Recent Advances in Fingerprint Verification

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More than a century has passed since Alphonse Bertillon first conceived and then industriously practiced the idea of using body measurements for solving crimes [18]. Just as his idea was gaining popularity, it faded into relative obscurity by a far more significant and practical discovery of the uniqueness of the human fingerprints[1]. Soon after this discovery, many major law enforcement departments embraced the idea of first "booking" the fingerprints of criminals, so that their records are readily available and later using leftover fingerprint smudges (latents), they could determine the identity of criminals. These agencies sponsored a rigorous study of fingerprints, developed scientific methods for visual matching of fingerprints and strong programs/cultures for training fingerprint experts, and applied the art of fingerprint identification for nailing down the perpetrators [6].

Despite the ingenious methods improvised to increase the efficiency of the manual method of fingerprint indexing and search, the ever growing demands on manual fingerprint identification quickly became overwhelming. The manual method of fingerprint indexing resulted in a highly skewed distribution of fingerprints into bins (types): most fingerprints fell into a few bins and this resulted in search inefficiencies. Fingerprint training procedures were time-intensive and slow. Further, demands imposed by painstaking attention needed to visually match the fingerprints of varied qualities, tedium of monotonic nature of the work, and increasing workloads due to a higher demand on fingerprint identification services, all prompted the law enforcement agencies to initiate research into acquiring fingerprints through electronic medium and automatic fingerprint identification based on the digital representation of the fingerprints. These efforts have led to development of automatic/semi-automatic fingerprint identification systems (AFIS) over the past few decades.

While law enforcement agencies were the earliest adopters of the fingerprint identification technology, more recently, increasing identity fraud has created a growing need for biometric technology[2] [9] for positive person identification in a number of non-forensic applications. Is this person authorized to enter this facility? Is this individual entitled to access the privileged information? Is the given service being administered exclusively to the enrolled users? Answers to questions such as these are valuable to business and government organizations.

[1] In 1893, the Home Ministry Office, UK, accepted that no two individuals have the same fingerprints.

[2] Biometric authentication, or simply biometrics, refers to use of distinctive physiological (e.g., fingerprints, face, retina, iris) and behavioral (e.g., gait, signature) characteristics for automatically identifying individuals

Since biometric identifiers cannot be easily misplaced, forged, or shared, they are considered more reliable for personal identification than traditional token or knowledge based methods. The objectives of biometric authentication are user convenience (e.g., money withdrawal without ATM card and PIN), better security (e.g., difficult to forge access), and higher efficiency (e.g., lower overhead for computer password maintenance). Tremendous success of the fingerprint based identification technology in law enforcement applications, decreasing cost of the fingerprint sensing devices, increasing availability of inexpensive computing power, and growing identity fraud/theft have all ushered in an era of fingerprint-based person identification applications in commercial, civilian, and financial domains.

Our objective is to present current state-of-the-art in fingerprint sensing and identification technology and to provide some insights into the strengths and limitations of the automation in matching fingerprints. There is a popular misconception in the pattern recognition and image processing academic community that automatic fingerprint verification is a fully solved problem since it was one of the first applications of machine pattern recognition almost fifty years ago. On the contrary, fingerprint verification is still a challenging and important pattern recognition problem. Here, we will focus only on the core technology underlying fingerprint verification rather than the details of the commercial systems. In particular, we will discuss on fingerprint sensing, representation, classification, and matching. With the increase in the number of commercial systems for fingerprint-based verification, proper evaluation protocols are needed. The first fingerprint verification competition (FVC2000) was a good start in establishing such protocols. In order to improve the verification performance, methods for integrating multiple matchers, multiple biometrics and mosaicing of multiple templates are being investigated. As fingerprints (biometrics) get increasingly embedded into various systems (e.g., cellular phones), it becomes increasingly important to analyze the impact of biometrics on the overall integrity of the system and its social acceptability. We will also summarize some of the security/privacy research issues related to fingerprint (biometrics) authentication systems. A selection of fingerprint related research is cited below to provide the audience some useful pointers for their further exploration of this topic.

Bibliography

Books and Surveys

1. J. Cowger, *Friction Ridge Skin: Comparison and Identification of Fingerprints.* Elsevier, New York, 1983.
2. Federal Bureau of Investigation, *The Science of Fingerprints: Classification and Uses.* U.S. Government Printing Office, Washington, D. C., 1984.
3. National Institute of Standards and Technology, *Guideline for The Use of Advanced Authentication Technology Alternatives.* Federal Information Processing Standards Publication 190, 1994.
4. J. Rafferty and J. Wegstein, *The LX39 latent Fingerprint Matcher.* U.S.A. Government Publication. National Bureau of Standards, Institute for Computer Sciences and Technology, 1978.

5. D. R. Ashbaugh, *Quantitative-Qualitative Friction Ridge Analysis: An Introduction to Basic and Advanced Ridgeology*, CRC Press, Boca Raton, 1999.
6. H. C. Lee and R. E. Gaensslen (editors), *Advances in Fingerprint Technology*, Elsevier, New York, 1991.
7. F. Galton, *Finger Prints*, London: McMillan, 1892.
8. H. Cummins and Charles Midlo, *Fingerprints, Palms and Soles: An Introduction to Dermatoglyphics*. Dover Publications, Inc., New York, 1961.
9. A. K. Jain, R. M. Bolle, and S. Pankanti (editors), *Biometrics: Personal Identification in a Networked Society*, Kluwer Academic Publishers, 1999.
10. L. Hong, "Automatic Personal Identification Using Fingerprints", Ph. D. Thesis, Department of Computer Science and Engineering, Michigan State University, East Lansing, 1998.
11. S. Prabhakar, "Automatic Fingerprint Matching", Ph. D. Thesis, Department of Computer Science and Engineering, Michigan State University, East Lansing, 2001.
12. L. C. Jain, U. Halici, I. Hayashi, and S. B. Lee (eds.), *Intelligent Biometric Techniques in Fingerprint and Face Recognition*, CRC Press, Boca Raton, 1999.
13. C. Chapel. *Fingerprinting - A Manual of Identification*. Coward McCann, New York, 1971.
14. A. Moenssens. *Fingerprint Techniques*. Chilton Book Company, London, 1971.
15. A. K. Jain and S. Pankanti, "Fingerprint classification and matching", In A. Bovik, editor, *Handbook for Image and Video Processing*. Academic Press, April 2000.
16. A. K. Jain, L. Hong and S. Pankanti, "Biometrics Identification", Comm. ACM, pp. 91-98, Feb. 2000.
17. J. L. Wayman, "National Biometric Test Center: Collected Works 1997-2000", http://www.engr.sjsu.edu/biometrics/nbtccw.pdf, 2000.
18. H. T. F. Rhodes. *Alphonse Bertillon: Father of Scientific Detection*. Abelard-Schuman, New York, 1956.
19. S. Pankanti, R. Bolle, and A. K. Jain (Guest Editors), Special Issue of the IEEE Computer Magazine on Biometrics, Feb 2000.
20. Proceedings of the First Audio and Video-Based Person Authentication, Crans-Montana, Switzerland, 12-14 March 1997.
21. Proceedings of the Second Audio and Video-Based Person Authentication, Washington D. C. USA, March 22-23, 1999
22. Proceedings of the IEEE, Special Issue on Biometrics, Vol. 85, No. 9, 1997.
23. B. Miller, "Vital signs of identity," IEEE Spectrum, Vol. 31, pp. 22-30, February 1994.
24. First Workshop on Automatic Identification Advanced Technologies, Stoney Brook, New York, United States, 1997.
25. Second Workshop on Automatic Identification Advanced Technologies, Morristown, New Jersey, United States, 1999.
26. Biometrics Consortium, www.biometrics.org.
27. International Biometrics Industry Association, www.ibia.org.
28. BIOAPI, www.bioapi.org.

Fingerprint Scanning Devices

29. Digital Biometrics, Inc., biometric identification products. http://www.digitalbiometrics.com.

30. Siemens ID Mouse. www.siemens.com.
31. Fidelica Fingerprint Scanner. www.fidelica.com
32. GemPlus, "Gemplus – Products, Services – Hardware – GemPC430", http://www.gemplus.com/products/hardware/gempcTouch440.htm.
33. Precise Biometrics, "Precise 100 A, SC", www.precisebiometrics.com.
34. Oxford Micro Devices Inc., "OMDI (finger) Imaging Technology that can help children", www.oxfordmicro.com.
35. Veritouch, "VR-3 (U)", www.veritouch.com.
36. *Access Control Applications using Optical Computing.* http://www.mytec.com.
37. *Edge Lit Hologram for Live-scan Fingerprinting.* http://eastview.org/ImEdge.
38. *Scanner Specifications.* ftp://ard.fbi.gov/pub/IQS/spec.
39. Thomson CSF. http://www.tcs.thomson-csf.com/fingerchip/FC_home.htm.
40. Y. Fumio, I. Seigo, and E. Shin, "Real-time fingerprint sensor using a hologram", *Applied Optics*, 31(11):1794, 1992.
41. J. Klett, "'Thermal imaging fingerprint technology," In *Proc. Biometric Consortium Ninth Meeting*, Crystal City, Virginia, April 1997.
42. Lexington Technology, Inc. *Lexington Technology, Inc. Homepage.* http://www.lexingtontech.com.
43. I. Seigo, E. Shin, and S. Takashi, "Holographic fingerprint sensor," *Fujitsu Scientific & Technical Journal*, 25(4):287, 1989.
44. Harris Semiconductor. *Harris Semiconductor Homepage.* http://www.semi.harris.com/fngrloc.
45. TRS. *Technology Recognition Systems Homepage.* http://www.betac.com/trs.
46. W. Bicz, D. Banasiak, P. Bruciak, Z. Gumienny, S. Gumulinski, D. Kosz, A. Krysiak, W. Kuczynski, M. Pluta, and G. Rabiej, *Fingerprint structure imaging based on an ultrasound camera.* http://www.optel.com.pl/article/english/article.htm.
47. N. D. Young, G. Harkin, R. M. Bunn, D. J. McCulloch, R. W. Wilks, and A. G. Knapp, "Novel fingerprint scanning arrays using polysilicon tft's on glass and polymer substrates," *IEEE Electron Device Letters*, 18(1):19–20, Jan 1997.
48. Digital Persona, "Optical Fingerprint Sensors", www.digitalpersona.com.
49. G. V. Piosenka and R. V. Chandos, "Unforgeable personal identification system", U. S. Patent 4,993,068, 1991.
50. D. R. Setlak, "Fingerprint sensor having spoof reduction features and related methods", U.S. Patent 5,953,441, 1999.
51. Lapsley et al., "Anti-fraud biometric scanner that accurately detects blood flow", U.S. Patent 5,737,439, 1998.

Fingerprint Enhancement

52. S. Ghosal, N. K. Ratha, R. Udupa, and S. Pankanti, "Hierarchical partitioned least squares filter-bank for fingerprint enhancement," *15th IAPR International Conference on Pattern Recognition*, Barcelona, Spain, Sep. 3-7, pp. 334-337, 2000.
53. P. E. Danielsson and Q. Z. Ye, "Rotation-invariant operators applied to enhancement of fingerprints," In *Proc. 9th ICPR*, pages 329–333, Rome, 1988.
54. T. Kamei and M. Mizoguchi, "Image filter design for fingerprint enhancement," In *Proc. ISCV' 95*, pages 109–114, Coral Gables, FL, 1995.
55. E. Kaymaz and S. Mitra, "A novel approach to Fourier spectral enhancement of laser-luminescent fingerprint images," *Journal of Forensic Sciences*, 38(3):530, 1993.

56. A. Sherstinsky and R. Picard, "M-Lattice: From Morphogenesis to Image Processing," *IEEE Transactions on Image Processing*, Vol. 5, No. 7, pp. 1137-1150, July 1996.
57. D. C. D. Hung, "Enhancement and Feature Purification of Fingerprint Images," *Pattern Recognition*, vol. 26, no. 11, pp. 1,661-1,671, 1993.
58. L. Hong, Y. Wan, and A. K. Jain, "Fingerprint Image Enhancement: Algorithm and Performance Evaluation," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 20, No. 8, pp. 777-789, 1998.
59. L. O'Gorman and J. V. Nickerson, "An Approach to Fingerprint Filter Design", *Pattern Recognition*, Vol. 22, No. 1, 29-38, 1989.
60. Q. Xiao and H. Raafat, "Fingerprint Image Postprocessing: A Combined Statistical and Structural Approach," *Pattern Recognition*, vol. 24, no. 10, pp. 985-992, 1991.
61. S. Prabhakar, A. K. Jain, J. Wang, S. Pankanti, and R. Bolle, "Minutiae Verification and Classification for Fingerprint Matching", *Proc. 15th International Conference on Pattern Recognition (ICPR)*, Vol. I, pp. 25-29, Barcelona, September 3-8, 2000.
62. L. Berdan and R. Chiralo, "Adaptive digital enhancement of latent fingerprints," In *Proc. Int. Carnahan Conf. on Electronic Crime Countermeasures*, pages 131–135, University of Kentucky, Lexington, Kentucky, 1978.
63. K. Millard, D. Monro, and B. Sherlock, "Algorithm for enhancing fingerprint images," *Electronics Letters*, 28(18):1720, 1992.
64. D. Sherlock, D. M. Monro, and K. Millard, "Fingerprint enhancement by directional Fourier filtering," *IEE Proc. Vis. Image Signal Processing*, 141(2):87–94, 1994.

Fingerprint Classification

65. M. M. S. Chong, T. H. Ngee, L. Jun, and R. K. L. Gay, "Geometric framework for Fingerprint Classification," *Pattern Recognition*, Vol. 30, No. 9, pp. 1475-1488, 1997.
66. K. Goto, T. Minami, and O. Nakamura, "Fingerprint classification by directional distribution patterns," *System Computer Controls*, 13:81–89, 1982.
67. D. Maio and D. Maltoni, "A structural approach to fingerprint classification," In *Proc. 13th ICPR*, pages 578–585, Vienna, 1996.
68. A. K. Jain, S. Prabhakar, and L. Hong, "A Multichannel Approach to Fingerprint Classification", *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 21, No. 4, pp. 348-359, 1999.
69. A. P. Fitz and R. J. Green, "Fingerprint Classification Using Hexagonal Fast Fourier Transform," *Pattern Recognition*, Vol. 29, No. 10, pp. 1587-1597, 1996.
70. A. Senior, "A Hidden Markov Model Fingerprint Classifier," *Proceedings of the 31st Asilomar conference on Signals, Systems and Computers*, pp. 306-310, 1997.
71. B. G. Sherlock and D. M. Monro, "A Model for Interpreting Fingerprint Topology," *Pattern Recognition*, Vol. 26, No. 7, pp. 1047-1055, 1993.
72. B. Moayer and K. Fu, "A Tree System Approach for Fingerprint Pattern Recognition," *IEEE Trans. Pattern Anal. and Machine Intell.*, vol. 8 no. 3, pp. 376-388, 1986.
73. C. L. Wilson, G. T. Candela, and C.I. Watson, "Neural Network Fingerprint Classification," *J. Artificial Neural Networks*, Vol. 1, No. 2, pp. 203-228, 1993.

74. C. V. Kameshwar Rao and K. Black, "Type Classification of Fingerprints: A Syntactic Approach," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 2, No. 3, pp. 223-231, 1980.
75. G. T. Candela, P. J. Grother, C. I. Watson, R. A. Wilkinson, and C. L. Wilson, "PCASYS: A Pattern-Level Classification Automation System for Fingerprints," *NIST Tech. Report NISTIR 5647*, August 1995.
76. K. Karu and A. K. Jain, "Fingerprint Classification," *Pattern Recognition*, Vol. 29, No. 3, pp. 389-404, 1996.
77. M. Kawagoe and A. Tojo, "Fingerprint Pattern Classification," *Pattern Recognition*, Vol. 17, No. 3, pp. 295-303, 1984.
78. R. Cappelli, D. Maio, and D. Maltoni, "Fingerprint Classification based on Multi-space KL", *Proc. Workshop on Automatic Identification Advances Technologies (AutoID'99)*, Summit (NJ), pp. 117-120, October 1999.
79. R. Cappelli, D. Maio, and D. Maltoni, "Combining Fingerprint Classifiers", *First International Workshop on Multiple Classifier Systems (MCS2000)*, Cagliari, pp.351-361, June 2000.
80. P. Baldi and Y. Chauvin, "Neural networks for fingerprint recognition," *Neural Computation*, 5(3):402–418, 1993.
81. B. Moayer and K. Fu, "An application of stochastic languages to fingerprint pattern recognition," *Pattern Recognition*, 8:173–179, 1976.
82. L. Hong and A. K. Jain, "Classification of Fingerprint Images," *11th Scandinavian Conference on Image Analysis*, June 7-11, Kangerlussuaq, Greenland, 1999.

Fingerprint Matching

83. R. Bahuguna, "Fingerprint verification using hologram matched filterings", In *Proc. Biometric Consortium Eighth Meeting*, San Jose, California, June 1996.
84. K. Balck and K. Rao, "A hybrid optical computer processing technique for fingerprint identification", *IEEE Trans. Computer*, 24:358–369, 1975.
85. B. Chatterjee and B. Mehtre, "Automatic fingerprint identification," *Journal of the Institution of Electronics and Telecom.*, 37(5/6):493, 1991.
86. M. Eleccion, "Automatic fingerprint identification," *IEEE Spectrum*, 10(9):36–45, 1973.
87. K. Fielding, J. Homer, and C. Makekau, "Optical fingerprint identification by binary joint transform correlation," *Optical Engineering*, 30:1958, 1991.
88. L. Frye, F. Gamble, and D. Grieser, "Real-time fingerprint verification system," *Applied Optics*, 31(5):652, 1992.
89. Q. Guisheng, C. Minde, Q. Shi, and N. Xue, "A new automated fingerprint identification system," *Computer Science Technology*, 4(4):289–294, 1989.
90. A. K. Hrechak and J. A. McHugh, "Automated Fingerprint Recognition Using Structural Matching," *Pattern Recognition*, Vol. 23, pp. 893-904, 1990.
91. A. K. Jain, L. Hong, S. Pankanti, and Ruud Bolle, "An identity authentication system using fingerprints," *Proceedings of the IEEE*, Vol. 85, No. 9, pp. 1365-1388, 1997.
92. A. K. Jain, L. Hong, and R. Bolle, "On-line Fingerprint Verification," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 19, No. 4, pp. 302-314, 1997.
93. A. K. Jain, S. Prabhakar, L. Hong, and S. Pankanti, "Filterbank-based Fingerprint Matching," *IEEE Trans. Image Processing*, Vol. 9, No. 5, pp. 846-859, May 2000.

94. A. Ross, S. Prabhakar, and A. K. Jain, "Fingerprint Matching Using Minutiae and Texture Features", to appear in *International Conference on Image Processing (ICIP)*, Greece, October 7-10, 2001.
95. D. Maio and D. Maltoni, "Direct Gray-Scale Minutiae Detection in Fingerprints," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 19, No. 1, pp. 27-40, 1997.
96. L. Coetzee and E. C. Botha, "Fingerprint Recognition in Low Quality Images," *Pattern Recognition*, Vol. 26, No. 10, pp. 1141-1460, 1993.
97. L. O'Gorman, "Fingerprint Verification," in *Biometrics: Personal Identification in a Networked Society*, A. K. Jain, R. Bolle, and S. Pankanti (editors), Kluwer Academic Publishers, pp. 43-64, 1998.
98. N. Ratha, K. Karu, S. Chen, and A . K. Jain, "A Real-Time Matching System for Large fingerprint Databases," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 18, No. 8, pp. 799-813, 1996.
99. N. Ratha, S. Chen, and A. K. Jain, "Adaptive Flow Orientation-Based Feature Extraction in Fingerprint Images," *Pattern Recognition*, Vol. 28, No. 11, pp. 1657-1672, 1995.
100. S. Chen and A. K. Jain, "A Fingerprint Matching Algorithm Using Dynamic Programming", *Technical Report*, Department of Computer Science and Engineering, Michigan State University, 1999.
101. X. Quinghan and B. Zhaoqi, "An Approach to Fingerprint Identification by Using the Attributes of Feature Lines of Fingerprints," *Proc. Eighth Int. Conf. Pattern Recognition*, pp. 663-665, Oct. 1986.
102. C. Banner and R. Stock, "The FBI's approach to automatic fingerprint identification (part I)," *FBI Law Enforcement Bulletin, U.S.A. Government Publication*, 44(1), 1975.
103. C. Banner and R. Stock, "The FBI's approach to automatic fingerprint identification (part II)," *FBI Law Enforcement Bulletin, U.S.A. Government Publication*, 44(2), 1975.
104. I. Hideki, K. Ryuj, and H. Yu, "A fast automatic fingerprint identification method based on a weighted-mean of binary image," *IEICE Transactions on Fundamentals of Electronic*, 76:1469, 1993.
105. D. Isenor and S. Zaky, "Fingerprint identification using graph matching," *Pattern Recognition*, 19:113–122, 1986.
106. G. Johnson, D. McMahon, S. Teeter, and G. Whitney, "A hybrid optical computer processing technique for fingerprint identification," *IEEE Trans. Computers*, 24:358–369, 1975.
107. B. Mehtre, "Fingerprint image analysis for automatic identification," *Machine Vision and Applications*, 6(2-3):124–139, 1993.
108. A. Roddy and J. Stosz, "Fingerprint features - statistical analysis and system performance estimates," *Proceedings of IEEE*, 85(9):1390–1421, 1997.
109. M. Sparrow and P. Sparrow, *A Topological Approach to The Matching of Single Fingerprints: Development of Algorithms for Use on Latent Fingermarks.* U.S.A. Government Publication. Gaithersburg, MD: U.S. Dept. of Commerce, National Bureau of Standards, Washington, D.C., 1985.
110. E. Szekly and V Szekly, "Image recognition problems of fingerprint identification," *Microprocessors and Microsystems*, 17(4):215–218, 1993.
111. M. Trauring, "Automatic comparison of fingerprint-ridge patterns," *Nature*, 197(4871):938–940, 1963.
112. J. Wegstein, *The M40 Fingerprint Matcher.* U.S.A. Government Publication. Washington D.C.: National Bureau of Standards, Technical Note 878, U.S Government Printing Office, 1972.

113. J. H. Wegstein, *An Automated Fingerprint Identification System*. U.S.A. Government Publication, Washington, 1982.
114. R. Germain, A Califano, and S. Colville, "Fingerprint matching using transformation parameter clustering," *IEEE Computational Science and Engineering*, 4(4):42–49, 1997.

Performance Evaluation

115. A. K. Jain, S. Prabhakar, and A. Ross, "Fingerprint Matching: Data Acquisition and Performance Evaluation", *MSU Technical Report TR99-14*, 1999.
116. A. K. Jain, S. Prabhakar, and S. Pankanti, "Twin Test: On Discriminability of Fingerprints" to appear in *3rd International Conference on Audio- and Video-Based Person Authentication*, Sweden, June 6-8, 2001.
117. D. Maio, D. Maltoni, R. Cappelli, J. L. Wayman, and A. K. Jain, "FVC2000: Fingerprint Verification Competition", *Proc. 15th International Conference Pattern Recognition*, Barcelona, September 3-8, 2000, http://bias.csr.unibo.it/fvc2000/.
118. J. G. Daugman and G. O. Williams, "A Proposed Standard for Biometric Decidability," in *Proc. CardTech/SecureTech Conf.*, pp. 223-234, Atlanta, GA, 1996.
119. J. L. Wayman, "Multi-finger Penetration Rate and ROC Variability for Automatic Fingerprint Identification Systems", *Technical Report*, San Jose State University, 1999, http://www.engr.sjsu.edu/biometrics/.
120. J. L. Wayman, "Technical Testing and Evaluation of Biometric Identification Devices," In *Biometrics: Personal Identification in Networked Society*, Anil K. Jain, Ruud Bolle, and S. Pankanti (editors), Kluwer Academic publishers, pp. 345-368, 1998.
121. United Kingdom Biometric Working Group, "Best Practices in Testing and Reporting Biometric Device Performance", Version 1.0, March 2000. http://www.afb.org.uk/bwg/bestprac10.pdf.
122. Unpublished 1995 report by Frank Torpay of Mitre Corporation using data extracted from the FBI's Identification Division Automated Services database of $22,000,000$ human-classified fingerprints.
123. R. Bolle, N. K. Ratha, and S. Pankanti, "Evaluating techniques for biometrics-based authentication systems", *Proc. 15th IAPR Int. Conference on Pattern Recognition*, Barcelona, Spain, Sep. 3-8, 2000.

Multimodal Fingerprint Systems

124. L. Hong, A. K. Jain and S. Pankanti, "Can Multibiometrics Improve Performance?", Proceedings AutoID'99, Summit, NJ, pp. 59-64, Oct 1999.
125. A. K. Jain, L. Hong, and Y. Kulkarni, "A Multimodal Biometric System using Fingerprint, Face, and Speech", *Proc. 2nd Int'l Conference on Audio- and Video-based Biometric Person Authentication*, Washington D.C., pp. 182-187, 1999.
126. A. K. Jain, S. Prabhakar, and S. Chen, "Combining Multiple Matchers for a High Security Fingerprint Verification System", Pattern Recognition Letters, Vol 20, No. 11-13, pp. 1371-1379, November 1999.
127. L. Hong and A. K. Jain, "Integrating Faces and Fingerprints For Personal Identification," *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol.20, No.12, pp. 1295-1307, 1998.
128. S. Prabhakar and A. K. Jain, "Decision-level Fusion in Fingerprint Verification" to appear in *Pattern Recognition*, 2001.

129. U. Dieckmann, P. Plankensteiner, and T. Wagner, "Sesam: a Biometric Person Identification System Using Sensor Fusion," *Pattern Recognition Letters*, Vol. 18, No. 9, pp. 827-833, 1997.
130. J. Kittler, M. Hatef, R. P. W. Duin, and J. Matas, "On Combining Classifiers", *IEEE Trans. on Patt. Anal. and Machine Intell.*, Vol. 20, No. 3, pp. 226-239, 1998.
131. T. K. Ho, J. J. Hull, and S. N. Srihari, "On Multiple Classifier Systems for Pattern Recognition", *IEEE Trans. Pattern Anal. and Machine Intell.*, Vol. 16, No. 1, pp. 66-75, 1994.

Miscellaneous

132. American National Standard for Information Systems, "Data Format for the Interchange of Fingerprint, Facial, & Scar Mark, & Tattoo (SMT) Information, Doc#ANSI/NIST-CSL ITL 1-2000, NIST Special Public Report 500-245", American National Standards Institute, New York, 2000
133. C. I. Watson and C. L. Wilson, "NIST Special Database 4, Fingerprint Database," National Institute of Standards and Technology, March 1992.
134. C. I. Watson and C. L. Wilson, "NIST Special Database 9, Fingerprint Database," National Institute of Standards and Technology, March 1992.
135. J. L. Wayman, "Daubert Hearing on Fingerprinting", http://www.engr.sjsu.edu/biometrics/publications_daubert.html.
136. R. Epstein and E. Hey, "Challenging the testimony of forensic identification experts in a post-daubert world: The new rules of the game", National Seminar for Federal Defenders, New Orleans, June 5-7, 2000.
137. J. Osterburg, T. Parthasarathy, T. E. S. Raghavan, and S. L. Sclove, "Development of a Mathematical Formula for the Calculation of Fingerprint Probabilities Based on Individual Characteristics", *Journal of the American Statistical Association*, No. 360, Vol. 72, 1997.
138. Problem Idents. http://onin.com/fp/problemidents.html.
139. R. Cappelli, A. Erol, D. Maio, and D. Maltoni, "Synthetic Fingerprint-image Generation", Proc. International Conference on Pattern Recognition (ICPR), Barcelona, Vol. 3, pp. 475-478, September 2000.
140. F. Karen, "Encryption, smart cards, and fingerprint readers," *IEEE Spectrum*, 26(8):22, 1989.
141. D. Mintie, "Welfare id at the point of transaction using fingerprint and 2D bar codes," In *Proc. CardTech/SecurTech, Volume II: Applications*, pages 469–476, Atlanta, Georgia, May 1996.
142. C. Stanley, "Are fingerprints a genetic marker for handedness?" *Behavior Genetics*, 24(2):141, 1994.
143. C. M. Brislawn, *The FBI Fingerprint Image Compression Standard.* http://www.c3.lanl.gov/ brislawn/FBI/FBI.html.
144. R. M. Bolle, S. E. Colville, and S. Pankanti, "System and method for determining ridge counts in fingerprint image processing," U.S. Patent No. 6,111,978, 2000.
145. R. Cappelli and D. Maio and D. Maltoni, "Modeling plastic distortion in fingerprints", *Iinternational Conference on advances in pattern Recognition (ICAPR2001)*, Rio Othon Palace Hotel, Rio de Jaeiro, Brazil, March 11–14, 2001.
146. A. W. Senior, R. Bolle, "Improved Fingerprint Matching by Distortion Removal", *IEICE Transactions Special issue on Biometrics*, to appear, 2001.

147. M. Yeung and S. Pankanti, "Verification Watermarks on Fingerprint Recognition and Retrieval", *Journal of Electronic Imaging*, vol. 9, No. 4, pp. 468-476, October 2000.
148. N. K. Ratha, J. Connell, and R. Bolle, "Secure Biometric Authentication", *Proc. 1999 IEEE Workshop on Automatic Identification Advanced Technologies*, October 28-29, Morristown, NJ, 1999.
149. N. Ratha, J. Connell, and R. Bolle, "Cancelable Biometrics", *Biometrics Consortium Workshop*, September 2000.
150. J. Woodward, "Biometrics: Identifying law and policy concerns", in *Biometrics: Personal identification in a networked society*, A. K. Jain, R. Bolle, and S. Pankanti (eds.), Kluwer Academic Publishers, 1999.