

Face Recognition Algorithms

Proyecto Fin de Carrera

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Abstract

The goal of this "proyecto fin de carrera" was to produce a review of the face detection and face recognition literature as comprehensive as possible. Face detection was included as a unavoidable preprocessing step for face recognition, and as an issue by itself, because it presents its own difficulties and challenges, sometimes quite different from face recognition. We have soon recognized that the amount of published information is unmanageable for a short term effort, such as required of a PFC, so in agreement with the supervisor we have stopped at a reasonable time, having reviewed most conventional face detection and face recognition approaches, leaving advanced issues, such as video face recognition or expression invariances, for the future work in the framework of a doctoral research. I have tried to gather much of the mathematical foundations of the approaches reviewed aiming for a self contained work, which is, of course, rather difficult to produce. My supervisor encouraged me to follow formalism as close as possible, preparing this PFC report more like an academic report than an engineering project report.

procedure has many applications like face tracking, pose estimation or compression. The next step -feature extraction- involves obtaining relevant facial features from the data. These features could be certain face regions, variations, angles or measures, which can be human relevant (e.g. eyes spacing) or not. This phase has other applications like facial feature tracking or emotion recognition. Finally, the system does recognize the face. In an identification task, the system would report an identity from a database. This phase involves a comparison method, a classification algorithm and an accuracy measure. This phase uses methods common to many other areas which also do some classification process -sound engineering, data mining et al.

These phases can be merged, or new ones could be added. Therefore, we could find many different engineering approaches to a face recognition problem. Face detection and recognition could be performed in tandem, or proceed to an expression analysis before normalizing the face [109].

1.4 Face detection

Nowadays some applications of Face Recognition don't require face detection. In some cases, face images stored in the data bases are already normalized. There is a standard image input format, so there is no need for a detection step. An example of this could be a criminal data base. There, the law enforcement agency stores faces of people with a criminal report. If there is new subject and the police has his or her passport photograph, face detection is not necessary. However, the conventional input image of computer vision systems are not that suitable. They can contain many items or faces. In these cases face detection is mandatory. It's also unavoidable if we want to develop an automated face tracking system. For example, video surveillance systems try to include face detection, tracking and recognizing. So, it's reasonable to assume face detection as part of the more ample face recognition problem.

Face detection must deal with several well known challenges[117, 125]. They are usually present in images captured in uncontrolled environments, such as surveillance video systems. These challenges can be attributed to some factors:

- Pose variation. The ideal scenario for face detection would be one in which only frontal images were involved. But, as stated, this is very unlikely in general uncontrolled conditions. Moreover, the performance of face detection algorithms drops severely when there are large pose variations. It's a major research issue. Pose variation can happen due to subject's movements or camera's angle.

- Feature occlusion. The presence of elements like beards, glasses or hats introduces high variability. Faces can also be partially covered by objects or other faces.
- Facial expression. Facial features also vary greatly because of different facial gestures.
- Imaging conditions. Different cameras and ambiental conditions can affect the quality of an image, affecting the appearance of a face.

There are some problems closely related to face detection besides feature extraction and face classification. For instance, face location is a simplified approach of face detection. It's goal is to determine the location of a face in an image where there's only one face. We can differentiate between face detection and face location, since the latter is a simplified problem of the former. Methods like locating head boundaries [59] were first used on this scenario and then exported to more complicated problems. Facial feature detection concerns detecting and locating some relevant features, such as nose, eye-brow, lips, ears, etc. Some feature extraction algorithms are based on facial feature detection. There is much literature on this topic, which is discussed later. Face tracking is other problem which sometimes is a consequence of face detection. Many system's goal is not only to detect a face, but to be able to locate this face in real time. Once again, video surveillance system is a good example.

1.4.1 Face detection problem structure

Face Detection is a concept that includes many sub-problems. Some systems detect and locate faces at the same time, others first perform a detection routine and then, if positive, they try to locate the face. Then, some tracking algorithms may be needed - see Figure 1.2.

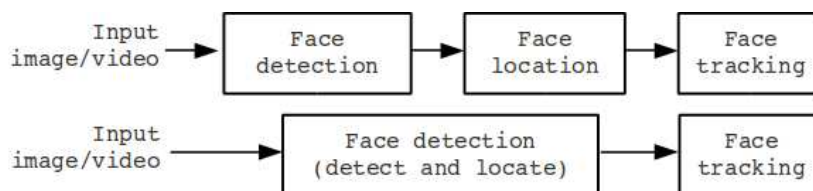


Figure 1.2: Face detection processes.

Face detection algorithms usually share common steps. Firstly, some data dimension reduction is done, in order to achieve a admissible response

time. Some pre-processing could also be done to adapt the input image to the algorithm prerequisites. Then, some algorithms analyze the image as it is, and some others try to extract certain relevant facial regions. The next phase usually involves extracting facial features or measurements. These will then be weighted, evaluated or compared to decide if there is a face and where is it. Finally, some algorithms have a learning routine and they include new data to their models.

Face detection is, therefore, a two class problem where we have to decide if there is a face or not in a picture. This approach can be seen as a simplified face recognition problem. Face recognition has to classify a given face, and there are as many classes as candidates. Consequently, many face detection methods are very similar to face recognition algorithms. Or put another way, techniques used in face detection are often used in face recognition.

1.4.2 Approaches to face detection

It's not easy to give a taxonomy of face detection methods. There isn't a globally accepted grouping criteria. They usually mix and overlap. In this section, two classification criteria will be presented. One of them differentiates between distinct scenarios. Depending on these scenarios different approaches may be needed. The other criteria divides the detection algorithms into four categories.

Detection depending on the scenario.

- **Controlled environment.** It's the most straightforward case. Photographs are taken under controlled light, background, etc. Simple edge detection techniques can be used to detect faces [70].
- **Color images.** The typical skin colors can be used to find faces. They can be weak if light conditions change. Moreover, human skin color changes a lot, from nearly white to almost black. But, several studies show that the major difference lies between their intensity, so chrominance is a good feature [117]. It's not easy to establish a solid human skin color representation. However, there are attempts to build robust face detection algorithms based on skin color [99].
- **Images in motion.** Real time video gives the chance to use motion detection to localize faces. Nowadays, most commercial systems must locate faces in videos. There is a continuing challenge to achieve the best detecting results with the best possible performance [82]. Another

approach based on motion is eye blink detection, which has many uses aside from face detection [30, 53].

Detection methods divided into categories

Yan, Kriegman and Ahuja presented a classifications that is well accepted [117]. Methods are divided into four categories. These categories may overlap, so an algorithm could belong to two or more categories. This classification can be made as follows:

- Knowledge-based methods. Ruled-based methods that encode our knowledge of human faces.
- Feature-invariant methods. Algorithms that try to find invariant features of a face despite it's angle or position.
- Template matching methods. These algorithms compare input images with stored patterns of faces or features.
- Appearance-based methods. A template matching method whose pattern database is learnt from a set of training images.

Let us examine them on detail:

Knowledge-based methods.

These are rule-based methods. They try to capture our knowledge of faces, and translate them into a set of rules. It's easy to guess some simple rules. For example, a face usually has two symmetric eyes, and the eye area is darker than the cheeks. Facial features could be the distance between eyes or the color intensity difference between the eye area and the lower zone. The big problem with these methods is the difficulty in building an appropriate set of rules. There could be many false positives if the rules were too general. On the other hand, there could be many false negatives if the rules were too detailed. A solution is to build hierarchical knowledge-based methods to overcome these problems. However, this approach alone is very limited. It's unable to find many faces in a complex image.

Other researches have tried to find some invariant features for face detection. The idea is to overcome the limits of our instinctive knowledge of faces. One early algorithm was developed by Han, Liao, Yu and Chen in 1997 [41]. The method is divided in several steps. Firstly, it tries to find eye-analogue pixels, so it removes unwanted pixels from the image. After performing the

segmentation process, they consider each eye-analogue segment as a candidate of one of the eyes. Then, a set of rule is executed to determinate the potential pair of eyes. Once the eyes are selected, the algorithms calculates the face area as a rectangle. The four vertexes of the face are determined by a set of functions. So, the potential faces are normalized to a fixed size and orientation. Then, the face regions are veriflicated using a back propagation neural network. Finally, they apply a cost function to make the final selection. They report a success rate of 94%, even in photographs with many faces. These methods show themselves efficient with simple inputs. But, what happens if a man is wearing glasses?

There are other features that can deal with that problem. For example, there are algorithms that detect face-like textures or the color of human skin. It is very important to choose the best color model to detect faces. Some recent researches use more than one color model. For example, RGB and HSV are used together successfully [112]. In that paper, the authors chose the following parameters

$$0.4 \leq r \leq 0.6, 0.22 \leq g \leq 0.33, r > g > (1 - r)/2 \quad (1.1)$$

$$0 \leq H \leq 0.2, 0.3 \leq S \leq 0.7, 0.22 \leq V \leq 0.8 \quad (1.2)$$

Both conditions are used to detect skin color pixels. However, these methods alone are usually not enough to build a good face detection algorithm. Skin color can vary significantly if light conditions change. Therefore, skin color detection is used in combination with other methods, like local symmetry or structure and geometry.

Template matching

Template matching methods try to define a face as a function. We try to find a standard template of all the faces. Different features can be defined independently. For example, a face can be divided into eyes, face contour, nose and mouth. Also a face model can be built by edges. But these methods are limited to faces that are frontal and unoccluded. A face can also be represented as a silhouette. Other templates use the relation between face regions in terms of brightness and darkness. These standard patterns are compared to the input images to detect faces. This approach is simple to implement, but it's inadequate for face detection. It cannot achieve good results with variations in pose, scale and shape. However, deformable templates have been proposed to deal with these problems.

Appearance-based methods

The templates in appearance-based methods are learned from the examples in the images. In general, appearance-based methods rely on techniques from statistical analysis and machine learning to find the relevant characteristics of face images. Some appearance-based methods work in a probabilistic network. An image or feature vector is a random variable with some probability of belonging to a face or not. Another approach is to define a discriminant function between face and non-face classes. These methods are also used in feature extraction for face recognition and will be discussed later. Nevertheless, these are the most relevant methods or tools:

- **Eigenface-based.** Sirovich and Kirby [101, 56] developed a method for efficiently representing faces using PCA (Principal Component Analysis). Their goal of this approach is to represent a face as a coordinate system. The vectors that make up this coordinate system were referred to as eigenpictures. Later, Turk and Pentland used this approach to develop a eigenface-based algorithm for recognition [110].
- **Distribution-based.** These systems were first proposed for object and pattern detection by Sung [106]. The idea is collect a sufficiently large number of sample views for the pattern class we wish to detect, covering all possible sources of image variation we wish to handle. Then an appropriate feature space is chosen. It must represent the pattern class as a distribution of all its permissible image appearances. The system matches the candidate picture against the distribution-based canonical face model. Finally, there is a trained classifier which correctly identifies instances of the target pattern class from background image patterns, based on a set of distance measurements between the input pattern and the distribution-based class representation in the chosen feature space. Algorithms like PCA or Fisher's Discriminant can be used to define the subspace representing facial patterns.
- **Neural Networks.** Many pattern recognition problems like object recognition, character recognition, etc. have been solved successfully by neural networks. These systems can be used in face detection in different ways. Some early researches used neural networks to learn the face and non-face patterns [93]. They defined the detection problem as a two-class problem. The real challenge was to represent the "images not containing faces" class. Other approach is to use neural networks to find a discriminant function to classify patterns using distance measures [106]. Some approaches have tried to find an optimal boundary between face and non-face pictures using a constrained generative model [91].

- Support Vector Machines. SVMs are linear classifiers that maximize the margin between the decision hyperplane and the examples in the training set. So, an optimal hyperplane should minimize the classification error of the unseen test patterns. This classifier was first applied to face detection by Osuna et al. [87].
- Sparse Network of Winnows. SNoWs were first used for detection by Yang et al. [118]. They defined a sparse network of two linear units or target nodes, one representing face patterns and the other for the non-face patterns. The SNoW had a incrementally learned feature space. New labeled cases served as positive example for one target and as a negative example for the remaining target. The system proved to be effective at the time, and less time consuming.
- Naive Bayes Classifiers. Schneiderman and Kanade described an object recognition algorithm that modeled and estimated a Bayesian Classifier [96]. They computed the probability of a face to be present in the picture by counting the frequency of occurrence of a series of patterns over the training images. They emphasized on patterns like the intensity around the eyes. The classifier captured the joint statistics of local appearance and position of the face as well as the statistics of local appearance and position in the visual world. Overall, their algorithm showed good results on frontal face detection. Bayes Classifiers have also been used as a complementary part of other detection algorithms.
- Hidden Markov Model. This statistical model has been used for face detection. The challenge is to build a proper HMM, so that the output probability can be trusted. The states of the model would be the facial features, which are often defined as strips of pixels. The probabilistic transition between states are usually the boundaries between these pixel strips. As in the case of Bayesians, HMMs are commonly used along with other methods to build detection algorithms.
- Information-Theoretical Approach. Markov Random Fields (MRF) can be used to model contextual constraints of a face pattern and correlated features. The Markov process maximizes the discrimination between classes (an image has a face or not) using the Kullback–Leibler divergence. Therefore, this method can be applied in face detection.
- Inductive Learning. This approach has been used to detect faces. Algorithms like Quinlan’s C4.5 or Mitchell’s FIND-S have been used for this purpose [32, 45].

References

- [1] Y. Adini, Y. Moses, and S. Ullma. Face recognition: the problem of compensating for changes in illumination direction. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 19:721–732, 1997.
- [2] N. Ahmed, T. Natarajan, and K. R. Rao. Discrete cosine transform. *IEEE Transactions on Computers*, 23:90–93, 1974.
- [3] F. Bach and M. Jordan. Kernel independent component analysis. *Journal of Machine Learning Research*, 3:1–48, 2002.
- [4] M. Ballantyne, R. S. Boyer, and L. Hines. Woody bledsoe: His life and legacy. *AI Magazine*, 17(1):7–20, 1996.
- [5] M. Bartlett, J. Movellan, and T. Sejnowski. Face recognition by independent component analysis. *IEEE Trans. on Neural Networks*, 13(6):1450–1464, November 2002.
- [6] P. Belhumeur, J. Hespanha, and D. Kriegman. Eigenfaces vs. fisherfaces: Recognition using class specific linear projection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 19(7):711–720, July 1997.
- [7] S. Bentin, T. Allison, A. Puce, E. Perez, and G. McCarthy. Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience*, 8(6):551–565, 1996.
- [8] V. Bevilacqua, L. Cariello, G. Carro, D. Daleno, and G. Mastronardi. A face recognition system based on pseudo 2d hmm applied to neural network coefficient. *Soft Computing - A Fusion of Foundations, Methodologies and Applications*, 12(7):615–621, 2007.
- [9] D. Bhattacharjee, D. K. Basu, M. Nasipuri, and M. Kundu. Human face recognition using fuzzy multilayer perceptron. *Soft Computing - A Fusion of Foundations, Methodologies and Applications*, 14(6):559–570, April 2009.

- [10] A.-A. Bhuiyan and C. H. Liu. On face recognition using gabor filters. In *Proceedings of World Academy of Science, Engineering and Technology*, volume 22, pages 51–56, 2007.
- [11] BIOID. Bioid face database. <http://www.bioid.com/support/downloads/software/bioid-face-database.html>.
- [12] V. Blanz and T. Vetter. A morphable model for the synthesis of 3d faces. In *Proc. of the SIGGRAPH'99*, pages 187–194, Los Angeles, USA, August 1999.
- [13] V. Blanz and T. Vetter. Face recognition based on fitting a 3d morphable model. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 25(9):1063–1074, September 2003.
- [14] W. W. Bledsoe. The model method in facial recognition. Technical report pri 15, Panoramic Research, Inc., Palo Alto, California, 1964.
- [15] W. W. Bledsoe. Man-machine facial recognition: Report on a large-scale experiment. Technical report pri 22, Panoramic Research, Inc., Palo Alto, California, 1966.
- [16] W. W. Bledsoe. Some results on multicategory pattern recognition. *Journal of the Association for Computing Machinery*, 13(2):304–316, 1966.
- [17] W. W. Bledsoe. Semiautomatic facial recognition. Technical report sri project 6693, Stanford Research Institute, Menlo Park, California, 1968.
- [18] W. W. Bledsoe and H. Chan. A man-machine facial recognition system—some preliminary results. Technical report pri 19a, Panoramic Research, Inc., Palo Alto, California, 1965.
- [19] E. M. Bronstein, M. M. Bronstein, R. Kimmel, and A. Spira. 3d face recognition without facial surface reconstruction, 2003.
- [20] R. Brunelli and T. Poggio. Face recognition: Features versus templates. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 15(10):1042–1052, October 1993.
- [21] J. S. Bruner and R. Tagiuri. The percepton of people. *Handbook of Social Psychology*, 2(17), 1954.

- [22] D. Cai, X. He, and J. Han. Semi-supervised discriminant analysis. *Computer Vision. IEEE 11th International Conference on Computer Vision*, 14:1–7, 2007.
- [23] H. Chang, A. Koschan, B. Abidi, and M. Abidi. Fusing continuous spectral images for face recognition under indoor and outdoor illuminants. *Machine Vision and Applications*, 21(2):201–215, February 2010.
- [24] L.-F. Chen, H.-Y. Liao, J.-C. Lin, and C.-C. Han. Why recognition in a statistics-based face recognition system should be based on the pure face portion: a probabilistic decision-based proof. *Pattern Recognition*, 34(5):1393–1403, 2001.
- [25] P. Comon. Independent component analysis, a new concept? *Signal Processing*, 36:287–314, 1994.
- [26] T. Cootes and C. Taylor. Statistical models of appearance for computer vision. Technical report, University of Manchester, March 2004.
- [27] T. Cootes, K. Walker, and C. Taylor. View-based active appearance models. In *Proc. of the IEEE International Conference on Automatic Face and Gesture Recognition*, pages 227–232, Grenoble, France, March 2000.
- [28] J. G. Daugman. Two-dimensional spectral analysis of cortical receptive field profiles. *Vision Research*, 20(10):847 – 856, 1980.
- [29] R. Diamond and S. Carey. Why faces are and are not special. an effect of expertise. *Journal of Experimental Psychology: General*, 115(2):107–117, 1986.
- [30] M. Divjak and H. Bischof. Real-time video-based eye blink analysis for detection of low blink-rate during computer use. In *1st International Workshop on Tracking Humans for the Evaluation of their Motion in Image Sequences (THEMIS)*, pages 99–107, Leeds, UK, September 2008.
- [31] B. Dudley. "e3: New info on microsoft's natal – how it works, multi-player and pc versions". *The Seattle Times*, June 3 2009.
- [32] N. Duta and A. Jain. Learning the human face concept from black and white pictures. In *Proc. International Conf. Pattern Recognition*, pages 1365–1367, 1998.

- [33] K. B. et al. *AI 2005*, chapter Multiple Face Tracking Using Kalman Estimator Based Color SSD Algorithm, pages 1229–1232. LNAI 3809. Springer-Verlag Heidelberg, 2005.
- [34] M. Fischler and R. Elschlager. The representation and matching of pictorial structures. *IEEE Transactions on Computers*, C-22(1):67 – 92, 1973.
- [35] A. Golstein, L. Harmon, and A. Lest. Identification of human faces. *Proceedings of the IEEE*, 59:748–760, 1971.
- [36] D. Graham and N. Allinson. *Face recognition: From Theory to Applications*, chapter Characterizing Virtual Eigensignatures for General Purpose Face Recognition, pages 446–465. 1998.
- [37] R. Gross, S. Baker, I. Matthews, and T. Kanade. Face recognition across pose and illumination. In S. Z. Li and A. K. Jain, editors, *Handbook of Face Recognition*. Springer-Verlag, June 2004.
- [38] R. Gross, J. Shi, and J. Cohn. Quo vadis face recognition? - the current state of the art in face recognition. Technical report, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA, June 2001.
- [39] G. Guo, S. Li, and K. Chan. Face recognition by support vector machines. In *Proc. of the IEEE International Conference on Automatic Face and Gesture Recognition*, pages 196–201, Grenoble, France, March 2000.
- [40] P. Hallinan. *A Deformable Model for Face Recognition Under Arbitrary Lighting Conditions*. PhD thesis, Univesity of Harvard, 1995.
- [41] C.-C. Han, H.-Y. M. Liao, K. chung Yu, and L.-H. Chen. *Lecture Notes in Computer Science*, volume 1311, chapter Fast face detection via morphology-based pre-processing, pages 469–476. Springer Berlin / Heidelberg, 1997.
- [42] X. He and P. Niyogi. Locality preserving projections. In *Proceedings of the Conference on Advances in Nerual Information Processing Systems*, 2003.
- [43] B. Heisele, P. Ho, and T. Poggio. Face recognition with support vector machines: Global versus component-based approach. In *Proc. of the Eighth IEEE International Conference on Computer Vision, ICCV 2001*, volume 2, pages 688–694, Vancouver, Canada, July 2001.

- [44] G. B. Huang, M. Ramesh, T. Berg, and E. Learned-Miller. Labeled faces in the wild: A database for studying face recognition in unconstrained environments. Technical Report 07-49, University of Massachusetts, Amherst, October 2007.
- [45] J. Huang, S. Gutta, and H. Wechsler. Detection of human faces using decision trees. In *Proc. Second International Conf. Automatic Face and Gesture Recognition*, pages 248–252, 1996.
- [46] J. Huang, B. Heisele, and V. Blanz. Component-based face recognition with 3d morphable models. In *Proc. of the 4th International Conference on Audio- and Video-Based Biometric Person Authentication, AVBPA*, pages 27–34, Guildford, UK, June 2003.
- [47] N. Intrator, D. Reisfeld, and Y. Yeshurun. Face recognition using a hybrid supervised/unsupervised neural network. *Pattern Recognition Letters*, 17:67–76, 1995.
- [48] A. Jain, R. Duin, and J. Mao. Statistical pattern recognition: A review. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22(1):4–37, January 2000.
- [49] K. Jonsson, J. Matas, J. Kittler, and Y. Li. Learning support vectors for face verification and recognition. In *Proc. of the IEEE International Conference on Automatic Face and Gesture Recognition*, pages 208–213, Grenoble, France, March 2000.
- [50] M. H. Jonsson, J. Matas, M. Hamouz, K. Jonsson, J. Kittler, Y. Li, C. Kotropoulos, A. Tefas, I. Pitas, T. Tan, H. Yan, F. Smeraldi, J. Bigun, N. Capdevielle, W. Gerstner, S. Ben-yacoub, Y. Abdeljaoued, and E. Mayoraz. Comparison of face verification results on the xm2vts database. In *Proceedings of the 15th ICPR*, pages 858–863. IEEE Computer Society Press, 2000.
- [51] A. Kadyrov and M. Petrou. The trace transform and its applications. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 23(8):811–823, August 2001.
- [52] S. Kare, A. Samal, and D. Marx. Using bidimensional regression to assess face similarity. *Machine Vision and Applications*, 21(3):261–274, 2008.

- [53] S. Kawato and N. Tetsutan. Detection and tracking of eyes for gaze-camera control. In *Proc. 15th Int. Conf. on Vision Interface*, pages 348–353, 2002.
- [54] T. Kenade. *Picture Processing System by Computer Complex and Recognition of Human Faces*. PhD thesis, Kyoto University, November 1973.
- [55] B. Kepenekci. *Face recognition using Gabor Wavelet Transformation*. PhD thesis, Te Middle East Technical University, September 2001.
- [56] M. Kirby and L. Sirovich. Application of the karhunen-loeve procedure for the characterization of human faces. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(1):103–108, 1990.
- [57] T. Kohonen. *Self-organization and associative memory*. Springer-Verlag, Berlin, 1989.
- [58] S. Kung and J. Taur. Decision-based neural networks with signal/image classification applications. *IEEE Transactions on Neural Networks*, 6(1):170–181, 1995.
- [59] K.-M. Lam and H. Yan. Fast algorithm for locating head boundaries. *Journal of Electronic Imaging*, 03(04):351–359, October 1994.
- [60] S. Lawrence, C. L. Giles, A. C. Tsoi, and A. D. Back. Face recognition: A convolutional neural network approach. *IEEE Transactions on Neural Networks*, 8:98–113, 1997.
- [61] J. Lee, J. Lee, B. Moghaddam, B. Moghaddam, H. Pfister, H. Pfister, R. Machiraju, and R. Machiraju. Finding optimal views for 3d face shape modeling. In *Proceedings International Conference on Automatic Face and Gesture Recognition*, pages 31–36, 2004.
- [62] J. Lee, B. Moghaddam, H. Pfister, and R. Machiraju. inding optimal views for 3d face shape modeling. In *Proc. of the International Conference on Automatic Face and Gesture Recognition, FGR2004*, pages 31–36, Seoul, Korea, May 2004.
- [63] T. Lee. Image representation using 2d wavelets. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 18(10):959–971, 1996.
- [64] S.-H. Lin, S.-Y. Kung, and L.-J. Lin. Face recognition/detection by probabilistic decision-based neural network. *IEEE Transactions on Neural Networks*, 8:114–132, 1997.

- [65] C. Liu and H. Wechsler. Face recognition using evolutionary pursuit. In *Proceedings of the Fifth European Conference on Computer Vision, ECCV'98*, volume 2, pages 596–612, Freiburg, Germany, 1998.
- [66] C. Liu and H. Wechsler. A unified bayesian framework for face recognition. In *roc. of the 1998 IEEE International Conference on Image Processing, ICIP'98*, pages 151–155, Chicago, USA, October 1998.
- [67] C. Liu and H. Wechsler. Comparative assessment of independent component analysis (ica) for face recognition. In *Proc. of the Second International Conference on Audio- and Video-based Biometric Person Authentication, AVBPA '99*, Washington D.C., USA, March 1999.
- [68] C. Liu and H. Wechsler. Evolutionary pursuit and its application to face recognition. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 22(6):570–582, June 2000.
- [69] F. Liu, Z. liang Wang, L. Wang, and X. yan Meng. *Affective Computing and Intelligent Interaction*, chapter Facial Expression Recognition Using HLAC Features and WPCA, pages 88–94. Springer Berlin / Heidelberg, 2005.
- [70] R. Louban. *Image Processing of Edge and Surface Defects Theoretical Basis of Adaptive Algorithms with Numerous Practical Applications*, volume 123, chapter Edge Detection, pages 9–29. Springer Berlin Heidelberg, 2009.
- [71] J. Lu, K. Plataniotis, A. Venetsanopoulos, and S. Li. Ensemble-based discriminant learning with boosting for face recognition. *IEEE Transactions on Neural Networks*, 17(1):166–178, January 2006.
- [72] X. Lu. Image analysis for face recognition. personal notes, May 2003.
- [73] K. V. Mardia and I. L. Dryden. The ar face database. Technical report, Purdue University, 1998.
- [74] K. Massy. "toyota develops eyelid-monitoring system". *Cnet reviews*, January 22 2008.
- [75] M. McWhertor. "sony spills more ps3 motion controller details to devs". *Kotaku. Gawker Media.*, June 19 2009. <http://kotaku.com/5297265/sony-spills-more-ps3-motion-controller-details-to-devs>.

- [76] R. Meir and G. Raetsch. An introduction to boosting and leveraging. In I. S. Mendelson and A. Smola, editors, *Advanced Lectures on Machine Learning*, pages 118–183. Springer, 2003.
- [77] B. Moghaddam. Principal manifolds and probabilistic subspaces for visual recognition. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(6):780–788, June 2002.
- [78] B. Moghaddam, T. Jebara, and A. Pentland. Bayesian face recognition. *Pattern Recognition*, 33(11):1771–1782, November 2000.
- [79] B. Moghaddam, J. Lee, H. Pfister, and R. Machiraju. Model-based 3d face capture with shape-from-silhouettes. In *Proc. of the IEEE International Workshop on Analysis and Modeling of Faces and Gestures, AMFG*, pages 20–27, Nice, France, October 2003.
- [80] B. Moghaddam and A. Pentland. Probabilistic visual learning for object representation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 19(7):696–710, July 1997.
- [81] N. Nain, P. Gour, N. Agarwal, R. P. Talawar, and S. Chandra. Face recognition using pca and lda with singular value decomposition(svd) using 2dlda. In *Proceedings of the World Congress on Engineering*, volume 1, 2008.
- [82] M. C. Nechyba, L. Brandy, and H. Schneiderman. *Lecture Notes in Computer Science*, volume 4625/2009, chapter PittPatt Face Detection and Tracking for the CLEAR 2007 Evaluation, pages 126–137. Springer Berlin / Heidelberg, 2009.
- [83] A. Nefian. Embedded bayesian networks for face recognition. In *Proc. of the IEEE International Conference on Multimedia and Expo*, volume 2, pages 133–136, Lusanne, Switzerland, August 2002.
- [84] A. Nefian and M. Hayes. Hidden markov models for face recognition. In *Proc. of the IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP’98*, volume 5, pages 2721–2724, Washington, USA, May 1998.
- [85] M. Nixon. Eye spacing measurement for facial recognition. *Proceedings of the Society of Photo-Optical Instrument Engineers, SPIE*, 575(37):279–285, August 1985.

- [86] U. of Stirling. Psychological image collection at stirling (pics). <http://pics.psych.stir.ac.uk/>.
- [87] E. Osuna, R. Freund, and F. Girosi. Training support vector machines: An application to face detection. *Proceedings of the IEEE Conf. Computer Vision and Pattern Recognition*, pages 130–136, June 1997.
- [88] K. Pearson. On lines and planes of closest fit to systems of points in space. *Philosophical Magazine*, 2(6):559–572, 1901.
- [89] P. Phillips, H. Moon, S. Rizvi, and P. Rauss. The feret evaluation methodology for face-recognition algorithms. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22(10):1090–1104, October 2000.
- [90] S. Pigeon and L. Vandendrope. The m2vts multimodal face database, o. In *Proceedings First International Conference on Audio- and Video-Based Biometric Person Authentication*, 1997.
- [91] F. Raphael, B. Olivier, and C. Daniel. A constrained generative model applied to face detection. *Neural Processing Letters*, 5(2):11–19, April 1997.
- [92] S. A. Rizvi, P. J. Phillips, and H. Moon. The feret verification testing protocol for face recognition algorithms, 1999.
- [93] H. A. Rowley, S. Baluja, and T. Kanade. Neural network-based face detection. *IEEE trans. Pattern Analysis and Machine Intelligence*, 20(1):23–38, January 1998.
- [94] F. Samaria. *Face Recognition Using Hidden Markov Models*. PhD thesis, University of Cambridge, 1997.
- [95] F. Samaria and A. Harter. Parameterisation of a stochastic model for human face identification. In *Proceedings of 2nd IEEE Workshop on Applications of Computer Vision*, Sarasota, FL, USA, December 1994. DB available at <http://www.cl.cam.ac.uk/research/dtg/attarchive/facedatabase.html>.
- [96] H. Schneiderman and T. Kenade. Probabilistic modeling of local appearance and spatial relationships for object recognition. *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, pages 45–51, 1998.

- [97] B. Scholkopf, A. Smola, and K.-R. Muller. Nonlinear component analysis as a kernel eigenvalue problem. Technical Report 44, Max-Planck-Institut fur biologische Kybernetik, 1996.
- [98] G. Shakhnarovich and B. Moghaddam. Face recognition in subspaces. In S. Z. Li and A. K. Jain, editors, *Handbook of Face Recognition*, page 35. Springer-Verlag, December 2004.
- [99] S. K. Singh, D. S. Chauhan, M. Vatsa, and R. Singh. A robust skin color based face detection algorithm. *Tamkang Journal of Science and Engineering*, 6(4):227–234, 2003.
- [100] P. Sinha, B. Balas, Y. Ostrovsky, and R. Russell. Face recognition by humans: 19 results all computer vision researchers should know about. *Proceedings of the IEEE*, 94(11):1948–1962, November November 2006.
- [101] L. Sirovich and M. Kirby. Low-dimensional procedure for the characterization of human faces. *Journal of the Optical Society of America A - Optics, Image Science and Vision*, 4(3):519–524, March 1987.
- [102] L. Sirovich and M. Meytlis. Symmetry, probability, and recognition in face space. *PNAS - Proceedings of the National Academy of Sciences*, 106(17):6895–6899, April 2009.
- [103] S. Srisuk and W. Kurutach. Face recognition using a new texture representation of face images. In *Proceedings of Electrical Engineering Conference*, pages 1097–1102, Cha-am, Thailand, November 2003.
- [104] S. Srisuk, M. Petrou, W. Kurutach, and A. Kadyrov. Face authentication using the trace transform. In *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, CVPR'03*, pages 305–312, Madison, Wisconsin, USA, June 2003.
- [105] T. J. Stonham. Practical face recognition and verification with wisard. In H. D. Ellis, editor, *Aspects of face processing*. Kluwer Academic Publishers, 1986.
- [106] K.-K. Sung. *Learning and Example Selection for Object and Pattern Detection*. PhD thesis, Massachusetts Institute of Technology, 1996.
- [107] L. Torres. Is there any hope for face recognition? In *Proc. of the 5th International Workshop on Image Analysis for Multimedia Interactive Services, WIAMIS*, Lisboa, Portugal, 21-23 April 2004.

- [108] S. Tulyakov. Review of classifier combination methods. *Studies in Computational Intelligence (SCI)*, 90:361–386, 2008.
- [109] M. Turk. A random walk through eigenspace. *IEICE Transactions on Information and Systems*, E84-D(12):1586–1595, December 2001.
- [110] M. Turk and A. Pentland. Eigenfaces for recognition. *Journal of Cognitive Neuroscience*, 3(1):71–86, 1991.
- [111] P. Viola and M. Jones. Robust real-time face detection. *International Journal of Computer Vision*, 57(2):137–154, May 2004.
- [112] K. Wan-zeng and Z. Shan-an. Multi-face detection based on downsampling and modified subtractive clustering for color images. *Journal of Zhejiang University SCIENCE A*, 8(1):72–78, January 2007.
- [113] S. Watanabe. Karhunen-loeve expansion and factor analysis theoretical remarks and applications. In *Proc. 4th Prague Conference on Information Theory*, 1965.
- [114] L. Wiskott, J.-M. Fellous, N. Krueger, and C. von der Malsburg. Face recognition by elastic bunch graph matching. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 19(7):775–779, 1997.
- [115] L. Wiskott, J.-M. Fellous, N. Krueger, and C. von der Malsburg. *Intelligent Biometric Techniques in Fingerprint and Face Recognition*, chapter Face Recognition by Elastic Bunch Graph Matching, pages 355–396. CRC Press, 1999.
- [116] M.-H. Yang. Face recognition using kernel methods. *Advances in Neural Information Processing Systems*, 14:8, 2002.
- [117] M.-H. Yang, D. Kriegman, and N. Ahuja. Detecting faces in images: A survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(1):34–58, January 2002.
- [118] M.-H. Yang, D. Roth, and N. Ahuja. A snow-based face detector. *Advances in Neural Information Processing Systems 12*, pages 855–861, 2000.
- [119] T. Yang and V. Kecman. Face recognition with adaptive local hyperplane algorithm. *Pattern Analysis Applications*, 13:79–83, 2010.
- [120] A. W. Yip and P. Sinha. Contribution of color to face recognition. *Perception*, 31:995–1003, 2002.

- [121] G. Zhang, L. Hu, and W. Jin. *Discovery Science*, volume 3245/2004 of *LNCS*, chapter Resemblance Coefficient and a Quantum Genetic Algorithm for Feature Selection, pages 125–153. Springer Berlin / Heidelberg, 2004.
- [122] G. Zhang, W. Jin, and L. Hu1. *CIS*, volume 3314/2005 of *LNCS*, chapter A Novel Feature Selection Approach and Its Application, pages 665–671. Springer-Verlag Berlin Heidelberg, 2004.
- [123] M. Zhang and J. Fulcher. Face recognition using artificial neural network group-based adaptive tolerance (gat) trees. *IEEE Transactions on Neural Networks*, 7(3):555–567, 1996.
- [124] W. Zhao and R. Chellappa. Image-based face recognition: Issues and methods. In M. D. B. Javidi, editor, *Image Recognition and Classification*, pages 375–402. Marcel Dekker, Inc., 2002.
- [125] W. Zhao, R. Chellappa, A. Rosenfeld, and P. Phillips. Face recognition: A literature survey. *ACM Computing Surveys*, pages 399–458, 2003.
- [126] D. Zhou and Z. Tang. Kernel-based improved discriminant analysis and its application to face recognition. *Soft Computing - A Fusion of Foundations, Methodologies and Applications*, 14(2):103–111, 2009.
- [127] S. Zhou, R. Chellappa, and B. Moghaddam. Intra-personal kernel space for face recognition. In *Proc. of the 6th International Conference on Automatic Face and Gesture Recognition, FGR2004*, pages 235–240, Seoul, Korea, May 2004.