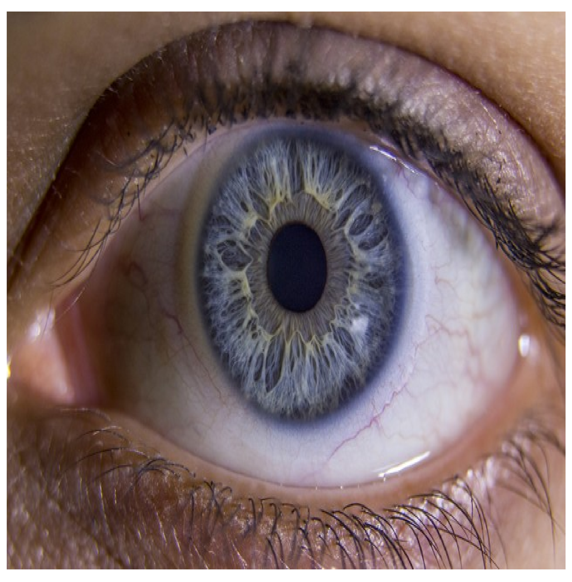

Iris Recognition using Consistent Corner Optical Flow

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Iris Segmentation and Normalization

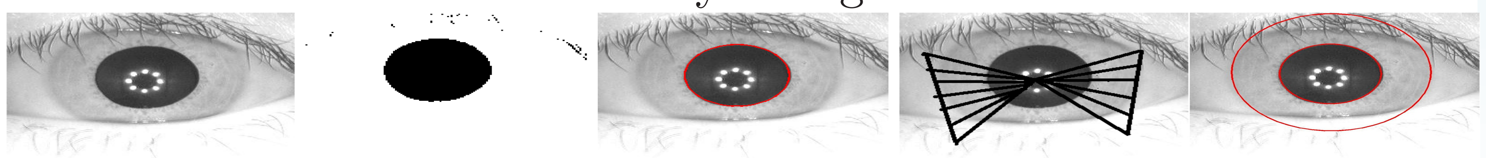
[A] Inner boundary localization: Edges are obtained over *thresholded* image using Sobel filters. Hough transform is improved by using the orientation of each pixel to reduce the search space from $3D$ *i.e* 3-tuple $< x, y, r >$ to $1D$ of the radius only. It makes use of the key observation that "*if an edge point lies on a circle, then the center of circle should lie on the normal to the edge direction (orientation) at that point*". Thus, for an edge point (x, y) in an image and for a radius r, the center coordinates (c_1^x, c_1^y) and (c_2^x, c_2^y), for two circles (one to its left and other to right half) can be computed as:

$$(c_1^x, c_1^y) = (x + r \cdot \sin\left(\theta(x, y) - \frac{\pi}{2}\right),\ \ y - r \cdot \cos\left(\theta(x, y) - \frac{\pi}{2}\right)) \quad (1)$$

$$(c_2^x, c_2^y) = (x - r \cdot \sin\left(\theta(x, y) - \frac{\pi}{2}\right),\ \ y + r \cdot \cos\left(\theta(x, y) - \frac{\pi}{2}\right)) \quad (2)$$

[B] Outer boundary localization: Circular integro-differential operator is applied over two non-occluded sectors which are selected empirically and inner boundary of iris is used for guidance. A simple heuristic that "*iris inner and outer boundaries have centers not necessarily concentric, but within a certain small window of each other*" is used for efficiency. Each of these candidates (c^x, c^y) and radius r defines a circle for the outer iris boundary. To prevent noise due to eyelids and lashes the circular summation is done over two empirically selected non-occluded sectors defined by $\alpha_{range}=(-\pi/4, \pi/6)^c \cup (5\pi/6, 5\pi/4)^c$.

Iris Normalization After iris is segmented from the image, it is transformed to polar coordinates in order to overcome the dimensional inconsistencies between eye images.

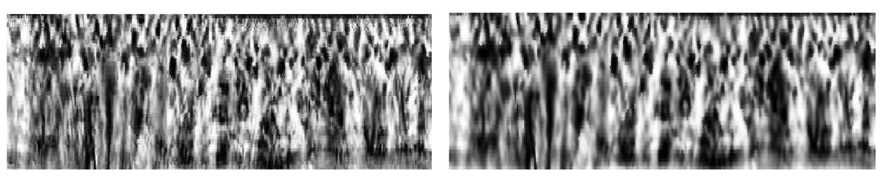


Original | Thresholded | Segmented Pupil | Sectors | Segmented Iris

Iris Enhancement

Normalized iris images are divided into blocks of size 8×8 and the mean of these blocks are considered as the coarse illumination of that block. This mean is expanded to the original size. Non-uniform illumination is compensated by subtracting estimated illumination from the original image. Then the contrast is enhanced using Contrast Limited Adaptive Histogram Equalization (CLAHE) and wiener filter is applied to reduce noise.

Normalized Iris | Estimated Illumination | Uniform Illumination

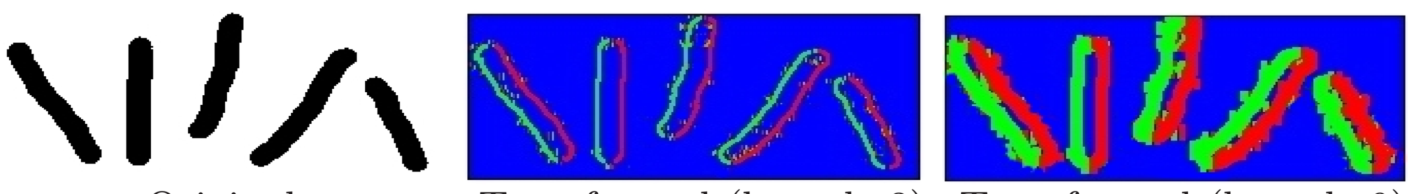


CLAHE Enhancement | Weiner Filtering

Iris Transformation

Noisy iris images are transformed into *vcode* and *hcode* respectively so as to obtain robust features. The gradient of any edge pixel will be positive if it lies on an edge created due to light to dark shade (*i.e. high to low gray value*) transition otherwise it have negative gradient value. The proposed transformation uses the sign of the gradient to calculate a 8-bit code for each pixel using x and y-direction derivatives of its 8 neighboring pixels to obtain *vcode* and *hcode* respectively.

$LGBP$ Transformation (Red: -ve gradient;Green: +ve gradient;Blue: zero gradient

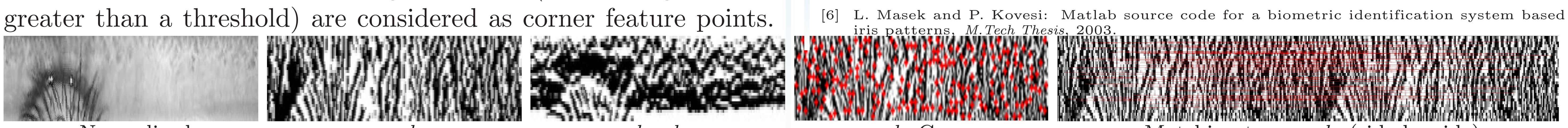


Original | Transformed (kernal=3) | Transformed (kernal=9)

Let $P_{i,j}$ be the $(i, j)^{th}$ pixel of an iris image P and $Neigh[l], l = 1, 2, ...8$ are the gradients of 8 neighboring pixels centered at pixel $P_{i,j}$ obtained by applying *scharr* kernel, then the k^{th} bit of the 8-bit code (termed as *lgbp_code*) is given by

$$lgbp\_code[k] = \begin{cases} 1 & \textbf{if } Neigh[k] > 0 \\ 0 & \textbf{otherwise} \end{cases} \quad (3)$$

Feature Extraction Using KLT Corner Detector [2]: Corners features from *vcode* and *hcode* are extracted by doing eigen analysis of hessian matrix of size 2×2, for each pixel and two possible eigen values λ_1 and λ_2 such that $\lambda_1 \geq \lambda_2$ are obtained. All pixels having $\lambda_2 \geq T$ (smaller eigen value greater than a threshold) are considered as corner feature points.



Normalized | *vcode* | *hcode* | *vcode* Corners | Matching two *vcode* (side by side)

Iris Matching using KL Tracking

The KL tracking [3] that is used to estimate sparse optical flow has been used for iris matching. It is assumed that the tracking performance of KL algorithm is good between features of same subject (genuine matching) while degrades substantially for others (imposter matching).

Consistent Optical Flow: It can be noted that true matches have the optical flow which can be aligned with the actual affine transformation between the two images. Hence the estimated optical flow direction is quantized into eight directions and the most consistent direction is selected as the one which has most number of successfully tracked features. Any corner matching other than the most consistent direction is considered as false matching corner. A dissimilarity measure, termed as Corners having Inconsistent Optical Flow ($CIOF$), has been proposed that estimates the tracking performance by evaluating some geometric and statistical quantities defined below

[a] Proximity Constraints: Euclidean distance between any corner and its estimated tracked location should be less than or equal to an empirically selected threshold TH_d. It depends upon the amount of translation and rotation in the sample images.

[b] Patch Dissimilarity: Tracking error defined as pixel-wise sum of absolute difference between a local patch centered at current corner and that of its estimated tracked location patch should be less than or equal to an empirically selected threshold TH_e. It ensures that the matching corners must have similar neighboring patch around it.

Algorithm 1 $CIOF(Iris_a, Iris_b)$

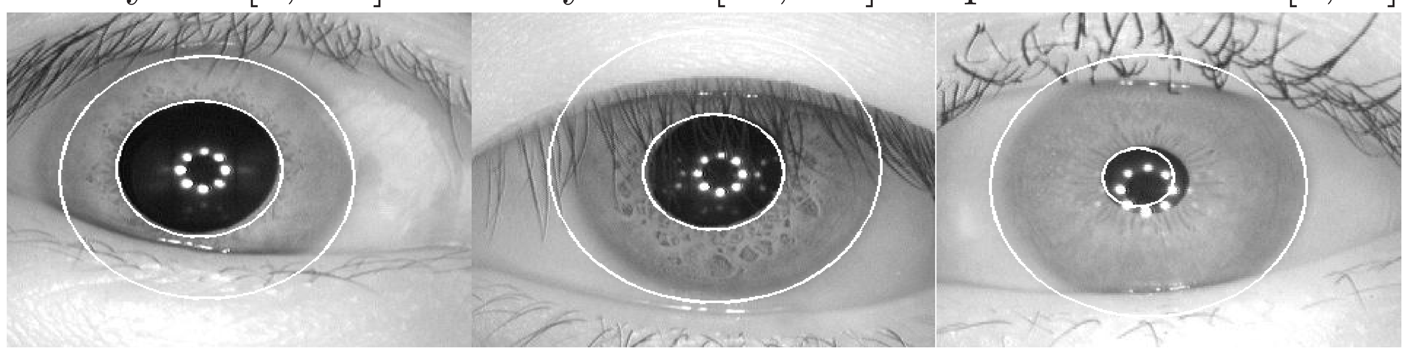
Require: The two *vcode* I_A^v,I_B^v and two *hcode* I_A^h,I_B^h of enhanced unwrapped Iris images $Iris_a, Iris_b$ respectively.
N_a^v, N_b^v,N_a^h and N_b^h are the number of corners in I_A^v, I_B^v, I_A^h, and I_B^h respectively.

Ensure: Return the symmetric function $CIOF(Iris_a, Iris_b)$.

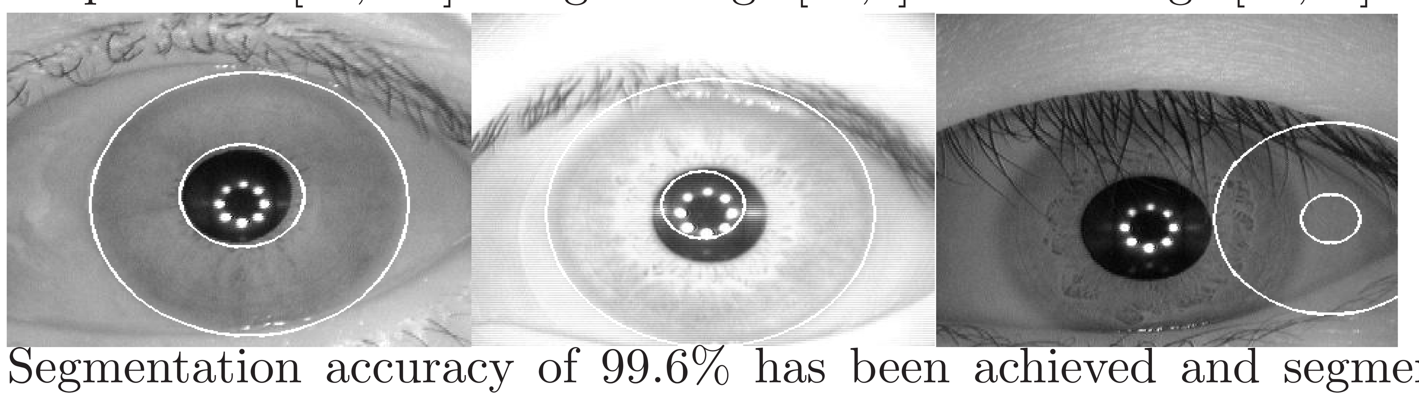
1: Track all the corners of *vcode* I_A^v in *vcode* I_B^v and that of *hcode* I_A^h in *hcode* I_B^h.
2: Calculate the number of successfully tracked corners in *vcode* tracking (*i.e.* stc_{AB}^v) and *hcode* tracking (*i.e.* stc_{AB}^h) that have their tracked position within TH_d and their local patch dissimilarity under TH_e.
3: Similarly calculate successfully tracked corners of *vcode* I_B^v in *vcode* I_A^v (*i.e.* stc_{BA}^v) as well as *hcode* I_B^h in *hcode* I_A^h (*i.e.* stc_{BA}^h).
4: Quantize optical flow direction for each successfully tracked corners into only eight directions (*i.e.* at $\frac{\pi}{8}$ interval) and obtain 4 histograms $H_{AB}^v, H_{AB}^h, H_{BA}^v and H_{BA}^h$ using $stc_{AB}^v, stc_{AB}^h, stc_{BA}^v, stc_{BA}^h$ respectively.
5: For each histogram, out of 8 bins the bin (*i.e.* direction) having the maximum corners will be considered as the consistent optical flow direction. The maximum value obtained from each histogram is termed as corners having consistent optical flow represented as $cof_{AB}^v, cof_{AB}^h, cof_{BA}^v$ and cof_{BA}^h
6: $ciof_{AB}^v = 1 - \frac{cof_{AB}^v}{N_a^v}$; $ciof_{BA}^v = 1 - \frac{cof_{BA}^v}{N_b^v}$;[Cor. with Inconsis. Opti. Flow (*vcode*)]
7: $ciof_{AB}^h = 1 - \frac{cof_{AB}^h}{N_a^h}$; $ciof_{BA}^h = 1 - \frac{cof_{BA}^h}{N_b^h}$;[Cor. with Inconsis. Opti. Flow (*hcode*)]
8: **return** $CIOF(Iris_a, Iris_b) = \frac{ciof_{AB}^v + ciof_{AB}^h + ciof_{BA}^v + ciof_{BA}^h}{4}$;[SUM RULE]

Iris Segmentation and Error Analysis

Eyelid [4,300] | Eyelash [15,288] | Spec.Reflection [5,68]



Pupil Noise [71,160] | Bright image [11,1] | Dark image [39,53]



Segmentation accuracy of 99.6% has been achieved and segmentation errors are classified into six classes as shown above also parametrized segmentation analysis is also carried out to infer the influence of parameters towards errors.

Iris Recognition Performance Analysis

Systems	Interval			Lamp		
	DI	CRR%	EER%	DI	CRR%	EER%
Daugman [1]	1.961	99.46	1.881	1.2420	98.90	5.59
Li Ma [5]	-	95.54	2.07	-	-	-
Masek [6]	1.99	99.58	1.09	-	-	-
K. Roy [4]	-	97.21	0.71	-	-	-
Proposed	**2.35**	**99.75**	**0.108**	**2.22**	**99.87**	**1.29**

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Experimental results