Biometrics (CSE 40537/60537)

Lecture 3: Iris recognition

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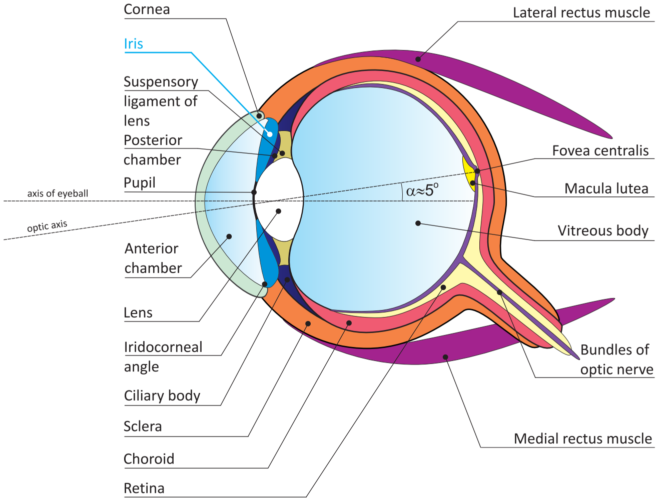
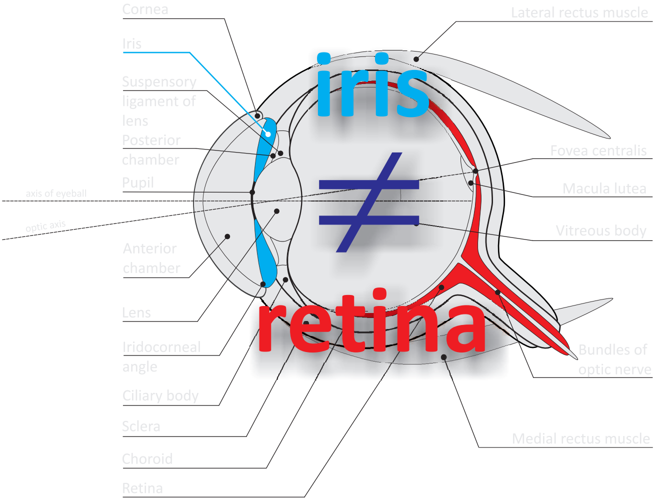
Lecture 3: Iris recognition

- Iris genesis and its structure
- Brief history of iris recognition
- Iris image capture and representation
- Iris image segmentation
- Building the iris code
- Iris code matching

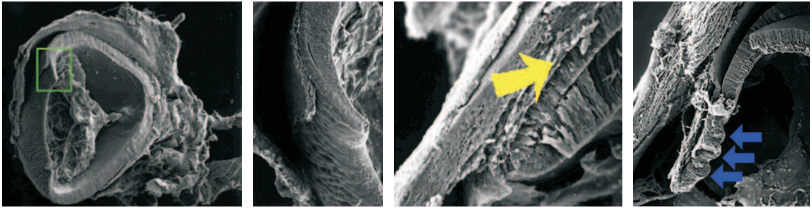
Iris as a part of the sight organ



Iris recognition vs. retina reocognition



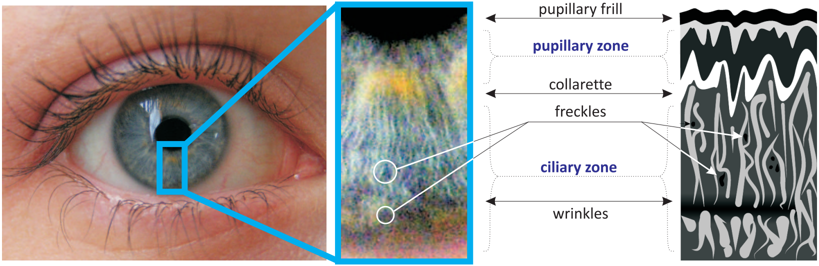
Genesis

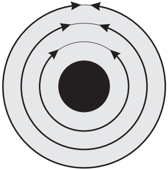


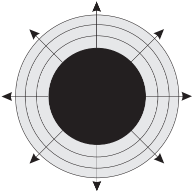
gestation week 8 gestation week 15

1. Turn of the second and third month of the gestation: iris starts to develop
2. The eight month of gestation: iris muscle is fully developed
3. Hypothesis 1: trabeculae of iris muscle stable until the death (contradictory to recent works on iris template aging)
4. Hypothesis 2: highly individual (random?) ‘ciliary processes’, very low genetic penetrance

Iris structure

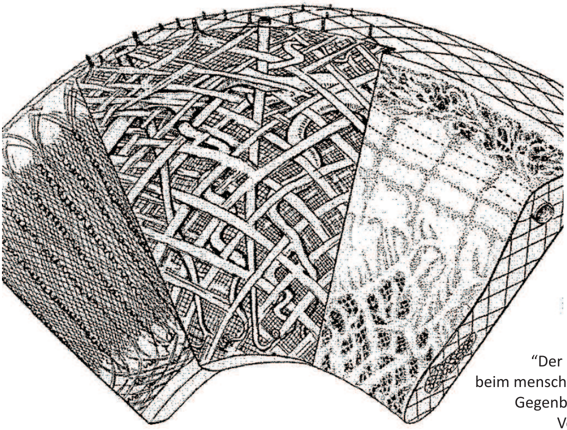






Iris structure

Complicated 3D meshwork of muscle beams, blood vessels and nerves ...



Source: Hans Rohen,
“Der bau der regenbogenhaut
beim menschen und einigen saugern”,
Gegenbaur Morphology Journal,
Vol. 91, pp. 140-181, 1951

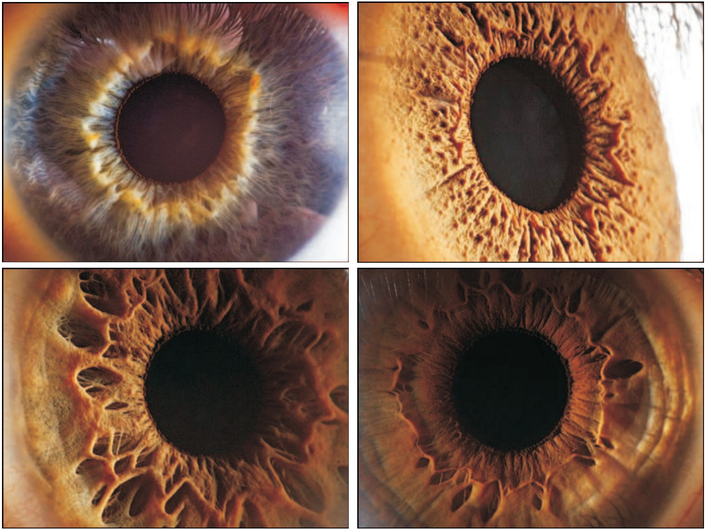
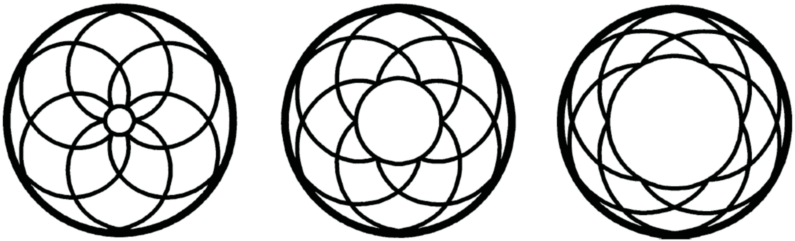


photo: Suren Manvelyan

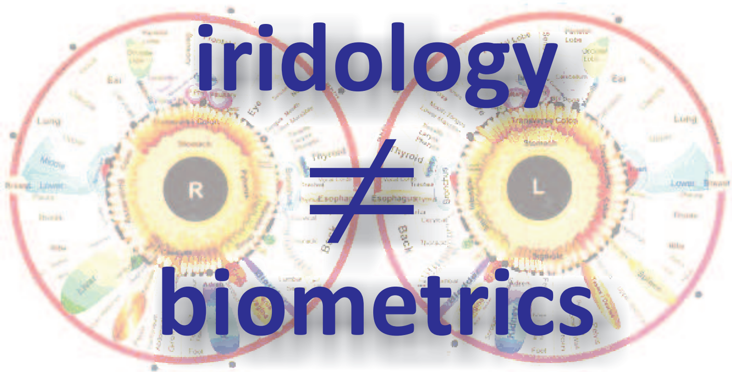
Iris structure

... which constricts and dilates in a nonlinear fashion



Source: H.J. Wyatt, “A minimum-wear-and-tear meshwork for the iris”, Vision Research, Vol. 40, pp. 2167--2176, 2000

Iris recognition vs. iridology



iridology maps taken from: http://www.anitawilson.com.au/Iridology.php

Iris recognition milestones

1. 1883: Alphonse Bertillon
   - eye color (not used today in iris recognition); extension of the *Bertillonage* system
2. 1936: Frank Burch
   - presentation of the iris recognition idea at the opening of the American Academy of Ophthalmology Annual Meeting
3. 1949: James Doggarts
   - one of a few reproductions of Burch's idea in ophthalmology textbooks
4. 1987: Aran Safir, Leonard Flom
   - US patent, somewhat based on Burch's idea

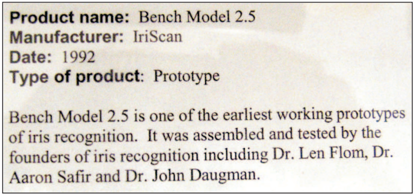
Iris recognition milestones

5. 1992: John Daugman
   - first algorithm of iris image coding based on two-dimensional Gabor filtering
   - first prototype of the iris recognition system (Bench Model 2.5)
6. 1994: John Daugman
   - iris code generation methodology becomes patented
   - the so called ‘Daugman’s method’ presents absolutely brilliant accuracy, and it becomes *de facto* standard in iris recognition, inspiring iris recognition scientists in their research
7. 2005: Safir’s and Flom’s patent expires, new solutions start to appear on the market

First applications of Daugman's method

Demonstration room in Iridian Technologies, Moorestown, Philadelphia, presenting an impressive history of Daugman's method applications. Picture taken by Adam Czajka in 2005 by courtesy of Iridian Technologies.

First applications of Daugman's method



Product name: Bench Model 2.5
Manufacturer: IriScan
Date: 1992
Type of product: Prototype

Bench Model 2.5 is one of the earliest working prototypes of iris recognition. It was assembled and tested by the founders of iris recognition including Dr. Len Flom, Dr. Aaron Safir and Dr. John Daugman.

Picture taken by Adam Czajka
by courtesy of Iridian Technologies
Moorestown, Philadelphia, 2005

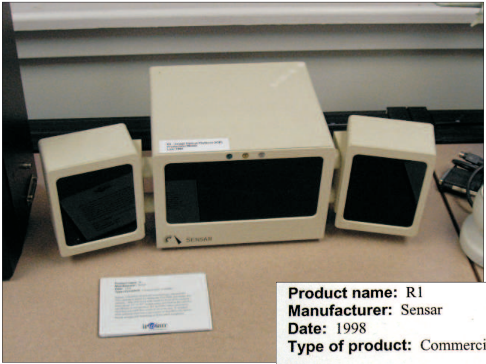
First applications of Daugman's method

Product name: IriScan 2100
Manufacturer: IriScan
Date: 1996
Type of product: Commercially available

The IriScan 2100 was the first commercially available iris recognition product. It was designed primarily for physical access applications and was installed in several prisons in the United States to authenticate identity during prisoner booking and release.

Picture taken by Adam Czajka
by courtesy of Iridian Technologies
Moorestown, Philadelphia, 2005

First applications of Daugman's method

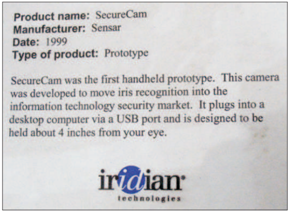


Picture taken by Adam Czajka
by courtesy of Iridian Technologies
Moorestown, Philadelphia, 2005

Product name: R1
Manufacturer: Sensar
Date: 1998
Type of product: Commercially available

Sensar, a licensee of IriScan's technology, released R1. This camera is noted for being the first fully automatic iris camera. The user need only stand in front of the camera from about 15" to 30" inches away and look at the unit for enrollment or recognition. R1 includes three cameras to first find you and then zoom in on your eye. It worked with software that was a pre-cursor to KnoWho for server based storage and matching of IrisCode® templates.

First applications of Daugman's method



Product name: SecureCam
Manufacturer: Sensar
Date: 1999
Type of product: Prototype

SecureCam was the first handheld prototype. This camera was developed to move iris recognition into the information technology security market. It plugs into a desktop computer via a USB port and is designed to be held about 4 inches from your eye.

iridian technologies

Picture taken by Adam Czajka
by courtesy of Iridian Technologies
Moorestown, Philadelphia, 2005

A life revealed: the Afghan girl

Spectacular application of Daugman's method

A life revealed: the Afghan girl

Spectacular application of Daugman's method

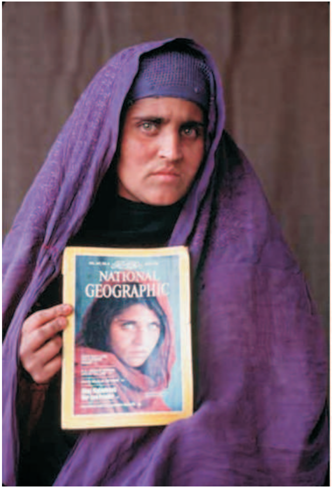
'Afghan girl'

National Geographic Magazine Cover, 1985

Photo of young Sharbat Gula by **Steve McCurry,** captured in 1984 in the refugee camp in Pakistan during the time of Soviet occupation of Afghanistan

A life revealed: the Afghan girl

Spectacular application of Daugman's method

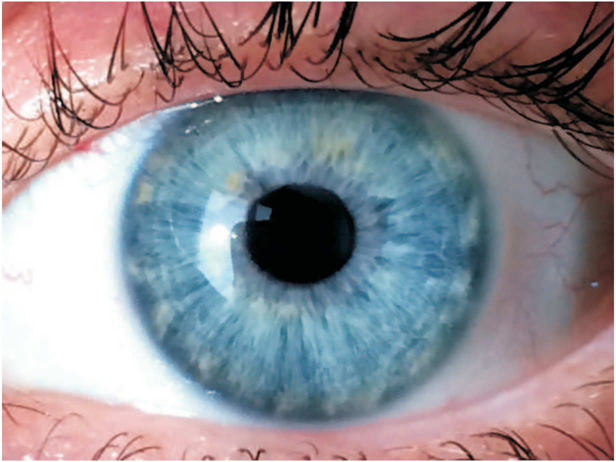


Prof. John Daugman applies his method for verification of the girl's identity

Sharbat Gula
Afghanistan, 2002

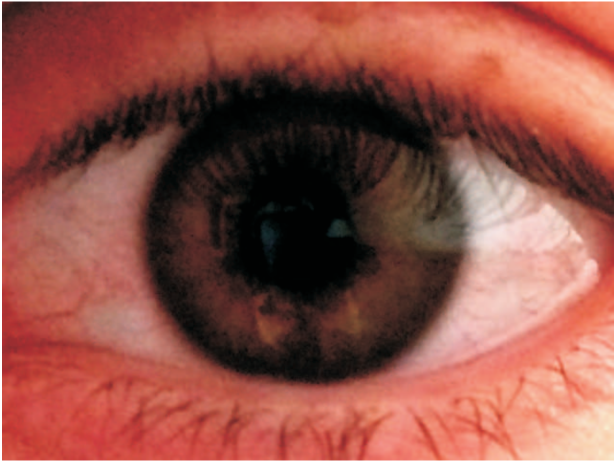
Use of visible light

Possible, sometimes necessary ...

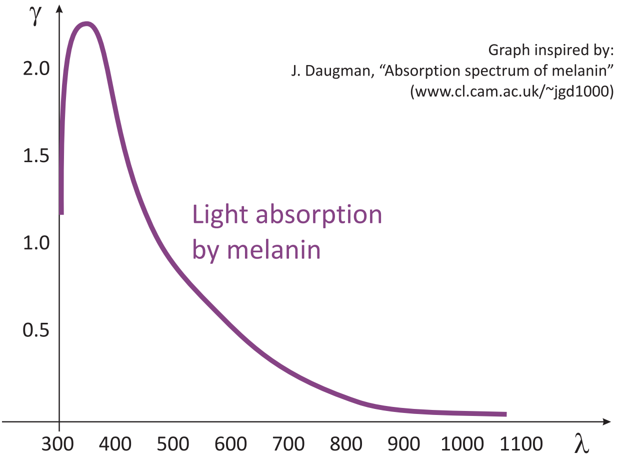


Use of visible light

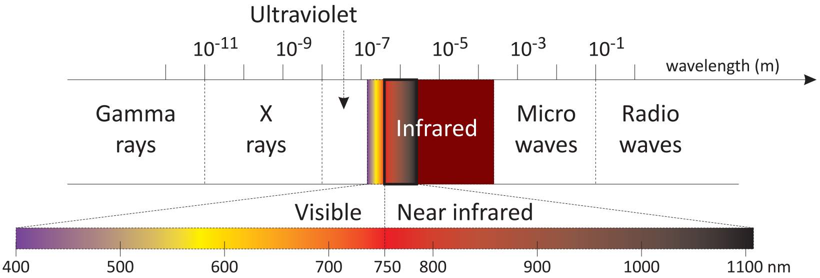
... but may be problematic for dark eyes



Melanin: important protective substance

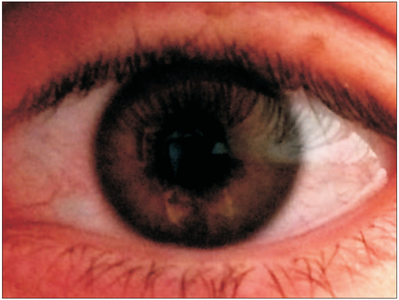


Is the visible light the only possibility?

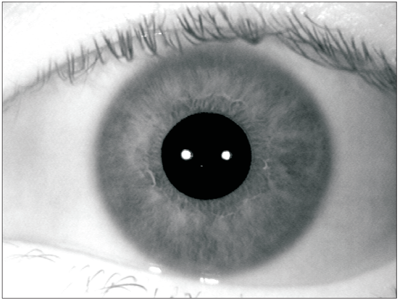


Visible vs. near infrared (NIR)

Example

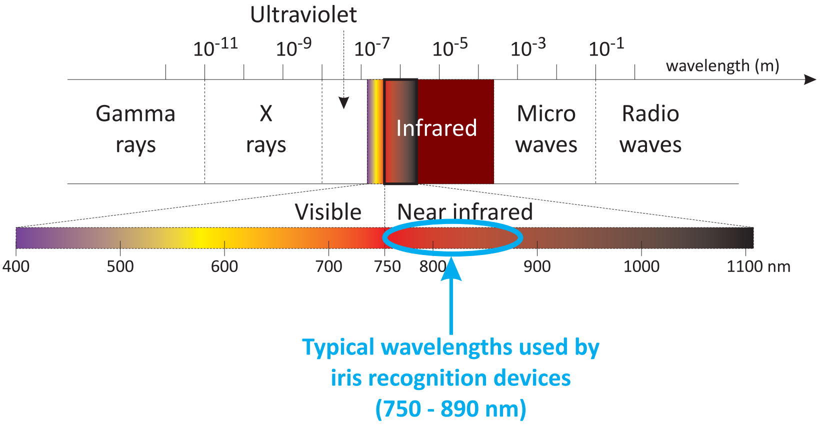


Visible light



Near infrared light (peak in 860 nm)

Is the visible light the only possibility?



Standard requirements

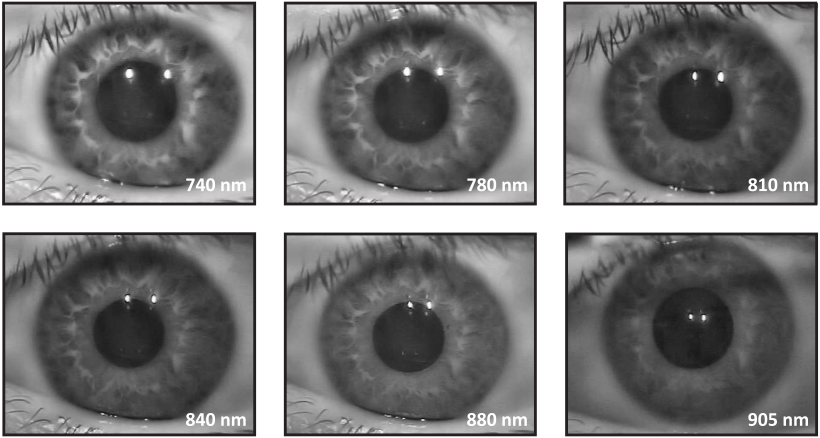
1. Eye safety
   - standards: IEC 60825-1:1993 (+ addendum A1:1997 and A2:2001), ANSI RP-27.1-96
   - Maximum Permissible Exposure (MPE) not greater than $0.1 * MPE_{\max}$, where $MPE_{\max}$ is the exposure resulting in severe eye damage in 50% of population
2. Image quality
   - standards: ISO/IEC 19794-6 and ISO/IEC 29794-6
   - wavelength (700-900 nm), resolution (at least 120 lines per iris diameter), usable iris area (at least 70%), gray levels (8 bit dynamic range, minimum 6 bits of useful information), pupil location (centered within the image), gaze (eye fully on-axis with the camera lens), no patterned contact lens, etc.
   - typical iris image resolution: 640×480 pixels

Typical problems

1. Iris: a small, three dimensional and fidgety object
    - conflict of interests: CCD sensitivity, exposure times and aperture vs. optical depth-of-field
2. User cooperation and habituation
3. Deformations and obstructions
    - easy: eyelids, specular reflections
    - hard: eyelashes, hairs, patterned contact lenses
    - iris constriction and dilation, *hippus*, pupil dynamics: surface warping, nonlinear deformations
    - head movement (important in high zoom)
    - off-axis gaze
4. Interoperability of capture devices
    - different wavelengths of illuminating light
    - different number and location of illuminants

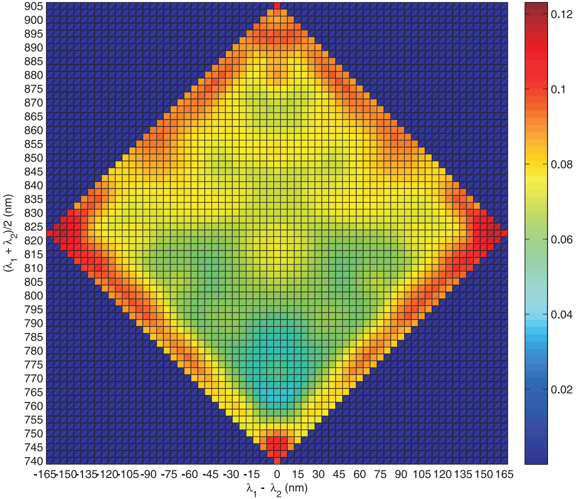
Interoperability of capture devices

Different wavelengths of illuminating light



Interoperability of capture devices

Different wavelengths of illuminating light



Iris imaging with user cooperation

Example devices

CrossMatch

IrisGuard: IG-H100

IG-AD100

Panasonic: ET-300

ET-100

(source: www.panasonic.com)

OKI IrisPass-M

(source: www.oki.com)

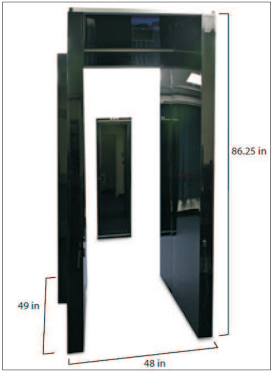
Iris imaging with (almost) no user cooperation

1. Use of multiple-resolution cameras (Sarnoff Corp., USA)
   - wide-angle camera for face detection
   - narrow-angle camera(s) for iris capture
2. Use of deformable mirrors (AOptix, USA)
   - idea used before in astronomical telescopes compensating the deformations introduced by the atmosphere
   - Zernike polynomials used to describe the deformations of the mirrors (in optics used for describing aberration of the lens)
   - fast (a fraction of a second) and at-the-distance capture (typically 1.5m – 2.5m)

Iris imaging with (almost) no user cooperation

AOptix Insight™ SD, 2008
(Biometrics 2008, London, UK)

AOptix Insight™ VM, 2010
(source: *Insight VM Datasheet*)



Iris-On-The-Move™ Gate
(source: *IOM Portal Datasheet*)

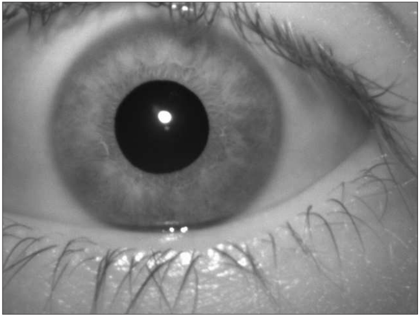
Iris imaging with (almost) no user cooperation

Example Iris-On-The-Move™ measurement

Source of raw image: MBGC 2008 dataset
Iris localization: Warsaw University of Technology

Current trend: miniaturization

Iris cameras by IriTech, USA



Example iris image compliant to ISO/IEC 19794-6

Current trend: miniaturization

Android-based ‘Fidelys’ smartwatch: working prototype

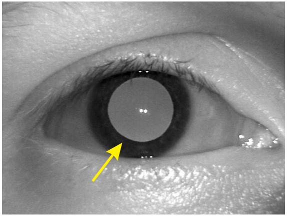
source: linuxgizmos.com/worlds-first-iris-recognition-smartwatch-runs-android, 2014

Current trend: miniaturization

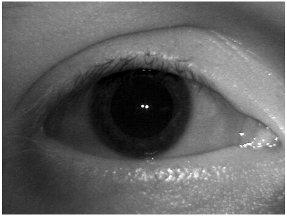
Android-based ‘Fidelys’ smartwatch: final product

source: linuxgizmos.com/worlds-first-iris-recognition-smartwatch-runs-android, 2014

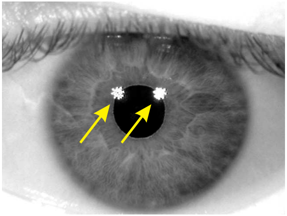
Position of the illuminants: not a simple choice



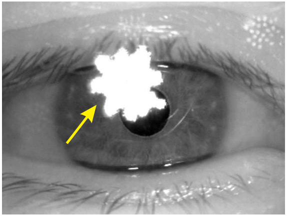
illuminants to close to the lens axis
(reflections from the retina, "red eye")



correct location of the illuminants
(reflections inside the pupil)



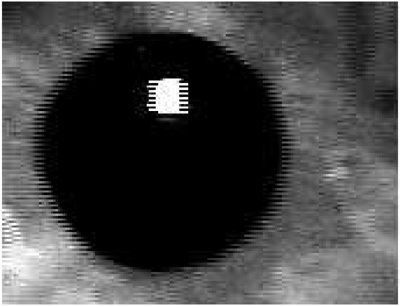
illuminants to far from the lens axis
(reflections obstruct the iris)

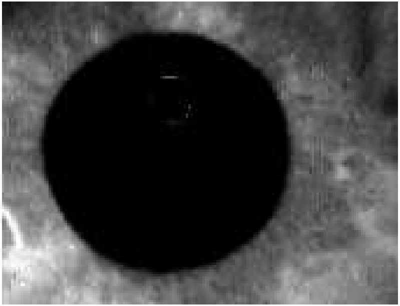


lens axis coincides with the reflection axis
(reflections from glasses obstruct the iris)

Iris image pre-processing

1. Enhancing image structure: removing sensor noise, compensating interlaced imaging, specular reflections removal
2. Enhancing image intensity: contrast enhancement, histogram equalization, linear trends removal





Iris image representation

ISO/IEC 19794-6

1. Raw image (ISO: UNCROPPED or KIND 1)
2. Image with standard resolution of 640×480 pixels (ISO: VGA or KIND 2)

Iris image representation

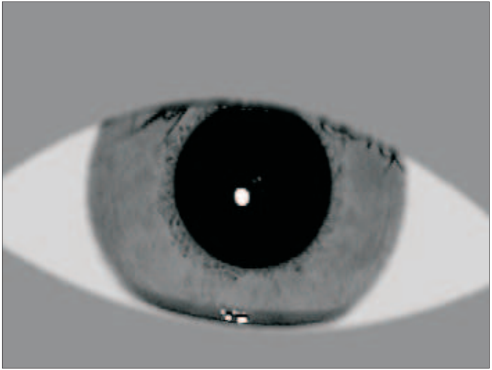
ISO/IEC 19794-6

3. Cropped image (ISO: CROPPED or KIND 3)

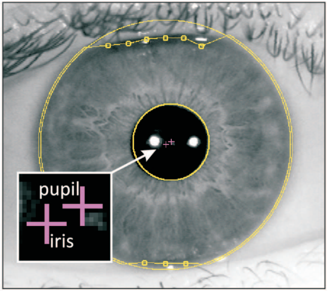
Iris image representation

ISO/IEC 19794-6

4. Cropped image with eyelids and sclera masked (ISO: CROPPED_AND_MASKED or KIND 7)



1. Typical assumptions
   - Iris and pupil approximated as circles: not necessarily true (especially for the pupil) but sufficient in most applications
   - Iris and pupil are not coaxial: pupil centers are shifted to the nasal corner of the eye
   - Eyelids approximated by parabolic curves



2. Elements to be localized
   - Outer (limbic) boundary (between the iris and the sclera)
   - Inner (pupillary) boundary (between the iris and the pupil)
   - Occlusions: eyelids approximation, removal of specular reflections and eyelashes

Iris and pupil localization

Integro-differential operator

$$\max_{r,x_0,y_0} \left| g_\sigma(r) * \frac{\delta}{\delta r} \oint_{r,x_0,y_0} \frac{I(x,y)}{2\pi r} ds \right|$$

where:

I – raw iris image

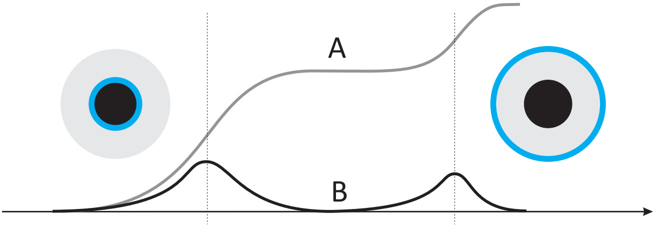
r, x_0, y_0 – parameters of the s curve (circle)

$g_\sigma(r) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(r-r_0)^2}{2\sigma^2}}$ – smoothing function

Iris and pupil localization

Integro-differential operator

$$\max_{r,x_0,y_0} \left| \underbrace{g_\sigma(r) * \frac{\delta}{\delta r} \underbrace{\oint_{r,x_0,y_0} \frac{I(x,y)}{2\pi r} ds}_{\text{A}}}_{\text{B}} \right|$$



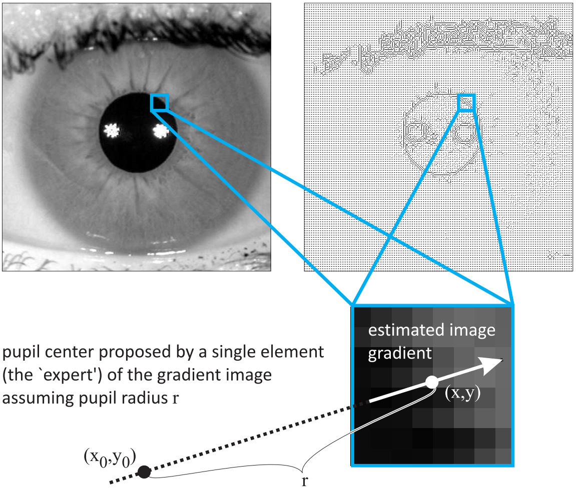
Iris and pupil localization

Integro-differential operator: implementations

1. Solving a classical minimization problem
2. Use of Hough transform
   - use of iris gradient image
   - accumulator matrix indexed by the curve parameters (for a circle: (r, x_0, y_0))
   - gradient image elements are the 'experts' proposing optimal parameters
   - may be applied for other simple curves (e.g. ellipses)

Iris and pupil localization

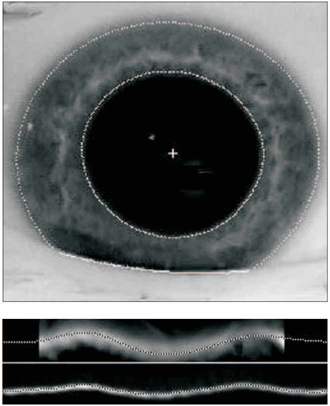
Application of the Hough transform



Iris and pupil localization

Fourier expansion

1. Edge detection in Cartesian or polar coordinates
2. Approximation of the edge functions by Fourier expansion in polar coordinates



source: J. Daugman, *New Methods in Iris Recognition*, IEEE Tran. on Systems, Man, and Cybernetics Part B: Cybernetics, Vol. 37, No. 5, October 2007

Iris and pupil localization

Fourier expansion

(+) Mathematically elegant ...

- DC component represents the best circular approximation
- each additional Fourier coefficient increases the accuracy of the approximation
- straightforward mapping between Cartesian and polar coordinate systems

Iris and pupil localization

Fourier expansion

(+) Mathematically elegant ...

- DC component represents the best circular approximation
- each additional Fourier coefficient increases the accuracy of the approximation
- straightforward mapping between Cartesian and polar coordinate systems

(−) ... but may bring some implementation difficulties

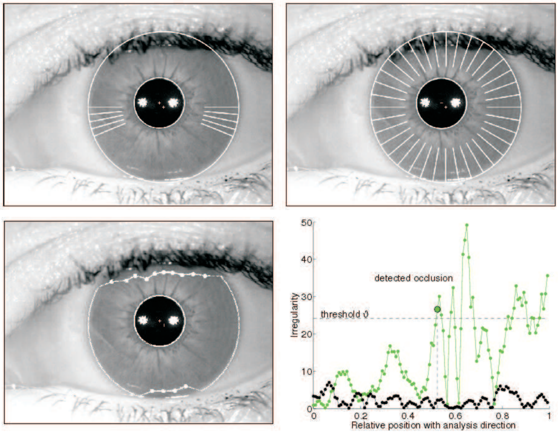
- incomplete boundaries weaken the confidence of the approximation
- edge detection requires filter kernels adequate to the edge ‘thickness’ (i.e. sensitive to narrow band of image spatial frequencies)
- number of Fourier coefficients dependent on the dataset used in estimation (ISO suggests 17 for the pupil and 5 for the iris)

Localization of occlusions

1. Supplementary to the pupil and iris localization
    - parametric methods used for pupil and iris localization, e.g. integro-differential operators (for eliptic and parabolic curves)
    - non-parametric methods implementing heuristic ideas based on localization of inconsistencies within the iris image
2. Performing all iris segmentation steps at once
    - Fourier expansion
    - active contours: curve evolution described by differential equations, possible to be adjusted to arbitrary shapes, time-consuming
3. Occlusions represented as the occlusion mask (pixels excluded from iris features extraction are masked)

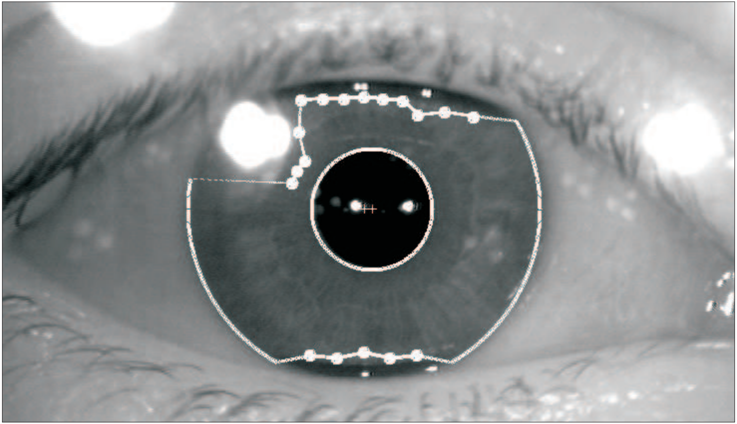
Localization of occlusions

Example: localization of inconsistencies within the iris image



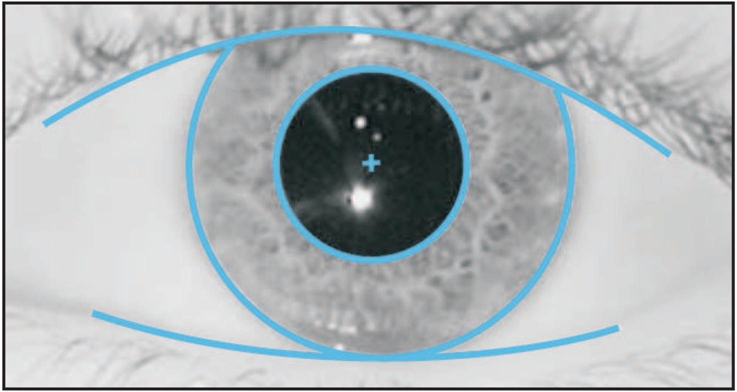
Localization of occlusions

Example: localization of inconsistencies within the iris image



Example segmentation result

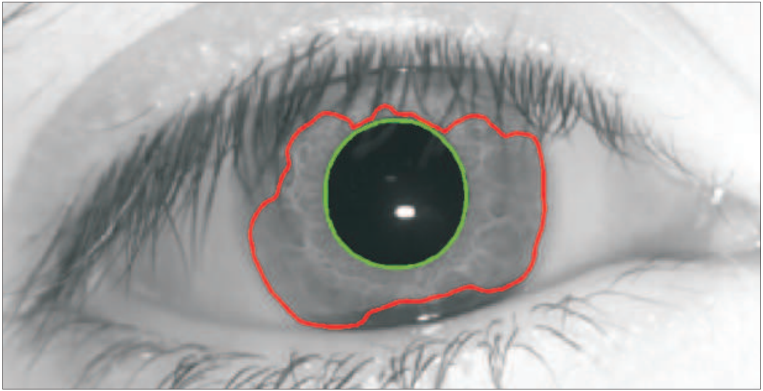
Application of the integro-differential operator



source: J. Daugman, "How Iris Recognition Works", IEEE Trans. CSVT 14(1), pp. 21–30, 2004

Example segmentation result

Application of active contours

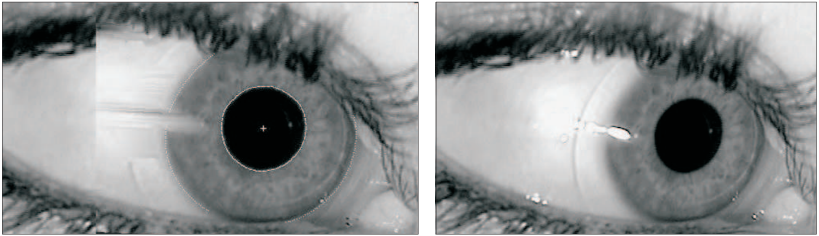


source: Weronika Gutfeter, 'Active contours for iris segmentation', B.Sc. thesis, Warsaw University of Technology, 2010

Post-segmentation processing

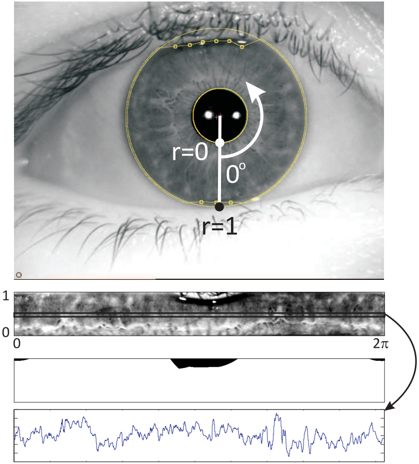
Correction of the off-axis gaze

1. Approximation by an ellipse
   - use of ellipse curves (instead of circles) in integro-differential operator
   - first-order coefficients of the Fourier expansion define the ellipse approximating the iris
2. Surface warping



source: J. Daugman, "New Methods in Iris Recognition", IEEE Tran. on Systems, Man, and Cybernetics, Part B: Cybernetics, Vol. 37, No. 5, October 2007

Iris in polar coordinate system



Segmented iris image

Iris image in polar coordinate system

Occlusion mask

Iris image intensity for a given radius as a function of the angle

Iris in polar coordinate system

Some obvious mathematics ...

$$I(x(r,\theta), y(r,\theta)) \rightarrow I(r,\theta)$$

$$x(r,\theta) = (1-r)x_p(\theta) + rx_l(\theta)$$

$$y(r,\theta) = (1-r)y_p(\theta) + ry_l(\theta)$$

where:

(x_p, y_p) : inner (pupillary) boundary point

(x_l, y_l) : outer (limbic) boundary point

$$r \in \langle 0; 1 \rangle, \quad \theta \in \langle 0; 2\pi \rangle$$

Building the iris code

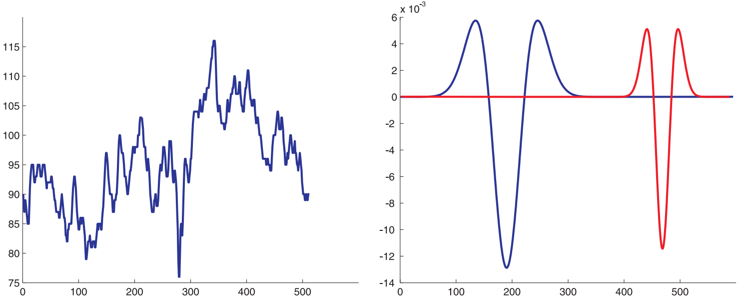
Typical approach

1. Filtering the iris image: use of different kernels, thus enhancing image properties for different resolutions (i.e. different frequency bands)
   - popular kernels: 1D/2D Gabor, LoG, Haar
   - alternative to filtering: use the transformation coefficients (i.e. no return to the image domain)
   - although iris pattern is rich in individual features in a very wide frequency spectrum, practice enforces using rather low frequencies in iris recognition (robust to distortions and camera noise)
2. Quantization of the filtering result: typically only the sign of each resulting value is codes → binary code, iris code

Zero-crossing approach

(initial proposal: W.W. Boles, 1997)

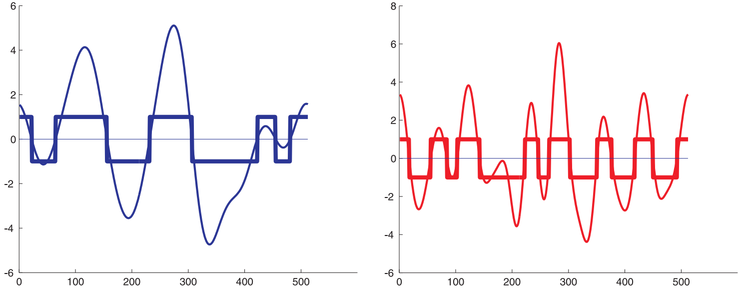
1. Filtering of the iris image intensity 1D functions
   (called by Boles the *iris signatures*)
   - use of the second derivative of the smoothing functions
     e.g. Laplacian of Gaussian



Left: iris image intensity (single 'stripe'). Right: example LoG kernels

Zero-crossing approach
(initial proposal: W.W. Boles, 1997)

2. Localization of zero-crossings and building a code
   - positive results coded as 1's, negative results coded as 0's



Filtering results (solid lines) and binary representation (step lines)

2D Gabor filtering approach

(inventor: John Daugman, 1993)

1. Use of 2D Gabor filters

$$J(r_0,\theta_0) = \underbrace{\int_\phi H(\phi;\theta_0,\beta) \underbrace{\int_\rho G(\rho;r_0,\alpha) I(\rho,\phi)\rho d\rho}_{\text{averaging in radial direction}} d\phi}_{\text{filtering in angular direction}}$$

where

$$H(\phi;\theta_0,\beta) = e^{-i\omega(\theta_0-\phi)} e^{-(\theta_0-\phi)^2/\beta^2}$$

and

$$G(\rho;r_0,\alpha) = e^{-(r_0-\rho)^2/\alpha^2}$$

Note: α and β are decay parameters in radial and angular directions, respectively; typical assumption is $\beta = 1/\omega$

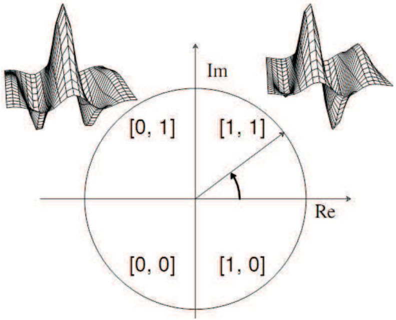
2D Gabor filtering approach

(inventor: John Daugman, 1993)

2. Encoding the signal phase

$$\mathrm{Re}_{r_0\theta_0} = \mathrm{sgn}\,\Re(J(r_0,\theta_0))$$

$$\mathrm{Im}_{r_0\theta_0} = \mathrm{sgn}\,\Im(J(r_0,\theta_0))$$

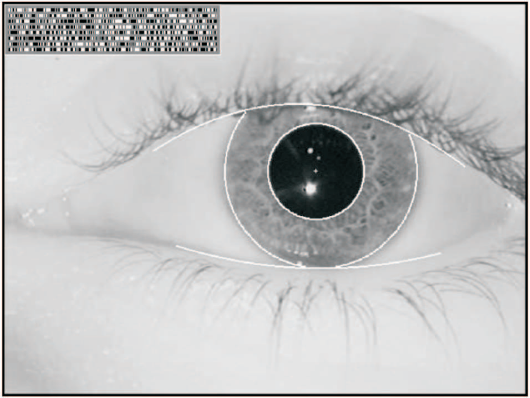


source: J. Daugman, *Probing the Uniqueness and Randomness of IrisCodes: Results From 200 Billion Iris Pair Comparisons*, Proceedings of the IEEE, Vol. 94, No. 11, November 2006

2D Gabor filtering approach

(inventor: John Daugman, 1993)

Example iris image and its iris code



Source: John Daugman, How Iris Recognition Works, IEEE Trans. on Circuits and Systems for Video Tech., Vol. 14, No. 1, Jan. 2004

Matching binary codes

1. Calculation of the normalized Hamming distance ($\mathrm{HD}_{\mathrm{norm}}$)

$$\mathrm{HD}_{\mathrm{norm}} = \frac{||(C_1 \otimes C_2) \cap M_1 \cap M_2||}{||M_1 \cap M_2||}$$

where: C is the iris code, M is the occlusion mask determining essential ('1') and not important ('0') bits, $\otimes$ is the exclusive disjunction (XOR), $\cap$ is the logical conjunction (AND)

Matching binary codes

1. Calculation of the normalized Hamming distance (HD_{norm})

$$\text{HD}_{\text{norm}} = \frac{||(C_1 \otimes C_2) \cap M_1 \cap M_2||}{||M_1 \cap M_2||}$$

   where: C is the iris code, M is the occlusion mask determining essential ('1') and not important ('0') bits, $\otimes$ is the exclusive disjunction (XOR), $\cap$ is the logical conjunction (AND)

2. Correction of the eyeball rotation
   - shifting one of the codes (left and right) $\Rightarrow$ multiple HD's
   - selecting the lowest Hamming distance
   - crucial in iris recognition

Matching binary codes

1. Calculation of the normalized Hamming distance (HD_{norm})

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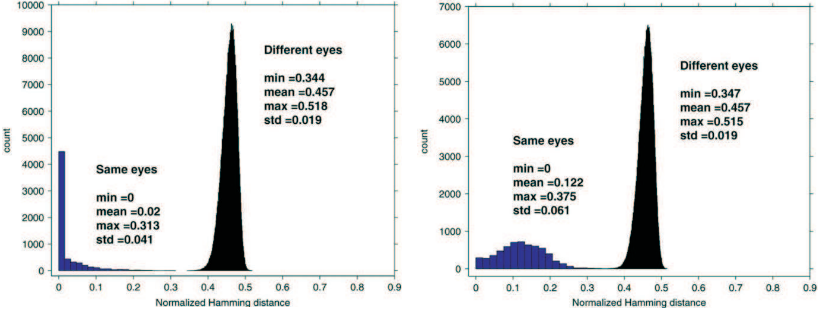
   where: C is the iris code, M is the occlusion mask determining essential ('1') and not important ('0') bits, $\otimes$ is the exclusive disjunction (XOR), $\cap$ is the logical conjunction (AND)

2. Correction of the eyeball rotation
   - shifting one of the codes (left and right) $\Rightarrow$ multiple HD's
   - selecting the lowest Hamming distance
   - crucial in iris recognition
3. Use of scalar threshold (set experimentally)
   - example: for Daugman's method HD_{thr}=0.33 (typically), i.e. about 2/3 of unoccluded bits in two codes must match

Statistical properties of the iris code

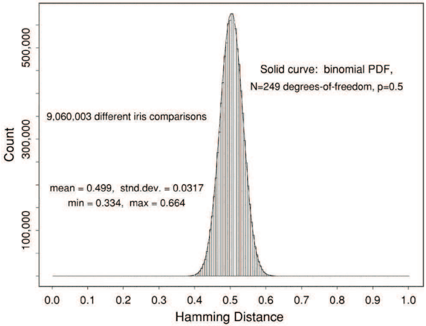
Impostor and genuine scores are well separated

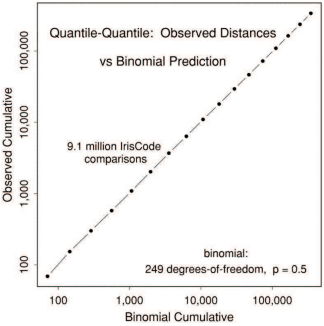


Source: F. Hao et al., A Fast Search Algorithm for a Large Fuzzy Database IEEE Trans. on Inf. Forensics and Security, Vol. 3, No. 2, 2008

Statistical properties of the iris code

Impostor scores have binomial distribution

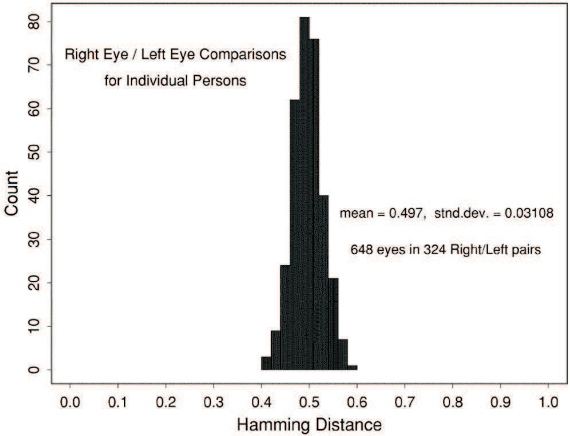




Source: John Daugman, How Iris Recognition Works, IEEE Trans. on Circuits and Systems for Video Tech., Vol. 14, No. 1, Jan. 2004

Statistical properties of the iris code

Identical twins have uncorrelated eyes



Source: John Daugman, How Iris Recognition Works, IEEE Trans. on Circuits and Systems for Video Tech., Vol. 14, No. 1, Jan. 2004

Statistical properties of the iris code

Use of binomial density function to model the impostor scores distribution

1. For N independent Bernoulli tries we have:

$$\sqrt{p(1-p)/N} = \sigma$$

where: p is the probability of 'success', σ^2 is the variance, and N represents the number of degrees of freedom

Statistical properties of the iris code

Use of binomial density function to model the impostor scores distribution

2. Choose some, example empirical values of $\widehat{p}$ and $\widehat{\sigma}$, namely

$$\widehat{p} = 1 - \widehat{q} = 1 - 0.499 = 0.501$$

$$\widehat{\sigma} = 0.0317$$

Statistical properties of the iris code

Use of binomial density function to model the impostor scores distribution

2. Choose some, example empirical values of $\widehat{p}$ and $\widehat{\sigma}$, namely

$$\widehat{p} = 1 - \widehat{q} = 1 - 0.499 = 0.501$$

$$\widehat{\sigma} = 0.0317$$

Then we get:

$$\widehat{N} = \widehat{p}(1 - \widehat{p})/\widehat{\sigma}^2 \approx 249 \neq N = 2048$$

where 2048 is the length of the iris code (number of bits)

What does it mean?

Statistical properties of the iris code

Use of binomial density function to model the impostor scores distribution

3. Typical confusions

- $\widehat{N}$ incorrectly interpreted as the number of 'unique iris features', or the number of 'unique points', or the number of 'iris minutia', and so on ...

Statistical properties of the iris code

Use of binomial density function to model the impostor scores distribution

3. Typical confusions

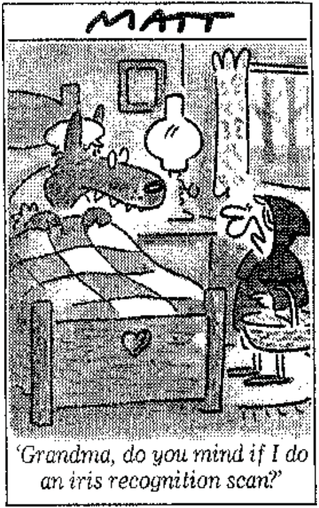
- $\widehat{N}$ incorrectly interpreted as the number of 'unique iris features', or the number of 'unique points', or the number of 'iris minutia', and so on ...
- $\widehat{N}$ divided by an average iris area gives a discrimination entropy (e.g. about 3.2 b/mm^2 for data used to generate a plot shown on slide No. 72); this is a property of the algorithm, and not the iris

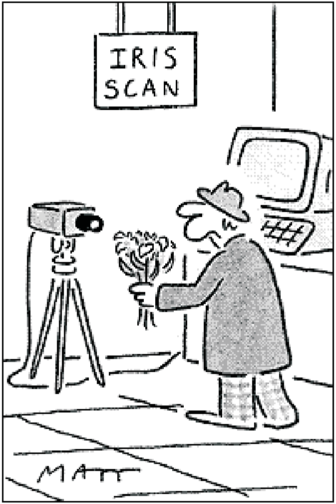
Billion persons have already their iris codes calculated ...

'As of August 2014, almost a billion persons worldwide have had their iris patterns mathematically encoded using the Daugman algorithms for enrollment in national ID or entitlements programmes. This number is projected to reach 1.3 billion persons when current national projects have been completed at the end of 2015.'

Source: `http://www.cl.cam.ac.uk/~jgd1000`

Thank you!


MATT
'Grandma, do you mind if I do an iris recognition scan?'


IRIS SCAN
MATT