems in recent years. Advances in digital computers, software technologies, and embedded systems have further catalyzed increased interest in commercially available biometric application systems. Biometric authentication can be regarded as a special technical area in the field of pattern classification. Research and development on biometric authentication have focused on two separate fronts: one covering the theoretical aspect of machine learning for pattern classification and the other covering system design and deployment issues of biometric systems. This book is meant to bridge the gap between these two fronts, with a special emphasis on the promising roles of modern machine learning and neural network techniques.

To develop an effective biometric authentication system, it is vital to acquire a thorough understanding of the input *feature space*, then develop proper mapping of such feature space onto the *expert space* and eventually onto the output *classification space*. Unlike the conventional template matching approach, in which learning amounts to storing representative example patterns of a class, the machine learning approach adopts representative statistical models to capture the characteristics of patterns in the feature domain. This book explores the rich synergy between various machine learning models from the perspective of biometric applications. Practically, the machine learning models can be adopted to construct a robust information processing system for biometric authentication and data fusion. It is potentially useful in a broad spectrum of application domains, including but not limited to biometric authentication.

This book is organized into four related parts.

1. Part I—Chapters 1 and 2—provides an overview of the state-of-the-art in face and speaker biometric authentication systems.

2. Part II—Chapters 3, 4, and 5—establishes the theoretical pillars of machine learning methods adopted in the book. To facilitate the development of effective biometric authentication systems, several modern machine learning models are instrumental in handling complex pattern recognition and classification problems. Part II discusses the expectation-maximization (EM)

algorithm (Chapter 3); describes the fundamental theory on Fisher's linear discriminant analysis (LDA) and support vector machines (SVMs) (Chapter 4); and offers comprehensive coverage of multi-layer learning models, in addition to well-known back-propagation (BP) algorithms (Chapter 5).

3. Part III—Chapters 6 and 7—proposes several flexible structural frameworks based on hierarchical and modular neural networks, under which machine learning modules can be incorporated as subsystems. The discussion introduces several expert-based modular networks, such as the so-called hierarchical mixture-of-experts (Chapter 6), as well as interclass learning strategies based on class-based modular networks (Chapter 7).

4. Part IV—Chapters 8, 9, and 10—presents the theoretical foundations behind the learning networks, which can find natural and fruitful applications in biometric authentication systems. The most important authentication application domains are face recognition and speaker verification. Specifically, Chapter 8 presents probabilistic neural networks for face biometrics, while Chapter 9 covers authentication by human voices. Several multicue data-fusion techniques are addressed in Chapter 10.

As suggested by the title, this book covers two main themes: (1) biometric authentication and (2) the machine learning approach. The ultimate objective is to demonstrate how machine learning models can be integrated into a unified and intelligent recognition system for biometric authentication. However, the authors must admit that the book's coverage is far from being comprehensive enough to do justice to either theme. First, the book does not address many important biometric authentication techniques such as signature, fingerprint, iris pattern, palm, DNA, and so on. The focus is placed strictly on visual recognition of faces and audio verification of speakers. Due to space constraints, the book has likewise overlooked many promising machine learning models. To those numerous contributors, who deserve many more credits than are given here, the authors wish to express their most sincere apologies.

In closing, *Biometric Authentication: A Machine Learning Approach* is intended for one-semester graduate school courses in machine learning, neural networks, and biometrics. It is also intended for professional engineers, scientists, and system integrators who want to learn systematic, practical ways of implementing computationally intelligent authentication systems based on the human face and voice.

Acknowledgments

This book is an outgrowth of many years of teaching and research on the subject of neural networks, pattern recognition, and biometric authentication. The authors are very much indebted to many students for their invaluable questions and contribution of examples and exercises. Some parts of the book are extracted from several

postgraduate students' dissertations. We wish to thank all of them, in particular M. C. Cheung, K. W. Cho, K. W. Ku, and K. K. Yiu. We also thank our research assistants, including K. Y. Leung, Chad Myers, Xinying Zhang, Yunnan Wu, C. H. Sit, C. L. Tsang, and W. M. Yu for their efforts in performing some of the simulations and proofreading numerous versions of the manuscript.

We have benefited greatly from frequent and enlightening exchanges and collaboration with many colleagues. To name a few: P. C. Ching, Helen Ming, Brian Mak, and M. H. Siu. Their enthusiastic participation in this project has made the prolonged process enjoyable and rewarding. We also thank Professor W. C. Siu, Professor Jin-Shiuh Taur, and Dr. Hong-Jian Zhang for their invaluable suggestions and comments. Our deep gratitude goes to the reviewers for their critical and constructive suggestions on the book's manuscript. Our sincere appreciation goes to the series editor, Professor Thomas Kailath, for many years of inspiration and friendship.

We have been very fortunate to have worked with Mr. Bernard Goodwin at Prentice Hall and production service coordinator Ms. Marilyn Rash, who have provided the highest professional assistance throughout this project. We are grateful to the Department of Electrical Engineering at Princeton University and the Department of Electronic and Information Engineering at The Hong Kong Polytechnic University for making available such a scholarly environment for both teaching and research.

M. W. Mak is with the Center for Multimedia Signal Processing, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong. S. Y. Kung was on sabbatical from Princeton University and was the Multimedia Distinguished Chair Professor of The Hong Kong Polytechnic University when this project commenced. We are pleased to acknowledge that the work presented in this book was in part supported by the Center for Multimedia Signal Processing, The Hong Kong Polytechnic University (Grant Nos. A442 and A464); the Research Grants Council, Hong Kong Special Administrative Region (Grant Nos. PolyU 5129/01E and PolyU5131/02E); and the Department of Electrical Engineering, Princeton University. This book is part of a series of publications under the leadership of Professor W. C. Siu, Director of the Center for Multimedia Signal Processing, The Hong Kong Polytechnic University.

Without the support and encouragement of many friends and colleagues, it would be impossible to write a book on such a diversified subject. Our heartfelt thanks go to the researchers who have contributed to the field of machine learning, neural networks, and biometrics, whose work provided the foundation for this book. We offer our sincere apologies for inevitably overlooking many critical topics and references due to time and space constraints.

Finally, the authors wish to acknowledge the generous and kind support of their families. This project would not have been completed so smoothly without their full understanding throughout this long process.