Corneal Topography: An Emerging Biometric System for Person Authentication

Nassima Kihal[1,2], Arnaud Polette[2,3], Salim Chitroub[1], Isabelle Brunette[4] and Jean Meunier[2]

[1]Signal and Image Processing Laboratory Electronics and Computer Science Faculty, USTHB, Algiers, Algeria.

[2] Department of Computer Science and Operations Research (DIRO), University of Montreal, Canada.

[3]Aix-Marseille University, CNRS, LSIS UMR 7296, France.

[4]Maisonneuve-Rosemont Hospital, Department of Ophthalmology, University of Montreal, Canada.

Corresponding author e-mail adress: meunier@iro.umontreal.ca

Abstract: Corneal topography is a non-invasive medical imaging technique to assess the shape of the cornea in ophthalmology. In this paper we demonstrate that in addition to its health care use, corneal topography could provide valuable biometric measurements for person authentication. To extract a feature vector from these images (topographies), we propose to fit the geometry of the corneal surface with Zernike polynomials, followed by a linear discriminant analysis (LDA) of the Zernike coefficients to select the most discriminating features. The results show that the proposed method reduced the typical d-dimensional Zernike feature vector (d=36) into a much lower r-dimensional feature vector (r=3), and improved the Equal Error Rate from 2.88% to 0.96%, with the added benefit of faster computation time.

1 Introduction

Biometrics refers to identity recognition of persons according to their physical or behavioral characteristics [CDJ05] [LBS11] [D03] [ZK11]. Many physical body parts and personal features have been used for biometric systems: fingers, hands, feet, faces, irises, retinas, ears, teeth, veins, voices, signatures, typing styles, gaits, odors, and DNA. Person recognition based on biometric features has attracted more attention in designing security system. In this paper we present a new biometric system based on corneal topography. Corneal topography is a non-invasive medical imaging technique to assess the shape of the cornea in ophthalmology. Figure 1 shows typical corneal topographies (images) of the anterior surface elevation from 2 different subjects. These images (a.k.a. elevation maps) show the measured height with respect to a reference (best-fit) sphere with pseudo-colors where warm colors depict points higher than the sphere and cool colors correspond to lower points. One can easily see that these maps are different from one individual to the other (uniqueness). The idea of using this physical characteristic for biometrics also comes from its stability during the life of the person (permanence) [BCI01]. However with age, the shape of the anterior and the posterior corneal surface might change slightly [DSV06], but this is a slow process that would only necessitate occasional update (e.g. every 5 years). Also corneal topographies are more practical to manipulate (measurability) compared with other data of biometric modalities that require pretreatment such as filtering, extraction of the region of interests etc. Actually, the corneal shape is certainly suitable for biometrics because it satisfies the following requirements: *Universality, Distinctiveness, Permanence and Collectability* [RNJ06].

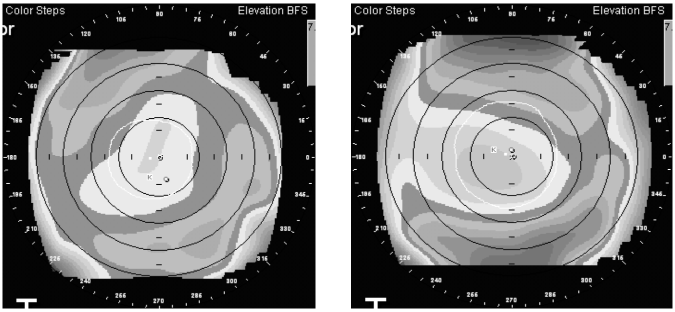


Figure 1: Typical topographies of 2 individuals (anterior surface elevation maps).

The proposed method describes the prototype of a biometric recognition system based on cornea where the corneal surface is modeled by using a Zernike polynomial decomposition [JGJ95][W92] limited to the first 36 coefficients (C_0^0 to C_7^7) and compared to evaluate their potential as biometric indicators. Our work extends the work of N.D. Lewis [L11] and shows that the corneal shape canreally be a good biometric alternative for individual recognition by selecting the most discriminating features of its geometry. For this reason we propose to apply Zernike polynomial decomposition, and then, LDA (*linear discriminant analysis*), [SML10] [NT10], to find better shape features. This new biometric system based on corneal topography is described as a block-diagram in Figure 2.

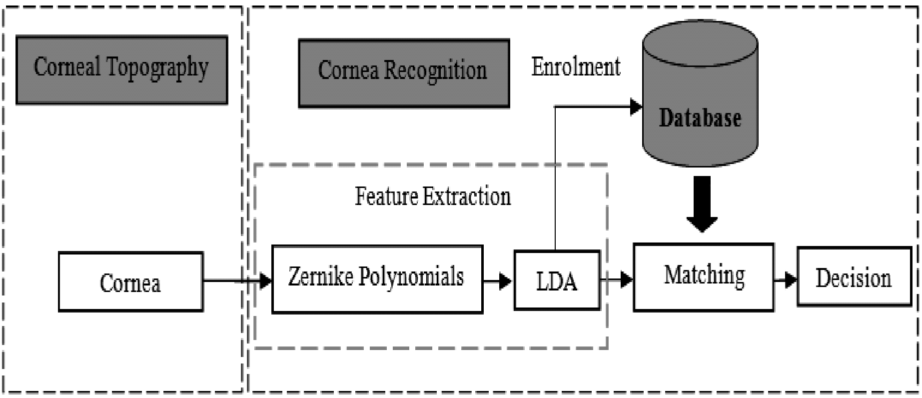


Figure 2: Block-diagram of the proposed cornea authentication system

2. **Description of the cornea database**

2.1 Cornea

The cornea is the outer transparent part of the eye, and covers nearly a fifth of the eyeball surface, with an average diameter of 11 mm. It is the main lens of the eye, responsible for two-thirds of the dioptric power (the remaining third is the eye lens), that transmits and focuses light into the eye with a refractive index of 1.377. The curvature radius of the anterior surface varies between 7 and 9 mm and is approximately 6.5 mm for the posterior surface. In this paper only the anterior surface geometry is considered, but the methodology could be applied to the posterior surface as well, or a combination of both.

2.2 Data and capture device

Corneal topography is a medical imaging method for the examination of the corneal shape. It is fast and easy (with in a few seconds) and could be adapted and simplified for biometric applications in the future. Currently a corneal topographer is relatively expensive ($20K and up) but this price tag could diminish with its wider use for biometrics. In this paper elevation maps are considered because they provide the full shape of the cornea while curvature maps are useful but limited to localized variations of shape. However curvature will be investigated in the future since they have had some success in matching 3D biometric data in the past [KK13] [KKZ11]. The database was done by using the Orbscan II topographer (Bausch & Lomb). Utilizing a scanning slit of light, it gives anterior (and posterior) surface elevation data with an error margin of 1 micron. The corneal shape was recorded as a uniformly spaced 101×101 grid (image) of raw elevations (Z), spaced by 0.1 mm along the X and Y axis. The cornea database is composed of 104 subjects, each has two (within-class) measures to assess repeatability leading to a total of 208 images (elevation topographies).

3. Feature extraction

In order to extract the features of the corneal shape, we present a methodology for analysing Orbscan II data. The technique involves decomposing the corneal height data in terms of the orthonormal set of Zernike polynomials [AHB94] [W92]. Then, a linear discriminant analysis (LDA) is used to select the features (combination of coefficients) which are the most effective to produce optimal cluster separability and consequently accurate recognition results.

3.1 Zernike polynomials

The Zernike polynomials area set of functions $\{Z_n^{\pm m}(\rho, \theta)\}$ that are orthonormal over the continuous unit circle. They have been used extensively for phase contrast microscopy, optical aberration theory, and interferometric testing to fit wave-front data. These functions are characterized by a polynomial variation in the radial direction ρ (for $0 \leq \rho \leq 1$) and a sinusoidal variation in the azimuthal direction θ. The polynomials are defined mathematically by

$$Z_n^{\mp m} = \begin{cases} \sqrt{2(n+1)}R_n^m(\rho)\cos m\theta for + m \\ \sqrt{2(n+1)}R_n^m(\rho)\sin m\theta \, for - m \\ \sqrt{(n+1)}R_n^m(\rho) \qquad\qquad for \;\; m = 0 \end{cases} \qquad (1)$$

Where

$$R_n^m(\rho) = \sum_{s=0}^{\frac{n-m}{2}} \frac{(-1)^s (n-s)!}{s!\left(\frac{n+m}{2} - s\right)!\left(\frac{n-m}{2} - s\right)!} \rho^{n-2s} \qquad (2)$$

n is the order of the polynomial in the radial direction ρ, and m is the frequency in the azimuthal direction θ. Since the Zernike polynomials are orthogonal over the continuous unit circle and the lower-order terms represent familiar corneal shapes. They appear to be an ideal set of functions for decomposing and analyzing corneal surface height. The reader is refered to [JGJ95] for more details on the use of Zernike polynomials for 3D surface shape encoding.

3.2 Preliminary tests

The corneal height data were decomposed into a linear combination of the Zernike functions, we took the first 36 Zernike coefficients as a feature vector for one cornea (d=36). For each individual we therefore have two feature vectors (two measures) of size 36. To show that the corneal topography can be a good biometric alternative, two sets of comparison were processed, 104 matching comparisons (with two different acquisitions from the same subject) and 5356 non-matching-comparisons (with two different acquisitions from two different subjects), by computing the absolute difference (AD) between all coefficients. Figure 3 shows the mean AD for each coefficient for the two tests. The more the difference between green and red bars for a particular

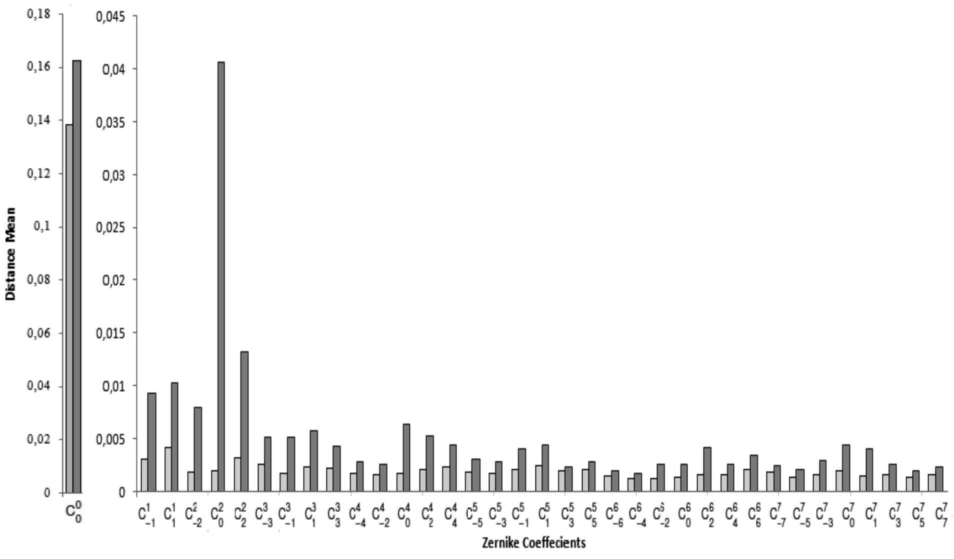


Figure 3: Mean difference for each Zernike coefficients within (green) and between (red) classes.

coefficient, the more this coefficient is selective for a biometric application. For this reason, we propose to select a combination of the most informative coefficients with LDA in the next section.

3.3 LDA for feature extraction

Linear discriminant analysis is a powerful method for pattern recognition yielding an effective representation that linearly transforms the original data space into a lower dimensional fature space where the data is as well separated as possible. We briefly describe it. Suppose that there are c classes (c=104) and each class has n training feature vector samples (n=2). The between-class and total scatter matrices of LDA are calculated using Eq (4) and Eq (5):

$$S_b = \sum_{i=1}^{c} \left(a_i^j - a_i\right)\left(a_i^j - a_i\right)^T \qquad (4)$$

$$S_t = \sum_{i=1}^{c} \sum_{j=1}^{n} \left(a_i^j - \bar{a}\right)\left(a_i^j - \bar{a}\right)^T \qquad (5)$$

where a_i^j denotes the jth training sample of the ith class, a_i stands for the mean of the ith class and $\bar{a}$ represents the mean of all the training samples. The eigen-equation of LDA is as follows:

$$S_b v = \lambda S_t v \qquad (6)$$

If all the eigenvalues of Eq (12) are ordered $\lambda_1 \geq \lambda_2 \geq \ldots$ and the corresponding eigenvectors are, $v_1, v_2 \ldots$, LDA exploits the eigenvectors corresponding to the first largest eigenvalues to transform the original d-dimensional vector of each sample (d=36) into a r dimensional vector. Let $x = \left[x_1 \ldots x_d\right]^T$ denote a sample, the LDA-based feature extraction result for x with regard to the first eigenvector is:

$$y_1 = x^T v_1 \qquad (7)$$

and so on for the other eigenvectors. Table1 shows an example of the Zernike coefficients and the results of LDA for one individual, where x=A_1 and A_2 represent the first and the second acquisition respectively. The λ_i represent eigenvalues in descending order. v_1 is the first eigenvector corresponding to the largest eigenvalue λ_1. From the eigenvalues in Table1 we see that the original information is mostly kept in the first eigenvectors. This can be interpreted as some Zernike coefficients (and their appropriate combinations) have a more powerful weight for discrimination of corneal topography. For instance, C_0^2 is discriminative (see Figure 3) because the red bar is much higher than the green bar (95% difference), this corresponds to a much higher (absolute) value in the vector v_1, conversely C_0^0 is not discriminative (9% difference) and the corresponding values in much smaller as expected. It is interesting to notice that Lewis [L11] removed this coefficient (with 3 others) in his analysis due to its high variance.

Table 1: Zernike coefficients and the results of LDA for one individual (x=A_1 and A_2)

	Zernike Coefficients		LDA Results	
	A_1	A_2	$\lambda_i \times 10^3$	v_1
C_0^0	2.1833	2.3125	1.8856	**-0.0005**
C_{-1}^1	-0.0106	-0.0136	0.1438	-0.0309
C_1^1	0.0023	0.0064	0.0718	-0.2686
C_{-2}^2	-0.0012	0.0007	0.0505	0.1110
C_0^2	-0.8383	-0.8389	0.0424	**-0.4379**
C_2^2	0.0017	-0.0027	0.0335	-0.0406
C_{-3}^3	-0.0024	-0.0004	0.0289	-0.0984
C_{-1}^3	-0.0021	-0.0044	0.0190	0.0911
C_1^3	0.0031	0.0034	0.0150	0.5013
C_3^3	-0.0045	-0.0015	0.0131	0.0290
…	…	…	…	…

4. Experimental result

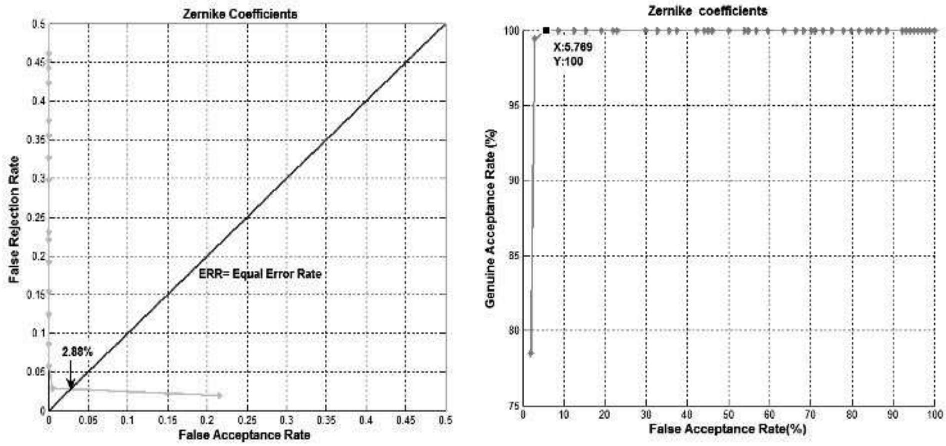
In order to analyze the performance of the proposed corneal biometric algorithm, we compared the feature vectors x and x' by computing this mean distance:

$$D\left(x,x'\right)=\frac{1}{N}\sum_{i=1}^{N}\left|x_i-x_i'\right| \qquad (8)$$

For the first experiment, we used the N=36 Zernike coefficients as cornea matcher 1, then a combination of Zernike coefficients with LDA as cornea matcher 2. To evaluate the performance of the system, the Equal Error Rate (EER) criterion was employed. The system threshold value was obtained using the EER criteria when False Acceptance Rate (FAR) equals False Reject Rate (FRR). This was determined from the Receiver Operating Characteristic (ROC) Curve. The lower the EER, the better is the system performance. Another performance measure is the Genuine Acceptance Rate: GAR=1-FRR. The lowest FAR that yields a GAR of 100% was selected from the ROC curve. Table 2 shows these results for matcher1 and matcher 2. In the latter case, different numbers (r) of features were tested, the best choice was r = 3 features and is used in the following. Fig. 4 and Fig. 5 show the ROC curves for the two matchers. With all Zernike coefficients the ERR was 2.88% and the GAR was improved to 100% with a FAR of 5.77% (See Figure 4 (a) and Figure 4 (b)). These results are similar to those of Lewis [L11] who reported EER of less than 4 percents with a similar approach and another dataset. With LDA and r =3 we achieved a 0.96% EER and a FAR of 0.96% (See Figure 5 (a) and Figure 5 (b)). This value 0.96% correponds to only one false acceptation out of the 104 identification attempts. This confirms the efficiency of cornea as biometrics and LDA for the selection of the most representative features from the combination of Zernike coefficients.

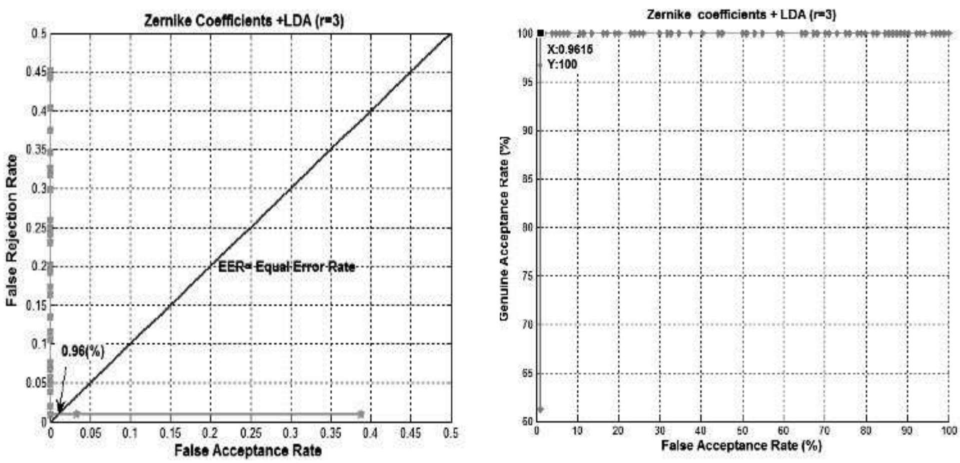
Table 2 Results for the two cornea matchers

Methodology		FAR(%)	EER(%)
Zernike	*r*	5.77	2.88
Zernike + LDA	1	20.2	7.82
	2	4.8	4.5
	3	0.96	0.96
	4	1.92	0.96
	5	0.96	0.96



(a) (b)

Figure: 4 ROC curves for all Zernike Coefficients ($d = 36$)



(a) (b)

Fig 5 ROC curves for Zernike Coefficients with LDA ($r = 3$)

5. Conclusion and future work

The objective of this work was to investigate *corneal topography* as an accurate biometric modality using shape discriminating features. Our proposed method by using LDA, convert a *d*-dimensional Zernike feature vector (d=36) into a smaller *r*-dimensional feature vector (r=3) allowing to keep the relevant 88% of information of the initial feature vector. The results obtained (EER less than 1%) confirm that corneal topography could be an effective biometric method. Moreover, we expect that the fusion of corneal features with other biometric modalities could achieve higher performance. In the future we plan to study : (1) other corneal shape descriptors such as curvature, (2) include the posterior surface in the biometric assessment, (3) realize a new biometric database with more within-class comparisons and (4) test other topographers such as the Pentacam (Oculus).

References

[CDJ05] Chen Y., Dass S. C., and Jain. A. K. "Fingerprint Quality Indices for Predicting Authentication Performance". In Fifth AVBPA, pages 160–170, Rye Brook, July 2005.

[LBS11] R. P. Lemes, O. R. P. Bellon, L. Silva, and Anil K. Jain, "Biometric Recognition of Newborns: Identification using Palmprints", IJCB, Washington, DC, Oct. 11-13, 2011.

[D03] J. Daugman, "The importance of being random: statistical principles of iris recognition", Patterns Recognition,36 (2003), 279-291.

[ZK11] Y. Zhou and A. Kumar, "Human identification using palm-vein images", IEEE Trans. Information Forensics & Security, vol. 6, pp. 1159-1274, Dec. 2011.

[DSV06] M. Dubbelman, V.A.D.P. Sicam, G.L. Van der Heijde."The shape of the anterior and posterior surface of the aging human cornea", Vision Research 46 (2006) 993–1001.

[BCI01] T. Buehren, M. J. Collins, D. R. Iskander, B. Davis, and B. Lingelbach,"The stability of corneal topography in the post-blink interval", Cornea, vol. 20, no. 8, 2001.

[RNJ06] A. Ross, K. Nandakumar and A.K. Jain, "Handbook of Multibiometrics", Springer Verlag, page19,2006.

[JGJ95] John E. Greivenkamp and Joseph M. Miller, "Representation of videokeratoscopic height data with Zernike polynomials", J. Opt. Soc. Am. A/Vol. 12, No. 10/October 1995.

[W92] R. H. Webb, "Zernike polynomial description of ophthalmic surfaces", in *Ophthalmic and Visual Optics,* Vol. 3 of 1992 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1992), pp. 38–41.

[L11] N. D. Lewis, "Corneal topography measurements for biometric applications", Ph.D. dissertation, University of Arizona, 2011.

[SML10] F. Song, D. Mei, and H. Li, "Feature selection based on linear discriminant analysis", in Proc. 2010 Int. Conf. Intelligent System Design and Engineering Application, Changsha, China, Nov./Dec. 2010, vol. 1, pp. 746-749.

[NT10] M. H. Nguyen, F. d. Torre. "Optimal feature selection for support vector machines", Pattern Recognition, 43 (3): March 2010.

[G11] D. Gatinel, "Topographie cornéenne", 2011, Elsevier Masson SAS. ISBN:978-2-294-71134-3

[KK13] A. Kumar and C. Kwong, "Towards contactless, low-cost and accurate 3D fingerprint identification", Proc. CVPR 2013, pp. 3438-3443 June 2013.

[KKZ11] V. Kanhangad, A. Kumar and D. Zhang, "A unified frame work for contactless hand verification", IEEE Trans. Info. Security Forensics, vol. 20, pp. 1415-1424, May 2011.