Handling Blur

Image Restoration

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Invariants to convolution

$$g(x,y) = (f * h)(x,y)$$

$$I(f * h) = I(f)$$

for any admissible *h*

$$I(f) \equiv \frac{\mathcal{F}(f)}{\mathcal{F}(Pf)}$$

1990s: Flusser et al., centrosymmetry assumption

Projection operators

$$I(f) \equiv \frac{\mathcal{F}(f)}{\mathcal{F}(Pf)}$$

$\mathcal{I}$ – the image space
$\mathcal{S} \subset \mathcal{I}$ – the PSF space closed under convolution
P : projection operator $\mathcal{I} \to \mathcal{S}$, $P^2 = P$

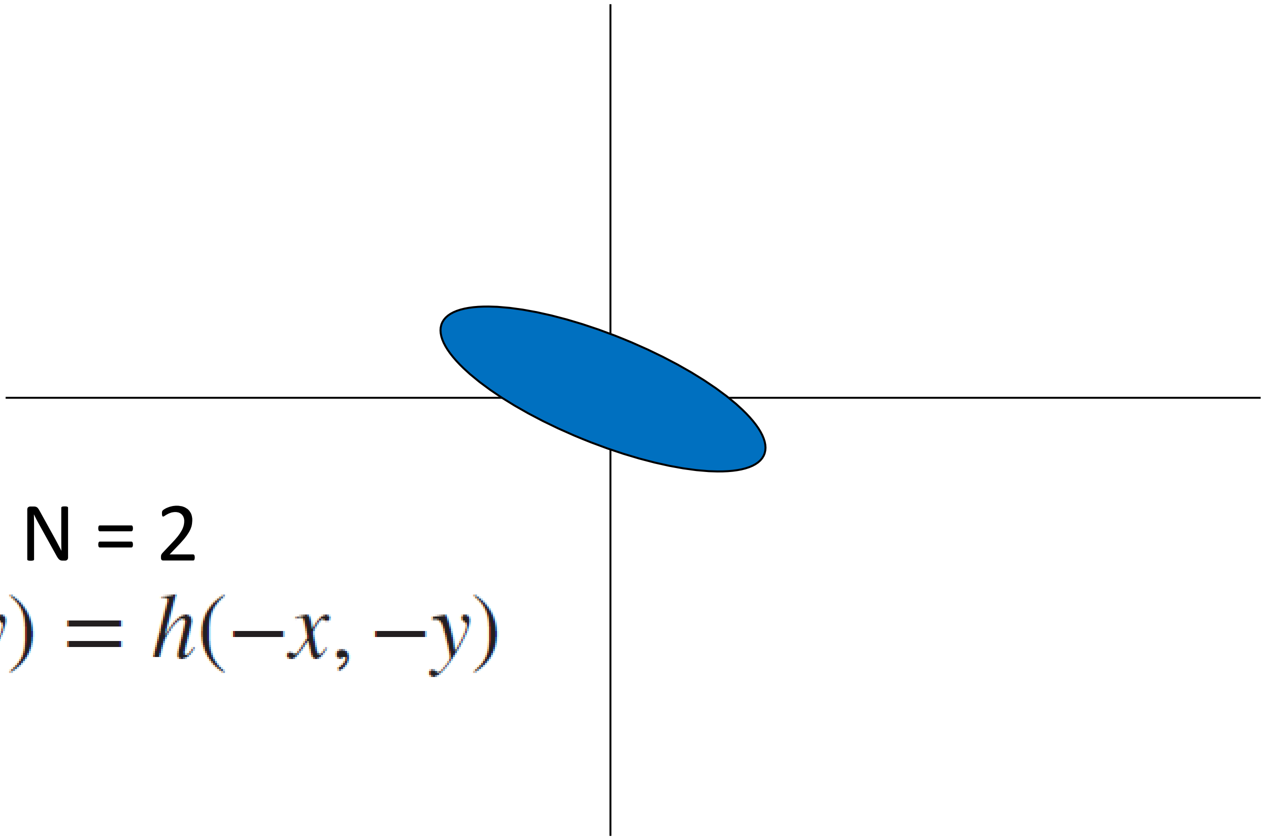
Applicability of the FTBI

- Which PSF spaces ***S*** are closed under convolution?
- For which ***S*** can we construct ***P*** ?
- Are there any [***S, P***] with non-trivial FTBI invariants?
- If yes, do they correspond with real-life PSF's?
- Calculation of the invariants in the image domain?

The answer is ...

Assumptions on the PSF

The PSF has N-fold rotation symmetry

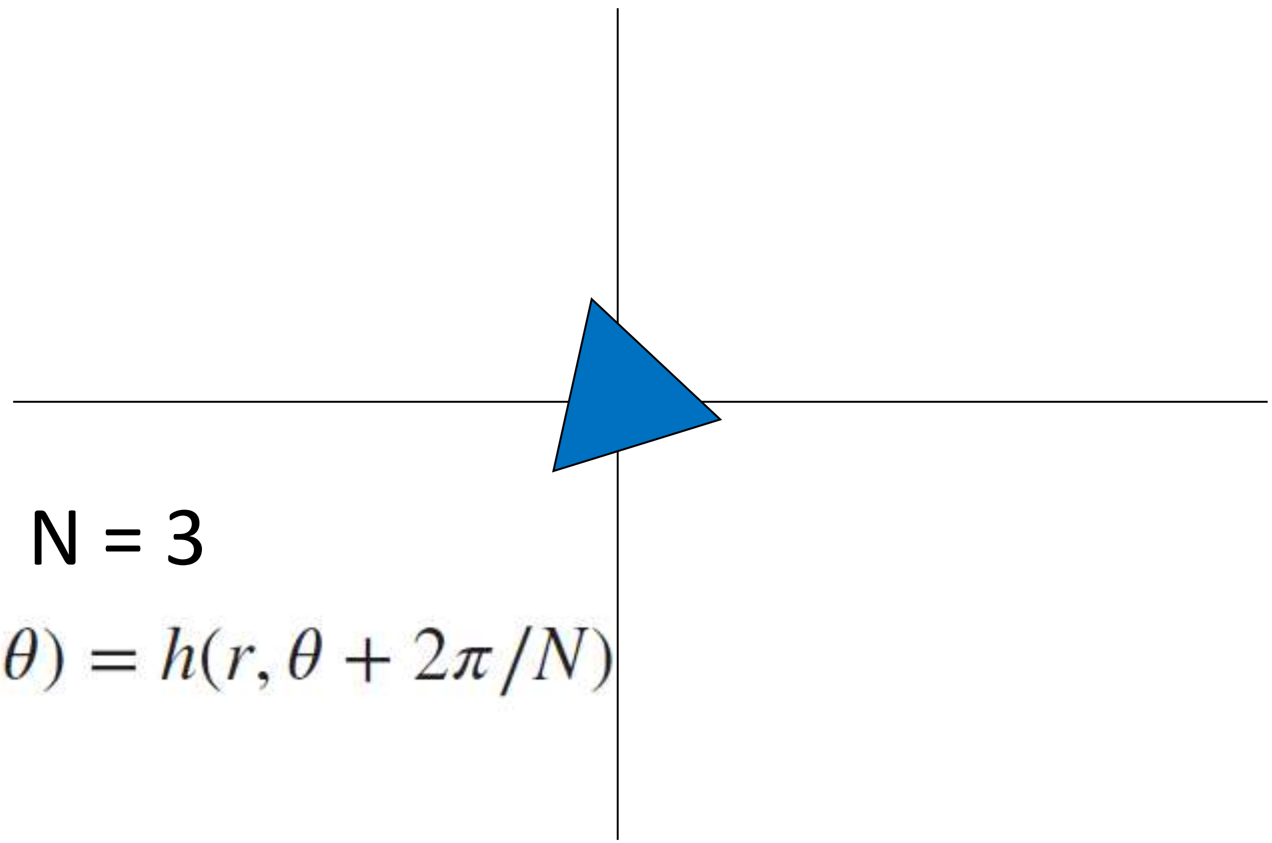


N = 2

$$h(x,y) = h(-x,-y)$$

Assumptions on the PSF

The PSF has *N*-fold rotation symmetry

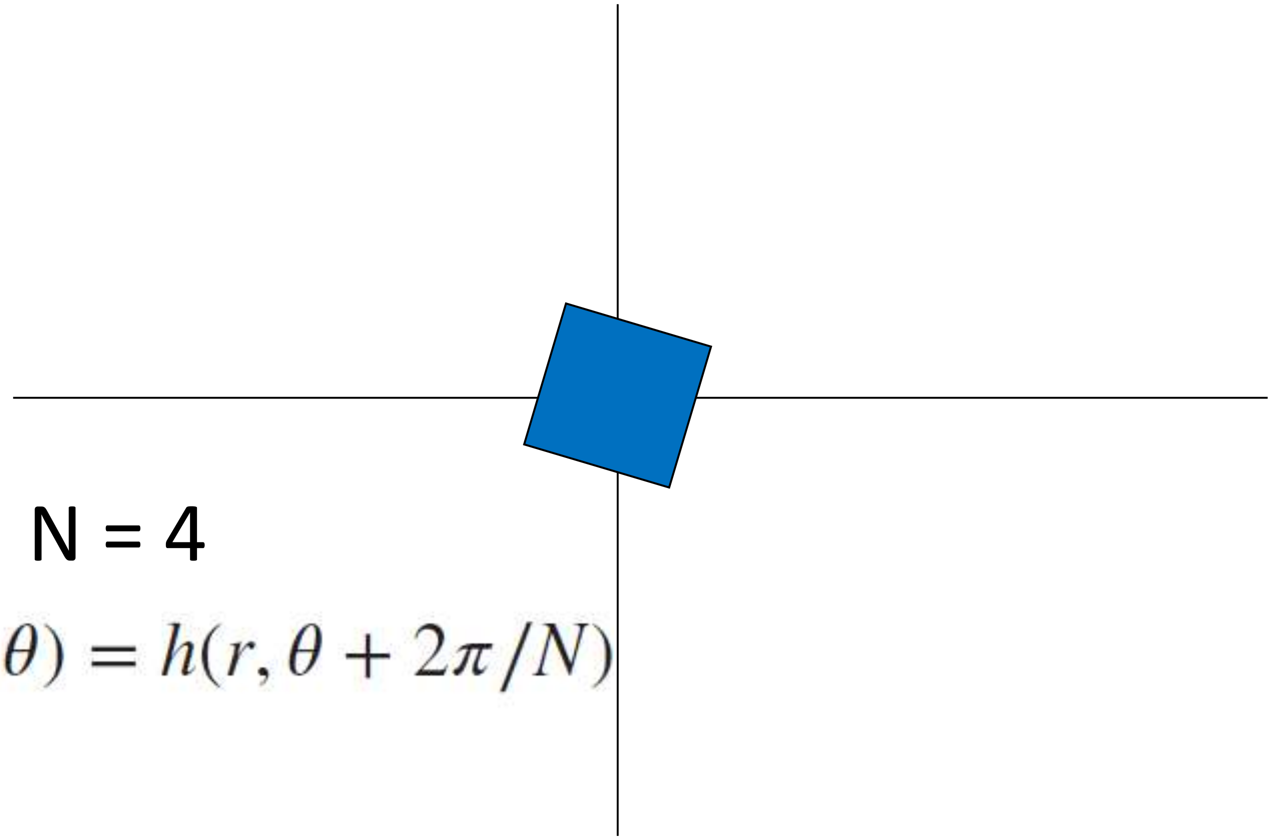


N = 3

$$h(r, \theta) = h(r, \theta + 2\pi/N)$$

Assumptions on the PSF

The PSF has N-fold rotation symmetry

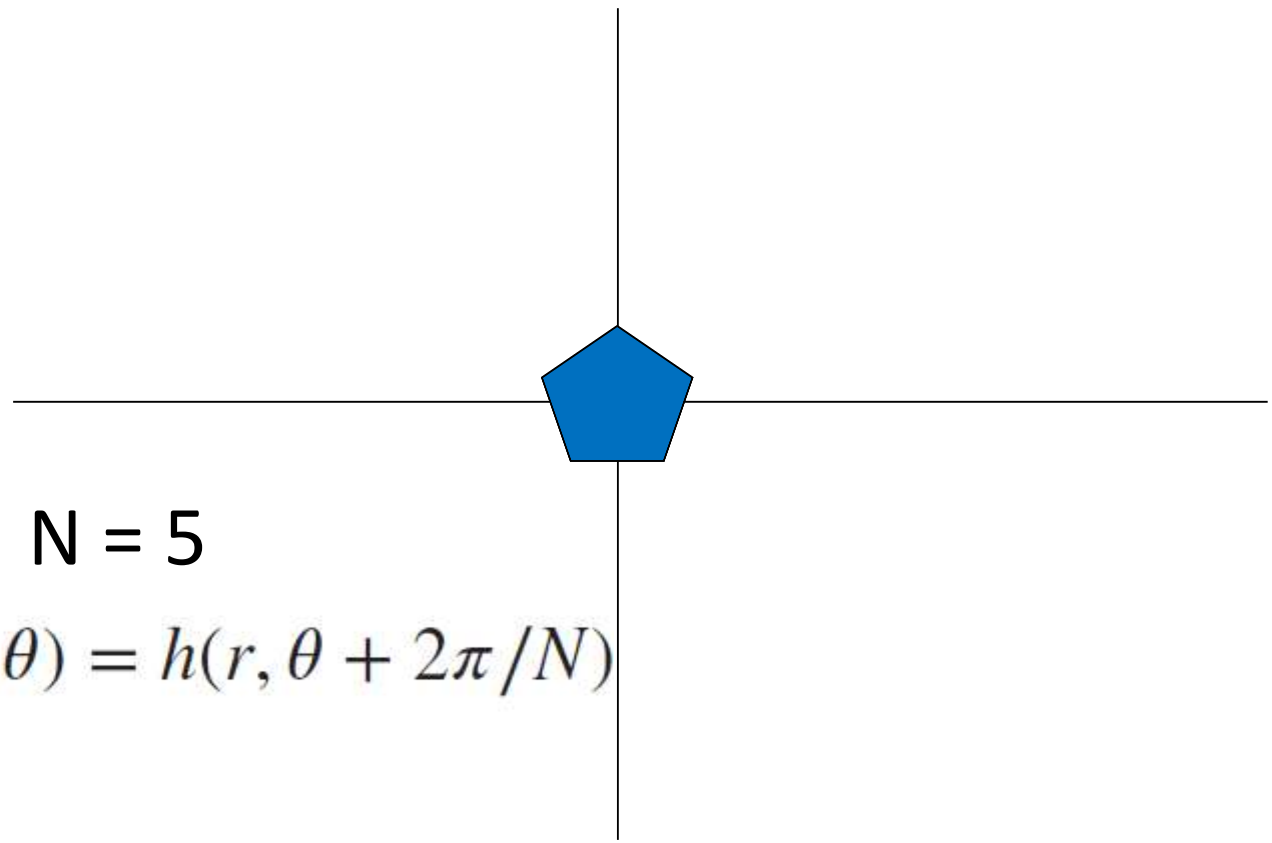


N = 4

$$h(r, \theta) = h(r, \theta + 2\pi/N)$$

Assumptions on the PSF

The PSF has N-fold rotation symmetry

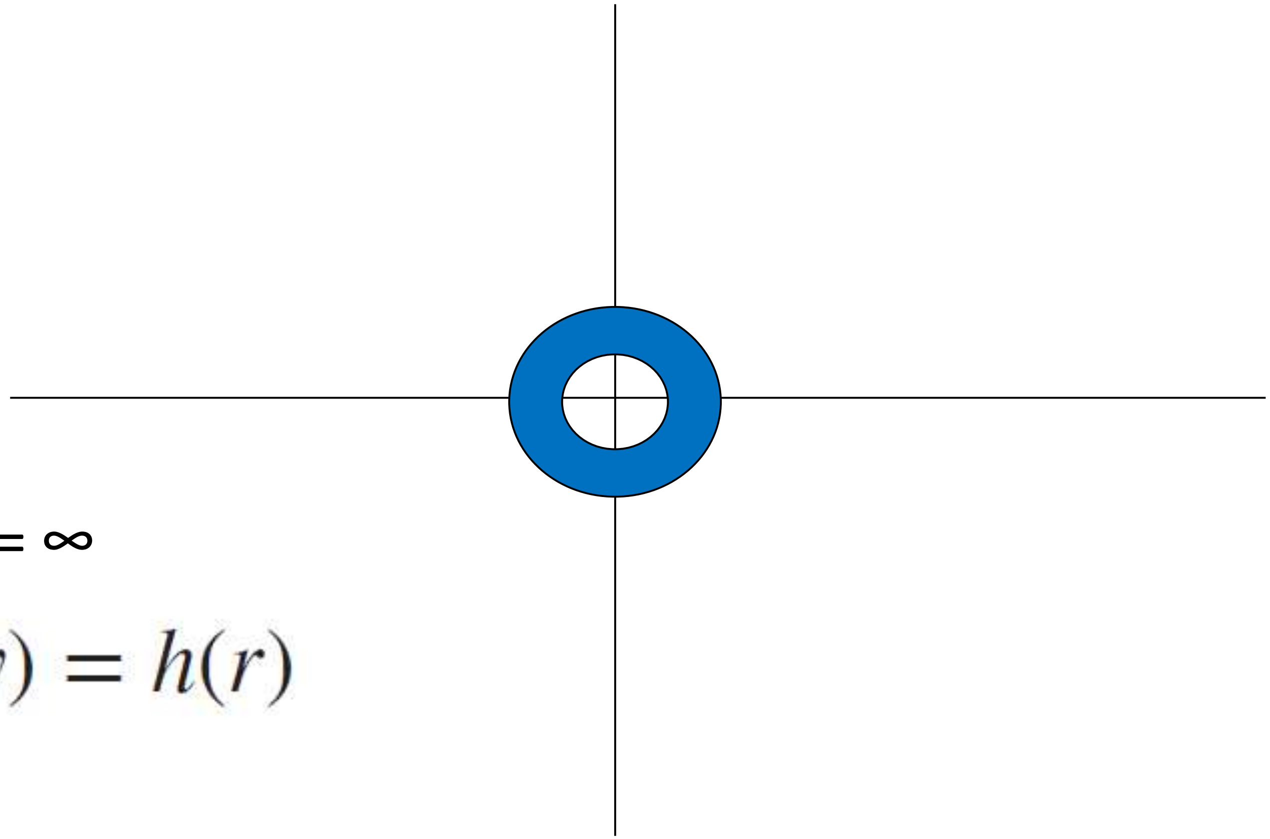


N = 5

$$h(r, \theta) = h(r, \theta + 2\pi/N)$$

Assumptions on the PSF

The PSF has N-fold rotation symmetry

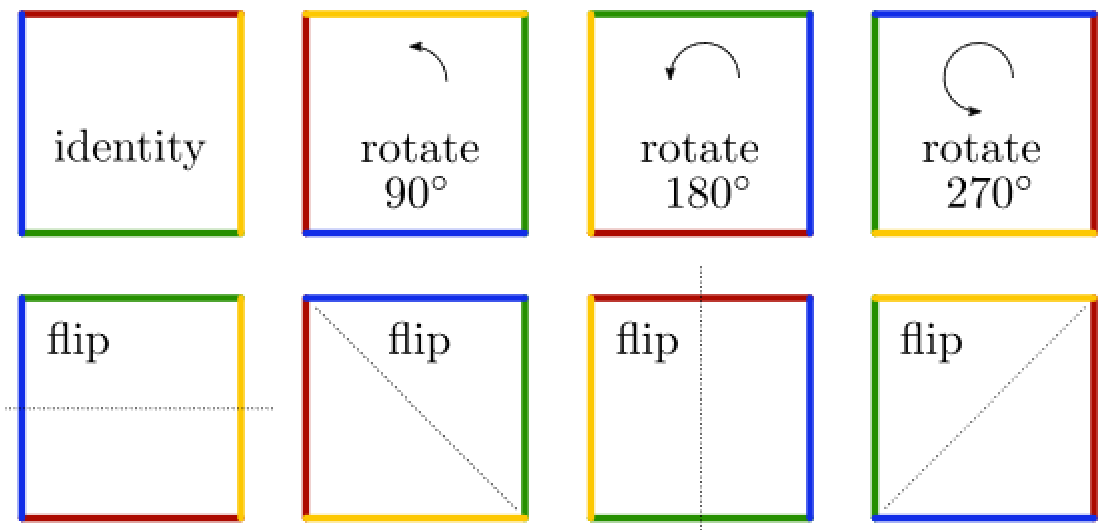


$N = \infty$

$$h(x, y) = h(r)$$

Assumptions on the PSF

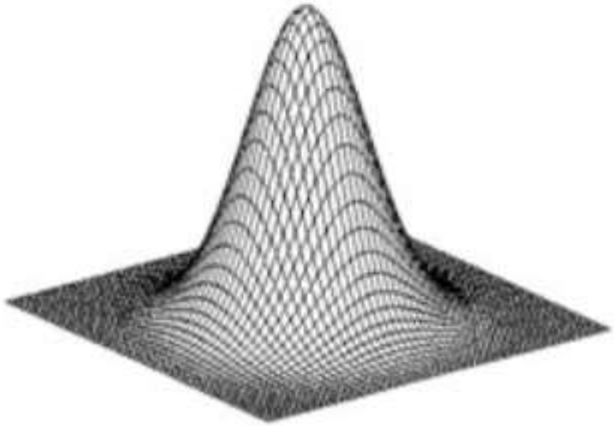
The PSF has N-fold dihedral symmetry



N-fold rotation symmetry and N mirror reflections

Assumptions on the PSF

The PSF has a Gaussian shape

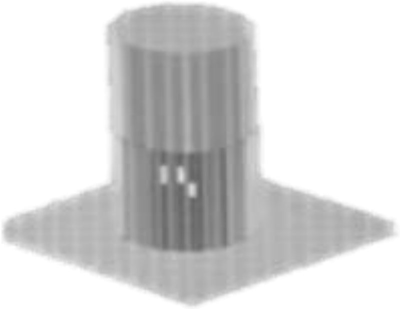


$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Assumptions on the PSF

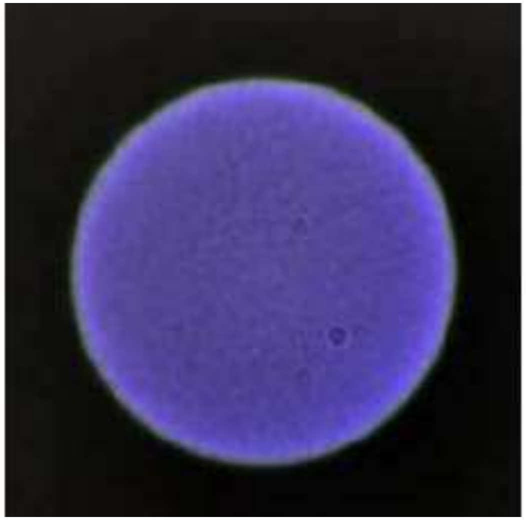
Out-of-focus blur, "geometric optic approximation"

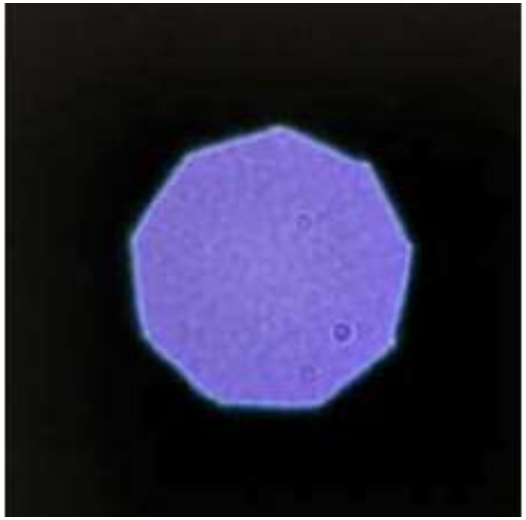
$$g(x,y) = (f * h)(x,y)$$

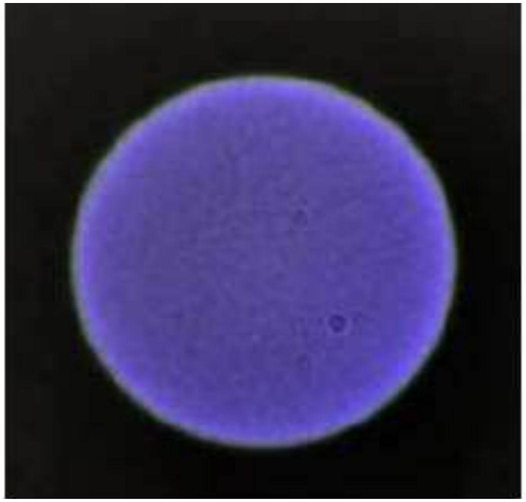
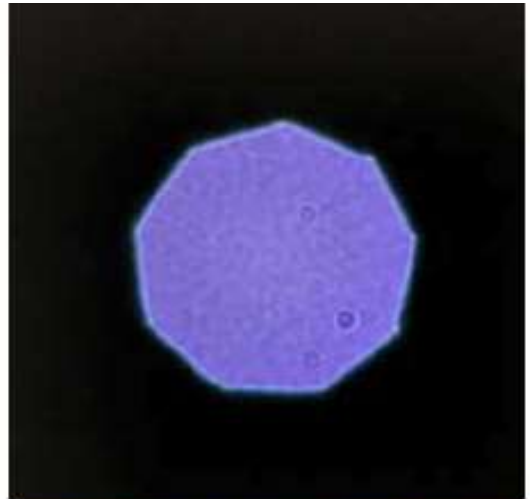
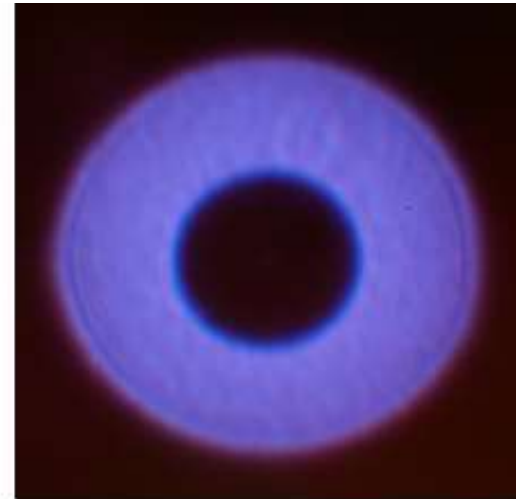


Is it realistic?

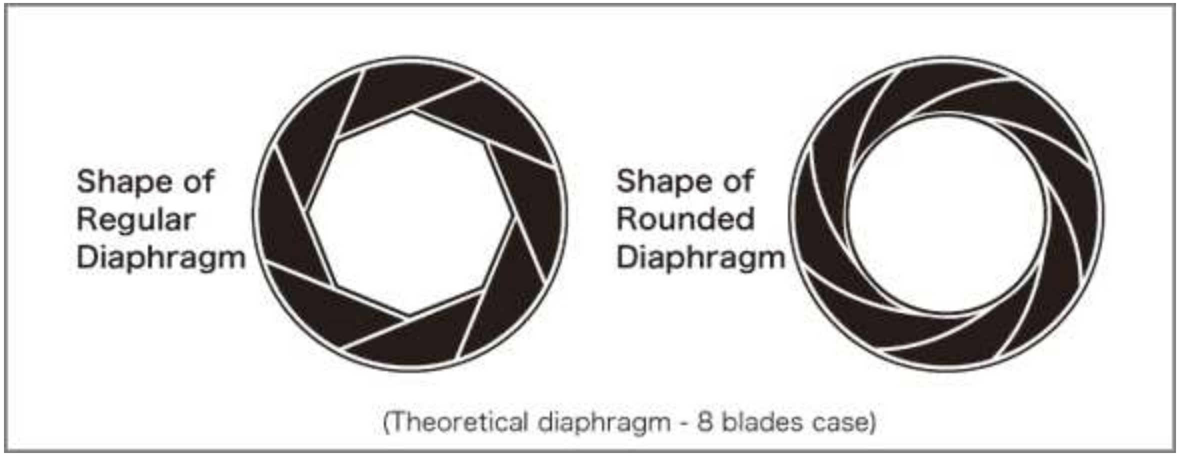
Assumptions on the PSF



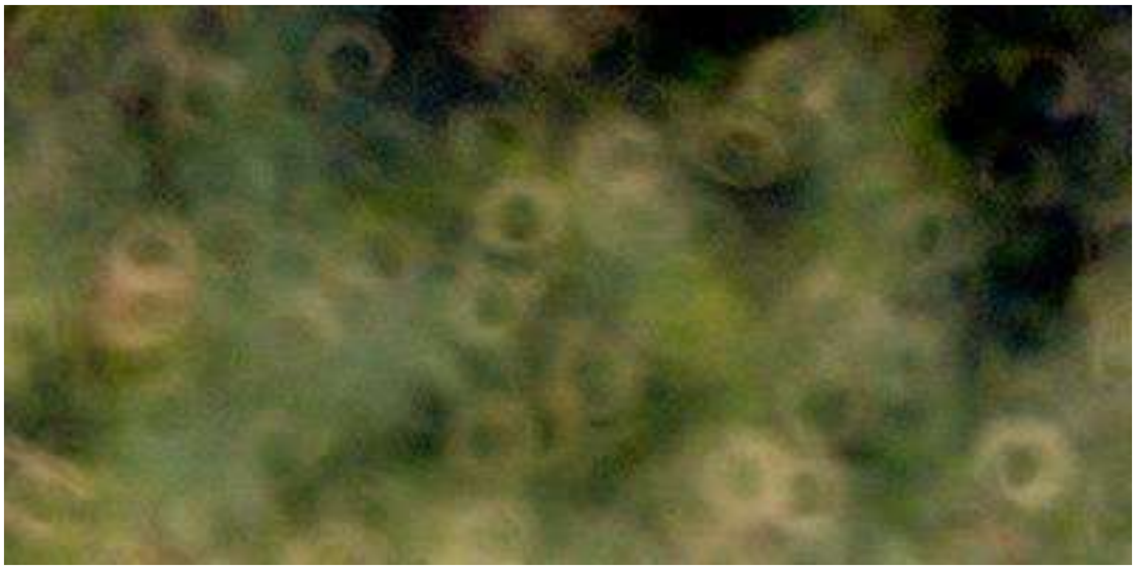


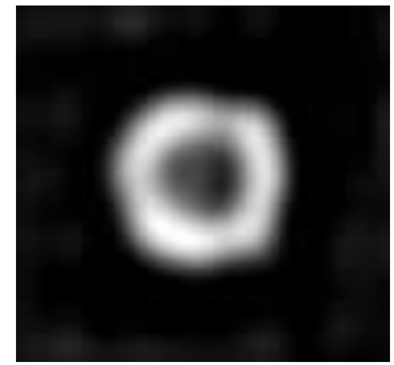





Assumptions on the PSF - apertures



Assumptions on the PSF - bokeh



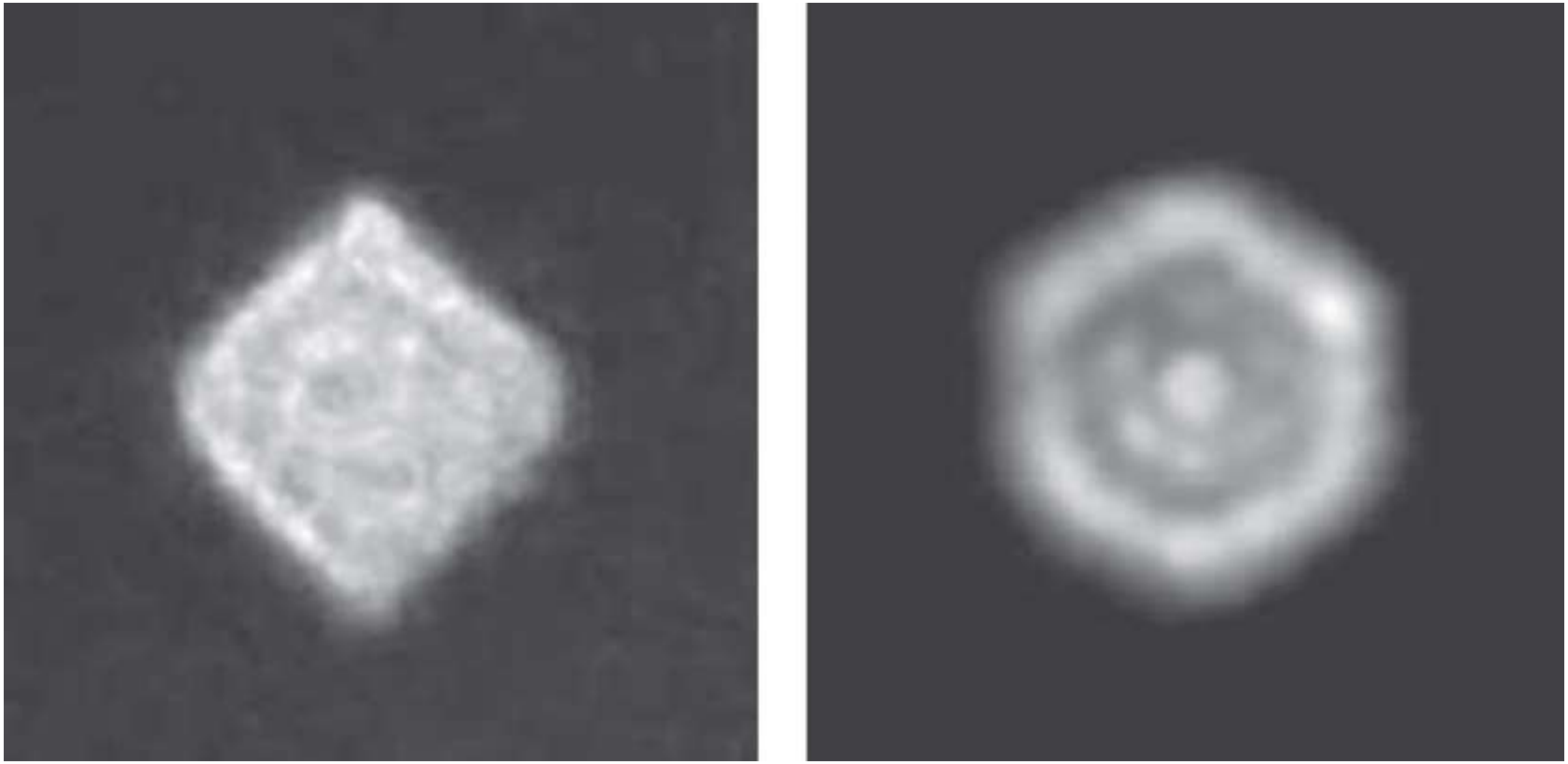


∞-fold rotation symmetry

Assumptions on the PSF - bokeh




Assumptions on the PSF - dihedral



What are moments?

Moments are "projections" of the image function into a polynomial basis

$f(x,y)$ – piecewise continuous image function defined on bounded $\Omega \subset \mathcal{R} \times \mathcal{R}$
$\{\mathcal{P}_{pq}(x,y)\}$ – set of polynomials defined on Ω

$$M_{pq} = \int\int \mathcal{P}_{pq}(x,y) f(x,y) dx dy$$

The most common moments

Geometric moments

$$m_{pq}^{(f)} = \int_{R^2} x^p y^q f(x,y) dx dy$$

(p + q) - the order of the moment

0th order - area

1st order - center of gravity $x_t = \frac{m_{10}}{m_{00}}, \quad y_t = \frac{m_{01}}{m_{00}}$

2nd order - moments of inertia

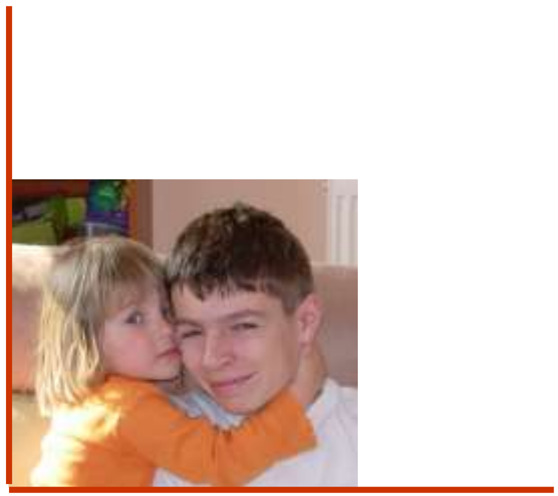
3rd order - skewness

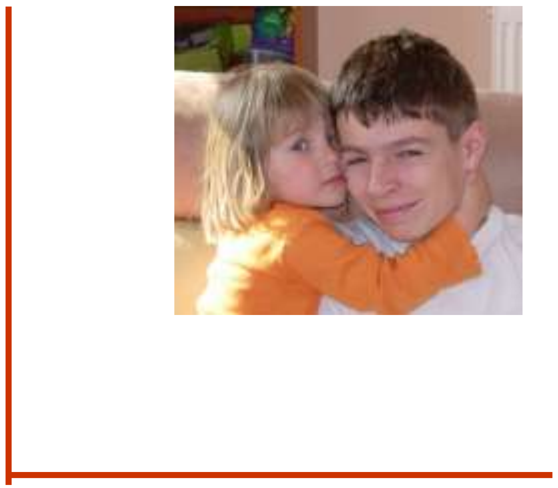
The most common moments

Central moments

$$\mu_{pq}^{(f)} = \int_{R^2} (x - x_t)^p (y - y_t)^q f(x,y)\,dx\,dy$$

$$x_t = m_{10}/m_{00}, \quad y_t = m_{01}/m_{00}$$





The most common moments

Normalized central moments

$$\nu_{pq} = \frac{\mu_{pq}}{\mu_{00}^{w}} \qquad w = \frac{p+q}{2} + 1$$

The most common moments

Complex moments

$$c_{pq}^{(f)} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x+iy)^p(x-iy)^q f(x,y)\,dx\,dy$$

The moments under convolution

$$g(x,y) = (f * h)(x,y)$$

Geometric/central

$$\mu_{pq}^{(g)} = \sum_{k=0}^{p} \sum_{j=0}^{q} \binom{p}{k} \binom{q}{j} \mu_{kj}^{(h)} \mu_{p-k,q-j}^{(f)}$$

Complex

$$c_{pq}^{(g)} = \sum_{k=0}^{p} \sum_{j=0}^{q} \binom{p}{k} \binom{q}{j} c_{kj}^{(h)} c_{p-k,q-j}^{(f)}$$

Applicability of the FTBI

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The answer is ...

Intuition: How to eliminate $c_{kj}^{(h)}$?

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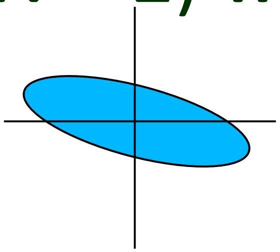
- centrosymmetric PSF (N = 2) with a unit integral

$$h(x, y) = h(-x, -y)$$



90% of blur invariants two fold rotation symmetry …

Intuition: How to eliminate $c_{kj}^{(h)}$?

$$c_{pq}^{(g)} = \sum_{k=0}^{p} \sum_{j=0}^{q} \binom{p}{k} \binom{q}{j} c_{kj}^{(h)} c_{p-k,q-j}^{(f)}$$

even

energy preserving

$$c_{00}^{(g)} = c_{00}^{(f)} c_{00}^{(h)} = c_{00}^{(f)}$$

$$c_{10}^{(g)} = c_{10}^{(f)} c_{00}^{(h)} + c_{00}^{(f)} c_{10}^{(h)} = c_{10}^{(f)} + c_{00}^{(f)} c_{10}^{(h)}$$

$$c_{20}^{(g)} = c_{20}^{(f)} + 2c_{10}^{(f)} c_{10}^{(h)} + c_{00}^{(f)} c_{20}^{(h)}$$

$$c_{30}^{(g)} = c_{30}^{(f)} + 3c_{20}^{(f)} c_{10}^{(h)} + 3c_{10}^{(f)} c_{20}^{(h)} + c_{00}^{(f)} c_{30}^{(h)}$$

Invariants to centrosymmetric convolution

$$\begin{aligned} C(3,0) &= \mu_{30}, \\ C(2,1) &= \mu_{21}, \\ C(1,2) &= \mu_{12}, \\ C(0,3) &= \mu_{03}. \end{aligned}$$

Invariants to centrosymmetric convolution

$$
\begin{aligned}
C(5,0) &= \mu_{50} - \frac{10\mu_{30}\mu_{20}}{\mu_{00}}, \\
C(4,1) &= \mu_{41} - \frac{2}{\mu_{00}}(3\mu_{21}\mu_{20} + 2\mu_{30}\mu_{11}), \\
C(3,2) &= \mu_{32} - \frac{1}{\mu_{00}}(3\mu_{12}\mu_{20} + \mu_{30}\mu_{02} + 6\mu_{21}\mu_{11}), \\
C(2,3) &= \mu_{23} - \frac{1}{\mu_{00}}(3\mu_{21}\mu_{02} + \mu_{03}\mu_{20} + 6\mu_{12}\mu_{11}), \\
C(1,4) &= \mu_{14} - \frac{2}{\mu_{00}}(3\mu_{12}\mu_{02} + 2\mu_{03}\mu_{11}), \\
C(0,5) &= \mu_{05} - \frac{10\mu_{03}\mu_{02}}{\mu_{00}}.
\end{aligned}
$$

Invariants to centrosymmetric convolution

$$C(p,q)^{(f)} = \mu_{pq}^{(f)} - \frac{1}{\mu_{00}^{(f)}} \sum_{n=0}^{p} \sum_{\substack{m=0 \\ 0<n+m<p+q}}^{q} \binom{p}{n}\binom{q}{m} C(p-n,q-m)^{(f)} \cdot \mu_{nm}^{(f)}$$

$$K(p,q)^{(f)} = c_{pq}^{(f)} - \frac{1}{c_{00}^{(f)}} \sum_{n=0}^{p} \sum_{\substack{m=0 \\ 0<n+m<p+q}}^{q} \binom{p}{n}\binom{q}{m} K(p-n,q-m)^{(f)} \cdot c_{nm}^{(f)}$$

where (p + q) is odd

What is the intuitive meaning of the invariants?

"measure of anti-symmetry"

What about FT domain?

Convolution invariants in FT domain

$$
\begin{aligned}
g &= f * h \\
G &= F \cdot H \\
|G| &= |F| \cdot |H| \\
\mathrm{ph}G &= \mathrm{ph}F + \mathrm{ph}H
\end{aligned}
$$

Convolution invariants in FT domain

$$\text{Centrosymmetric } h(x,y) \Longrightarrow \text{real } H(u,v)$$

$$\text{ph}H \in \{0;\pi\}$$

$$\tan(\text{ph}G) = \tan(\text{ph}F)$$

Back to projection operators

Invariants to convolution

$$I(f) \equiv \frac{\mathcal{F}(f)}{\mathcal{F}(Pf)}$$

$\mathcal{I}$ – the image space
$\mathcal{S} \subset \mathcal{I}$ – the PSF space closed under convolution
P : projection operator $\mathcal{I} \rightarrow \mathcal{S}$, $P^2 = P$

Invariants to convolution

$$\mathcal{F}(Pf)(\mathbf{u}) \cdot I(f)(\mathbf{u}) = \mathcal{F}(f)(\mathbf{u})$$

Taylor expansion
of Fourier transform

$$\mathcal{F}(f)(\mathbf{u}) = \sum_{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}^{(f)} \mathbf{u}^{\mathbf{p}}$$

$$\sum_{\mathbf{p} \in D} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}^{(f)} \mathbf{u}^{\mathbf{p}} \cdot \sum_{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} A_{\mathbf{p}} \mathbf{u}^{\mathbf{p}} = \sum_{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}^{(f)} \mathbf{u}^{\mathbf{p}}$$

Invariants to convolution

$$\sum_{\mathbf{p}\in D} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}^{(f)} \mathbf{u}^{\mathbf{p}} \cdot \sum_{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} A_{\mathbf{p}} \mathbf{u}^{\mathbf{p}} = \sum_{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}^{(f)} \mathbf{u}^{\mathbf{p}}$$

comparing the coefficients of the same powers of **u**

$$\sum_{\substack{\mathbf{k}\in D}}^{\mathbf{p}} \frac{(-2\pi i)^{|\mathbf{k}|}}{\mathbf{k}!} \frac{(-2\pi i)^{|\mathbf{p}-\mathbf{k}|}}{(\mathbf{p}-\mathbf{k})!} m_{\mathbf{k}} A_{\mathbf{p}-\mathbf{k}} = \frac{(-2\pi i)^{|\mathbf{p}|}}{\mathbf{p}!} m_{\mathbf{p}}$$

$$\sum_{\substack{\mathbf{k}\in D}}^{\mathbf{p}} \binom{\mathbf{p}}{\mathbf{k}} m_{\mathbf{k}} A_{\mathbf{p}-\mathbf{k}} = m_{\mathbf{p}}$$

General definition of blur invariants in the image domain

$$\sum_{\mathbf{k}\in D}^{\mathbf{p}} \binom{\mathbf{p}}{\mathbf{k}} m_{\mathbf{k}} A_{\mathbf{p}-\mathbf{k}} = m_{\mathbf{p}}$$

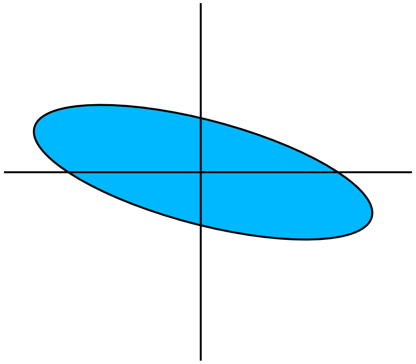
$$m_{\mathbf{0}} A_{\mathbf{p}} = m_{\mathbf{p}} - \sum_{\substack{\mathbf{k}\in D \\ \mathbf{k}\neq \mathbf{0}}}^{\mathbf{p}} \binom{\mathbf{p}}{\mathbf{k}} m_{\mathbf{k}} A_{\mathbf{p}-\mathbf{k}}$$

A_p ~ moments of the primordial image I(f) of f

No need of I(f) construction ! No need of FT !

Invariants to centrosymmetric PSF

centrosymmetric PSF ($N = 2$) with a unit integral



$$S \equiv C_2 = \{h \in \mathcal{I} \,|\, h(x,y) = h(-x,-y)\}$$

Invariants to centrosymmetric PSF

Invariants to centrosymmetric PSF

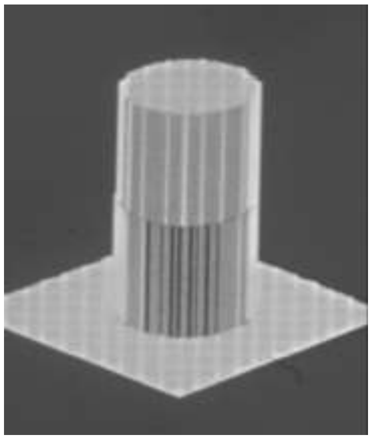
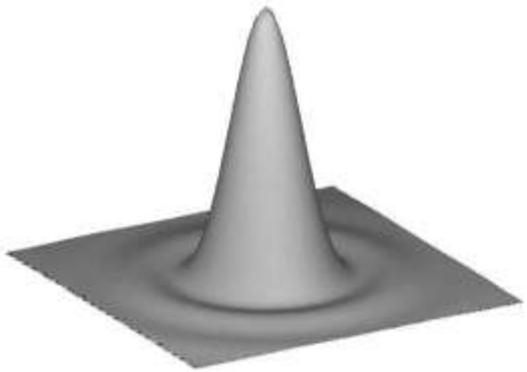
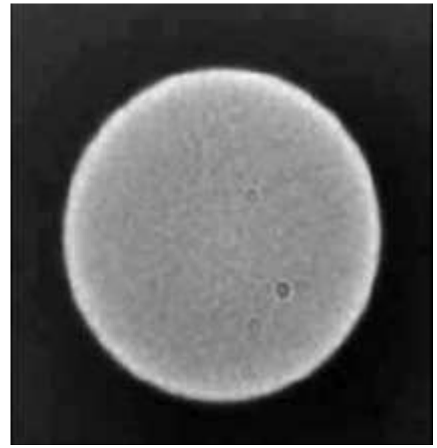
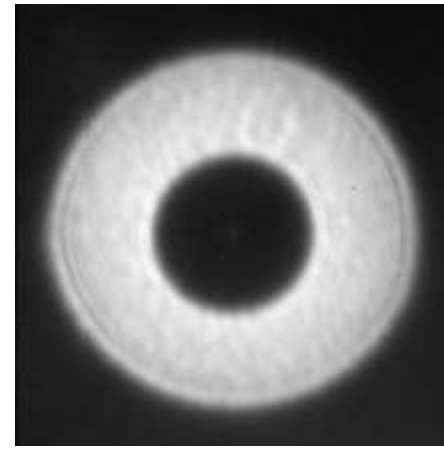
$$(P_2 f)(x,y) = (f(x,y) + f(-x,-y))/2$$

$$I_2(f) = \frac{F}{P_2 F} \qquad I_2(f) = 1 + i \tan(\mathrm{ph}\, F)$$

$$K(p,q)^{(f)} = c_{pq}^{(f)} - \frac{1}{c_{00}^{(f)}} \sum_{n=0}^{p} \sum_{\substack{m=0 \\ 0<n+m<p+q}}^{q} \binom{p}{n} \binom{q}{m} K(p-n, q-m)^{(f)} \cdot c_{nm}^{(f)}$$

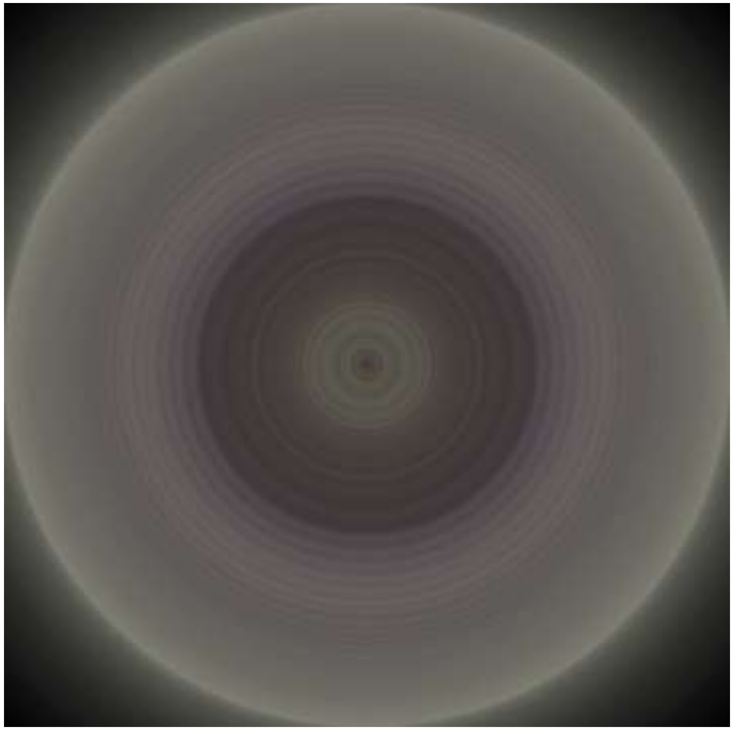
D = {**p**| such that |**p**| is even}.

Invariants to circularly symmetric PSF

$$S \equiv C_\infty = \{h \in \mathcal{I} \,|\, h(r,\theta) = h(r)\}$$

Invariants to circularly symmetric PSF



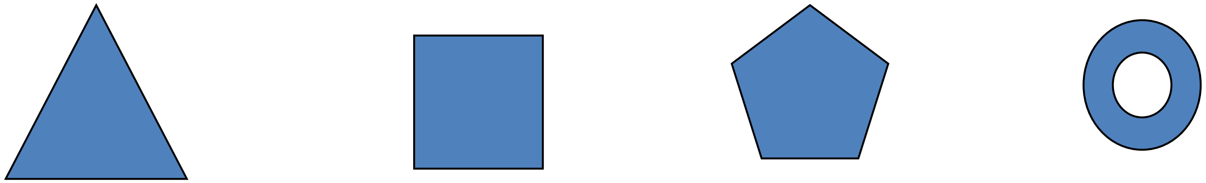
Invariants to circularly symmetric PSF

$$(P_\infty f)(r) = \frac{1}{2\pi} \int_0^{2\pi} f(r,\theta)\, d\theta$$

$$K_\infty(p,q)^{(f)} = c_{pq}^{(f)} - \frac{1}{c_{00}^{(f)}} \sum_{n=1}^{q} \binom{p}{n} \binom{q}{n} K_\infty(p-n, q-n)^{(f)} \cdot c_{nn}^{(f)}$$

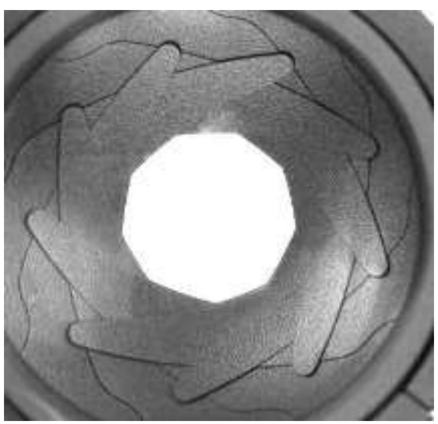
$$D = \{(p,p) | p \geq 0\}$$

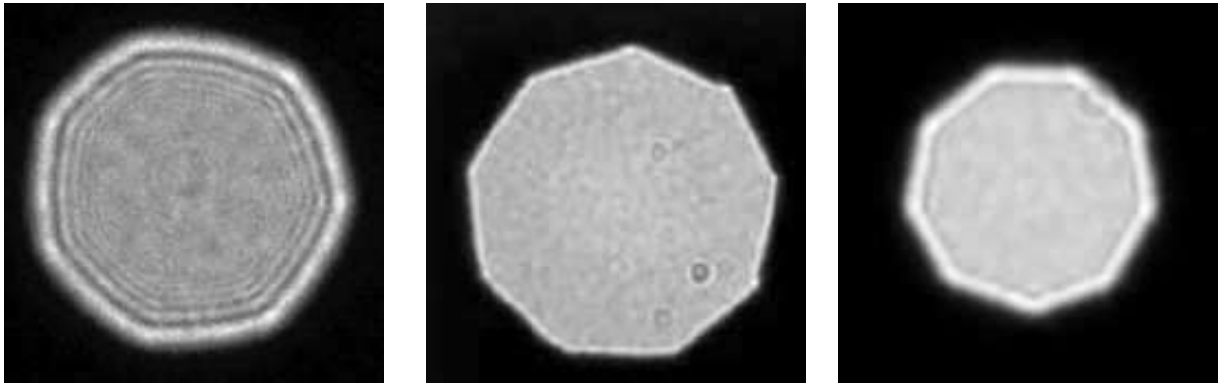
Invariants to N-fold rotational PSF



out-of-focus blur on a polygonal aperture

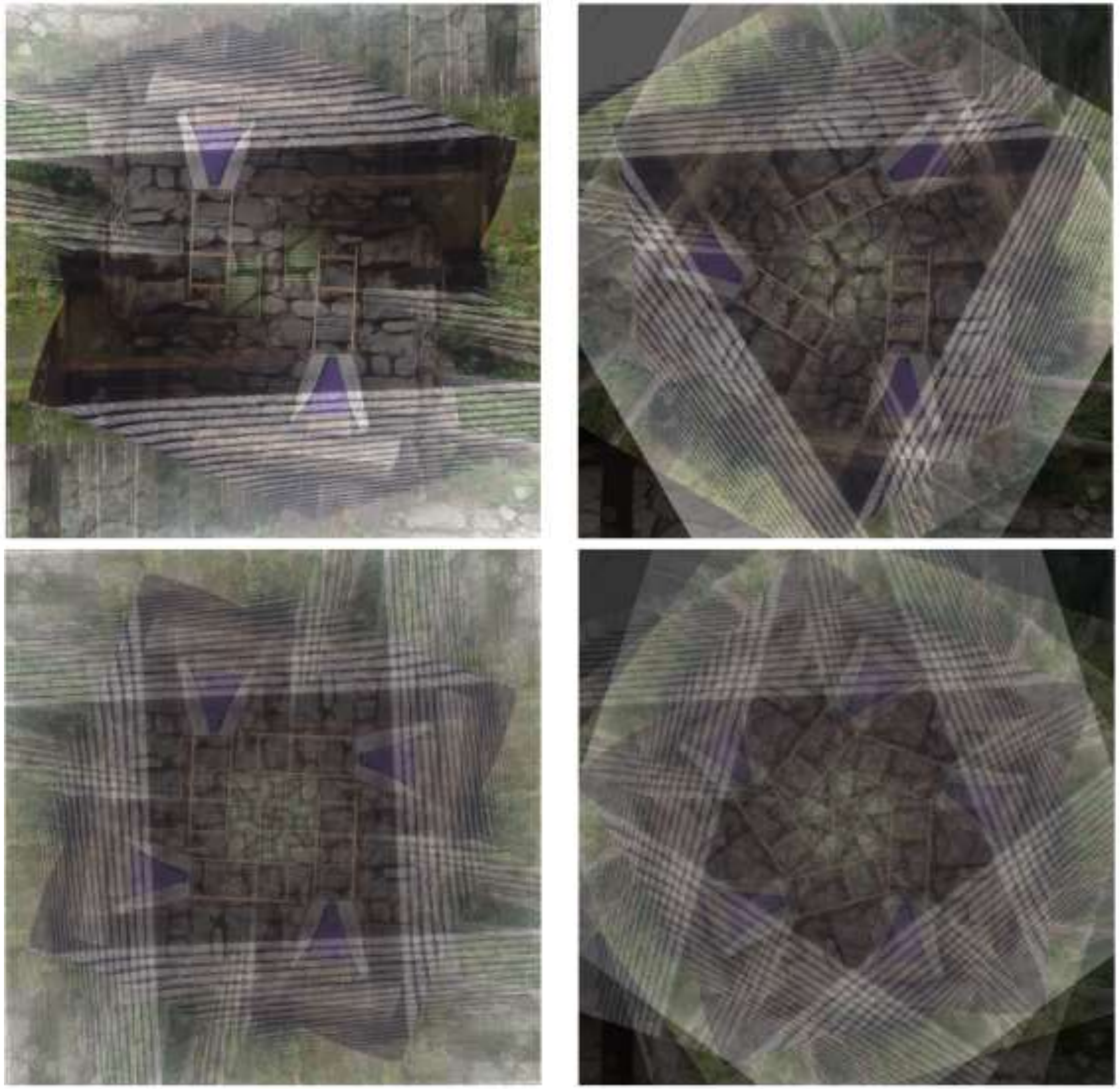
an aperture - physical diaphragm blades





$$S \equiv C_N = \{h \in \mathcal{I} \,|\, h(r,\theta) = h(r, \theta + 2\pi/N)\}$$

Invariants to N-fold rotational PSF



Invariants to N-fold rotational PSF

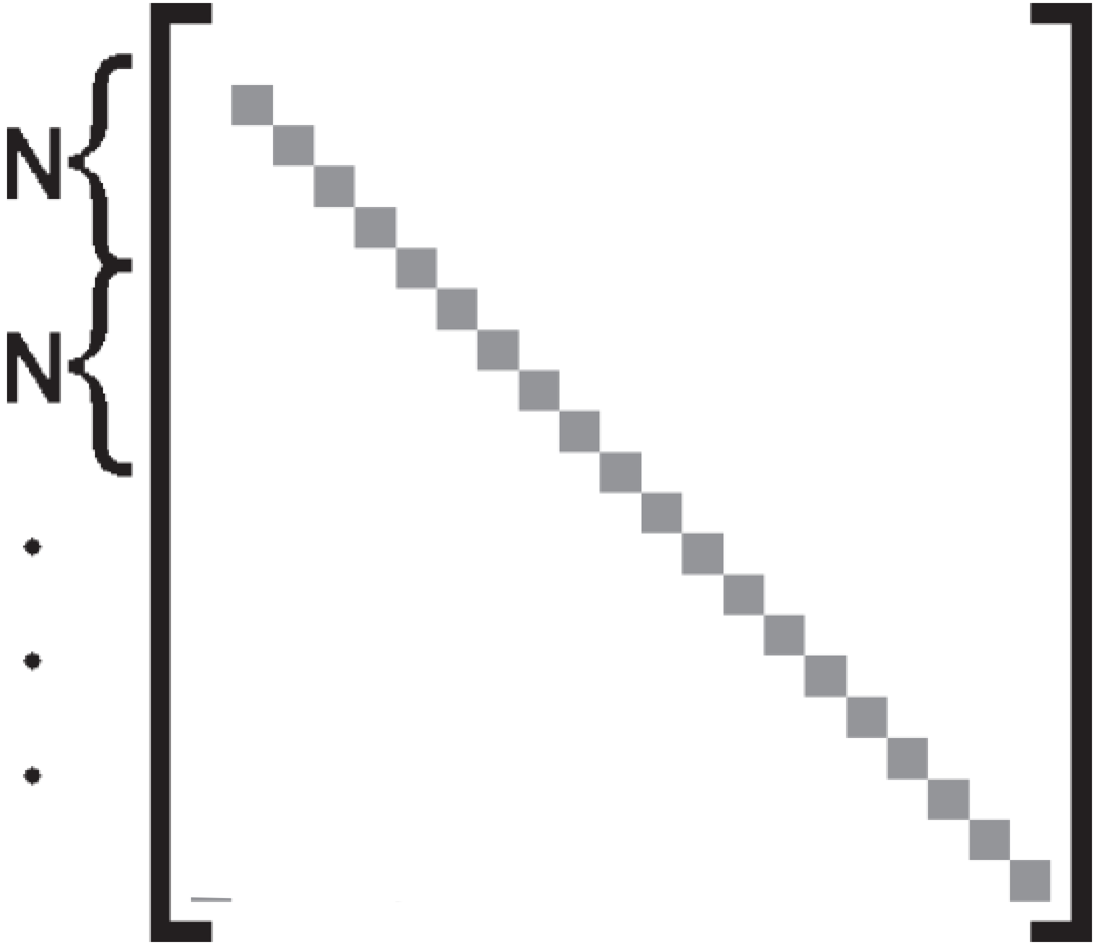
$$(P_N f)(r,\theta) = \frac{1}{N}\sum_{j=1}^{N} f(r, \theta + \alpha_j)$$

$$\alpha_j = 2\pi j/N$$

$$K_N(p,q)^{(f)} = c_{pq}^{(f)} - \frac{1}{c_{00}^{(f)}} \sum_{n=0}^{p} \sum_{\substack{m=0 \\ 0<n+m \\ (n-m)/N \text{ is integer}}}^{q} \binom{p}{n}\binom{q}{m} K_N(p-n, q-m)^{(f)} \cdot c_{nm}^{(f)}$$

$$D_N = \{(p,q) | (p-q)/N \text{ is integer}\}$$

Invariants to N-fold rotational PSF



$$\mathbf{K}_{ij} = K_N(i-1, j-1)$$

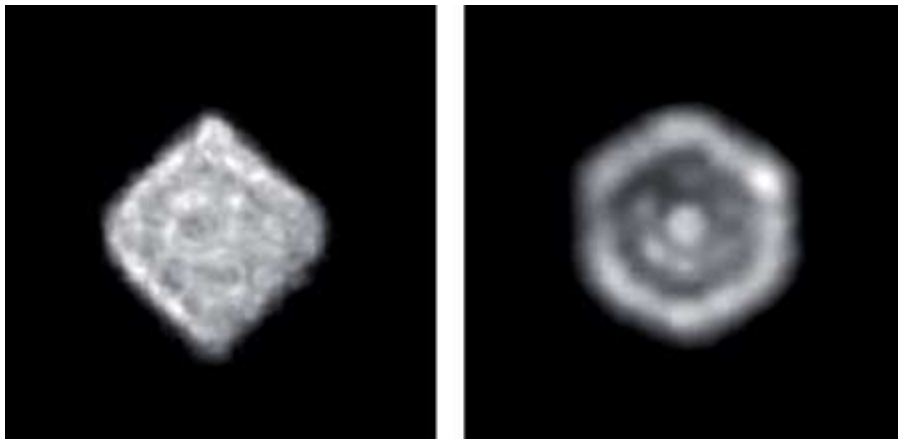
Invariants to N-fold rotational PSF

overestimate N → lose invariance

underestimate N → lose discriminability

different cameras → greatest common divisor

Invariants to N-fold dihedral symmetry PSF



N-FRS plus axial

$$f^{\alpha}(\mathbf{x}) = f(S\mathbf{x}) \qquad S = \begin{pmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha \end{pmatrix}$$

$$S \equiv D_N = \{h \in C_N | \exists \alpha \ \text{ such that } \ h(x,y) = h^{\alpha}(x,y)\}$$

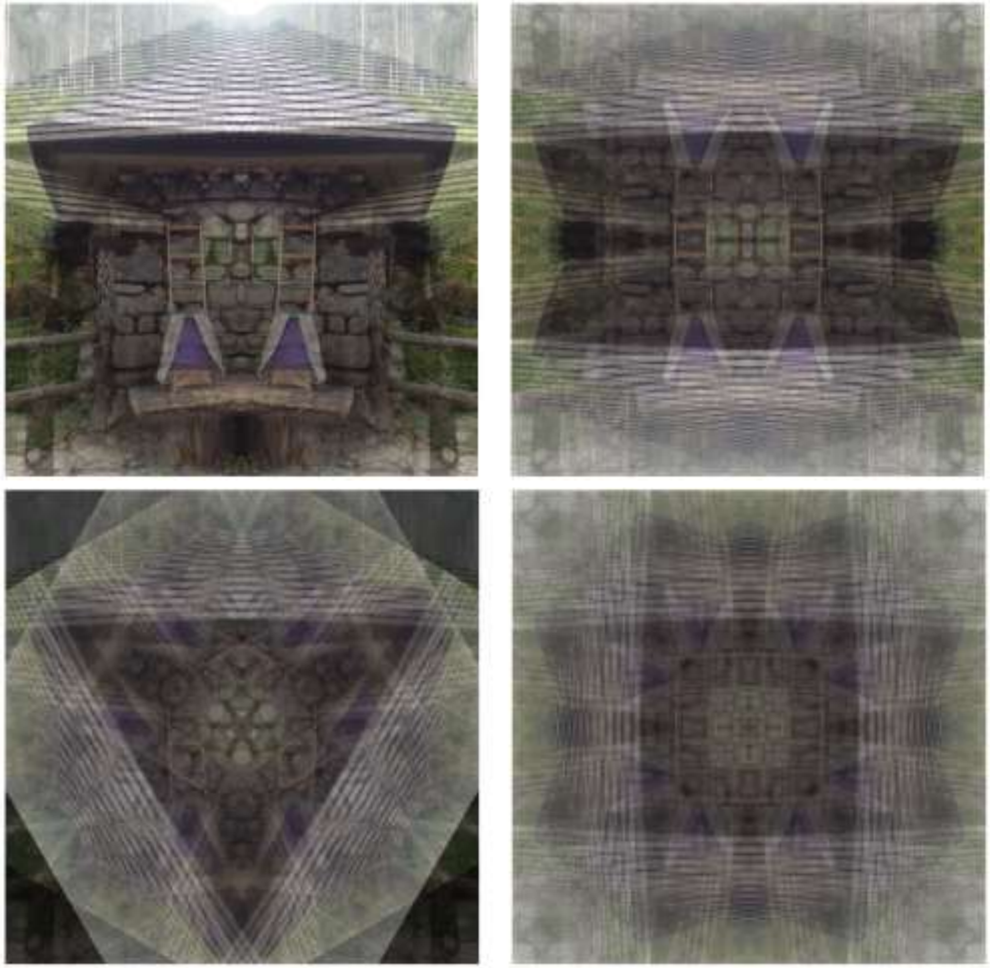
$$S \equiv C_N = \{h \in \mathcal{I} | h(r,\theta) = h(r,\theta + 2\pi/N)\}$$

Invariants to N-fold dihedral symmetry PSF

for any finite N, D_N is not closed under convolution

The closure property is preserved only if
the angle α is known and fixed for the whole S

Invariants to N-fold dihedral symmetry PSF



Invariants to N-fold dihedral symmetry PSF

$$Q_N^\alpha f = P_N((f + f^\alpha)/2)$$

$$L_N^\alpha(p,q) = c_{pq} - \frac{1}{2c_{00}} \sum_{\substack{j=0 \\ 0<j+k \\ (j-k)/N \text{ is integer}}}^{p} \sum_{k=0}^{q} \binom{p}{j} \binom{q}{k} L_N^\alpha(p-j, q-k) \cdot (c_{jk} + c_{kj} e^{2i\alpha(p-q)})$$

Limitation - the axis orientation must be known and fixed

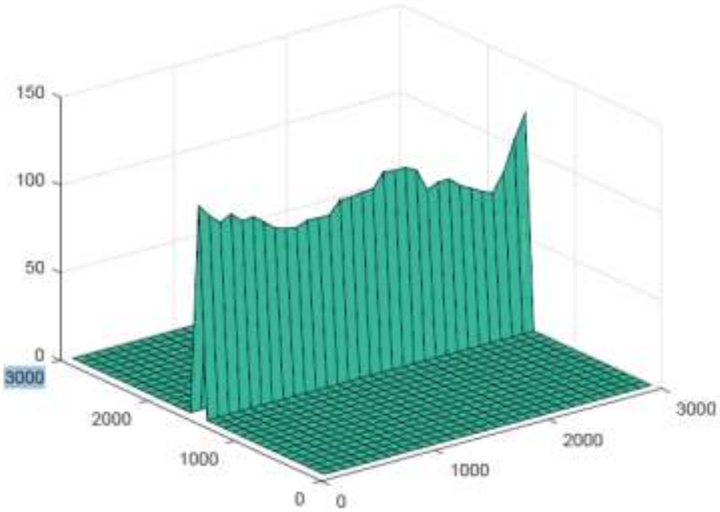
Invariants to directional blur PSF

“motion” blur

$$h(x, y) = h_1(x)\delta(y)$$

S - set of all functions of the given form

Invariants to directional blur PSF



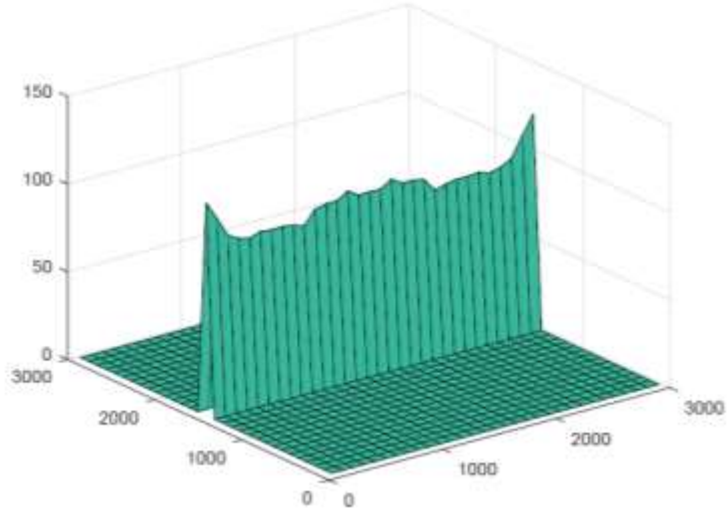
$$(Pf)(x,y) = \delta(y) \int f(x,y)\mathrm{d}y$$

$$D = \{(p,q) | q = 0\}$$

$$M(p,q) = m_{pq} - \frac{1}{m_{00}} \sum_{k=1}^{p} \binom{p}{k} M(p-k,q) m_{k,0}$$

"motion" blur – direction has to be known

Invariants to directional blur PSF



$$h_1(-x) = h_1(x)$$

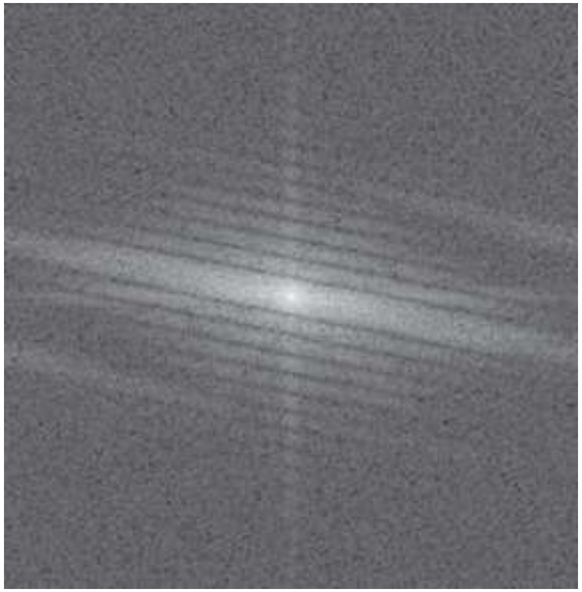
+ symmetry assumption

$$D^s = \{(p,q) | p = 2k, q = 0\}$$

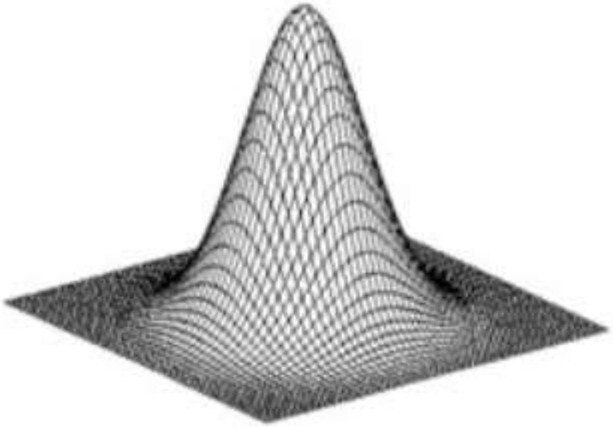
$$(P^s f)(x,y) = \delta(y)\frac{1}{2}\int (f(-x,y) + f(x,y))\mathrm{d}y$$

$$M^s(p,q) = m_{pq} - \frac{1}{m_{00}} \sum_{\substack{k=2 \\ k \text{ even}}}^{p} \binom{p}{k} M^s(p-k,q)\, m_{k,0}$$

Invariants to directional blur PSF



Invariants to Gaussian PSF



$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

$$S_G = \{aG_\sigma | \sigma \geq 0, a \neq 0\}$$

- symmetric - special case of circular symmetry blur
- asymmetric – special case of 2-fold dihedral PSF
- designed – higher discriminability

- not “image function” – no bounded support
- set of Gaussians not a vector space

Invariants to Gaussian PSF

circularly symmetric 2D Gaussian

$$c_{pq}^{(G_\sigma)} = \begin{cases} (2\sigma^2)^p p! & p = q \\ 0 & p \neq q \end{cases}$$

$$P_G f(x,y) = c_{00}^{(f)} G_s(x,y) \equiv \frac{c_{00}^{(f)}}{2\pi s^2} e^{-\frac{x^2+y^2}{2s^2}}$$

$$s^2 = c_{11}^{(f)} / 2c_{00}^{(f)}$$

$P_G f$ has the same c_{00} and c_{11} as f

Invariants to Gaussian PSF

$$K_G(p,q)^{(f)} = c_{pq}^{(f)} - \sum_{k=1}^{q} k! \binom{p}{k} \binom{q}{k} \left(\frac{c_{11}^{(f)}}{c_{00}^{(f)}} \right)^k K_G(p-k, q-k)^{(f)}$$

$$K_G(p,q)^{(f)} = \sum_{j=0}^{q} j! \binom{p}{j} \binom{q}{j} \left(-\frac{c_{11}^{(f)}}{c_{00}^{(f)}} \right)^j c_{p-j,q-j}^{(f)}$$

If $p = q = 1$ → the invariant is zero

Combined moment invariants

set *S* of the admissible PSFs - closed also w.r.t. the considered geometric transformations

N-FRS blur ($N > 2$) + affine transform
dihedral blur + general rotation
Gaussian radially symmetric blur + affine transform
directional blur + rotation

any blur + translation and/or uniform scaling

Combined moment invariants rotation

N-FRS blur, based on complex moments

radial Gaussian blur, based on complex moments

$$K'(p,q) = e^{-i(p-q)\alpha} \cdot K(p,q)$$

$$I = \prod_{j=1}^{n} K(p_j, q_j)^{k_j} \qquad \sum_{j=1}^{n} k_j(p_j - q_j) = 0$$

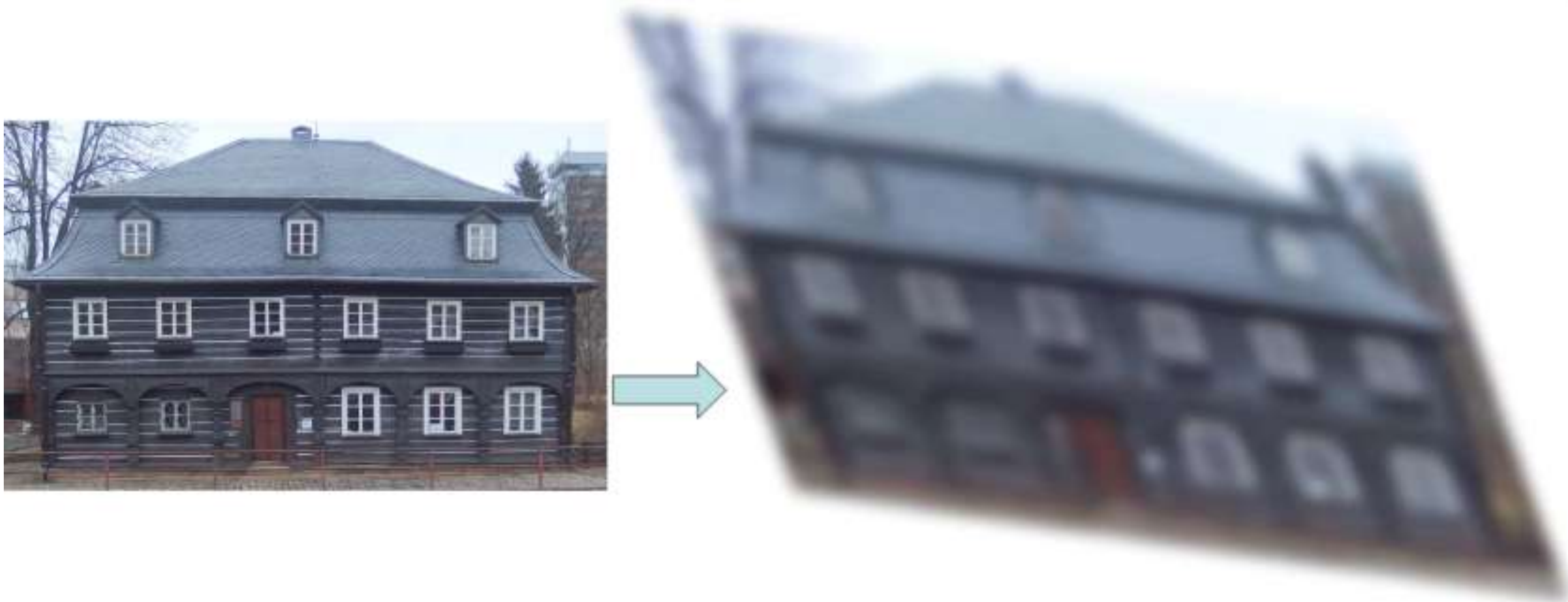
$$K(p,q)K(1,2)^{p-q}$$

Combined moment invariants dihedral

restrict the admissible rotation angles to integer multiples of π / N

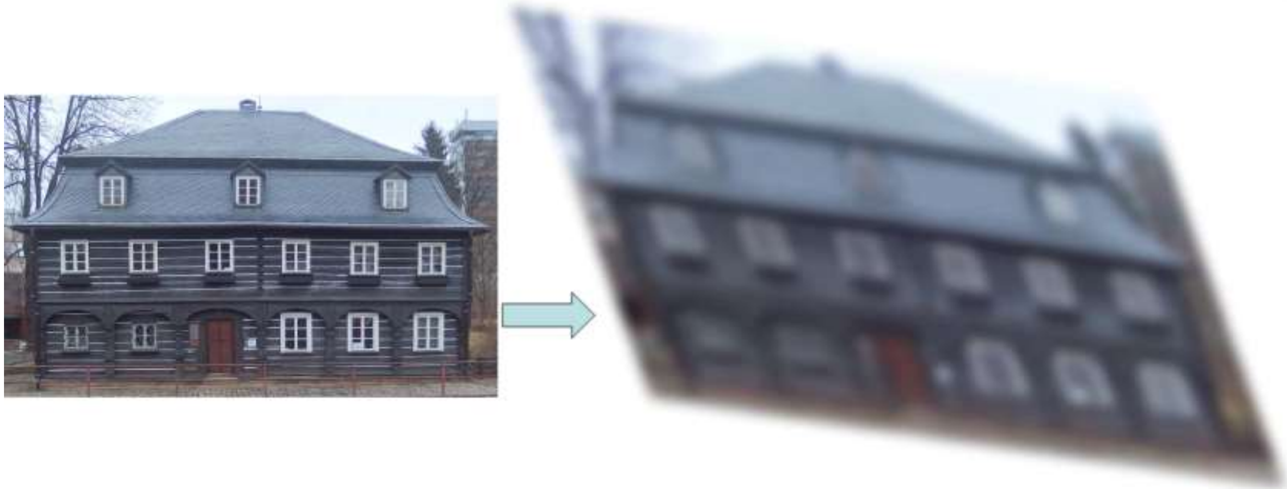
$$L_N^{\alpha}(p,q)' = e^{-i(p-q)\theta} \cdot L_N^{\alpha}(p,q)$$

Invariants to convolution and affine transform



centrosymmetric PSF
other not closed under AT

Invariants to convolution and affine transform



$I(\mu_{00},\ldots,\mu_{PQ})$ affine moment invariant

$C(p,q)$ blur invariant

$I(C(0,0),\ldots,C(P,Q))$ combined blur-affine invariant CBAI

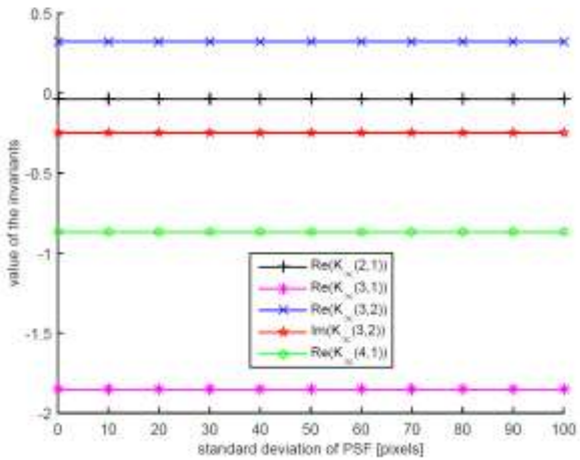
Reported applications of convolution and combined invariants

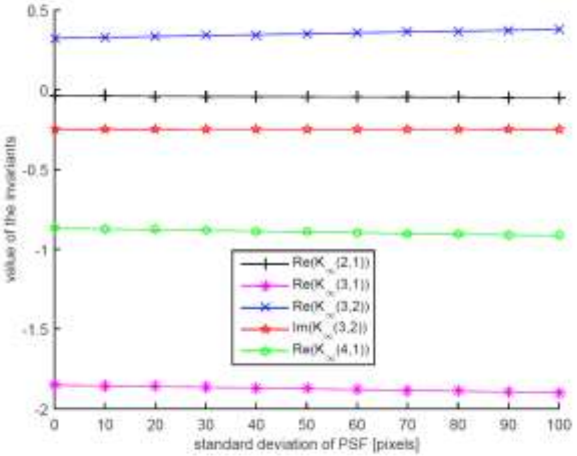
- Character/digit/symbol recognition in the presence of vibration, linear motion or out-of-focus blur

- Robust image registration (medical, satellite, …)

- Detection of image forgeries

Robustness of blur invariants

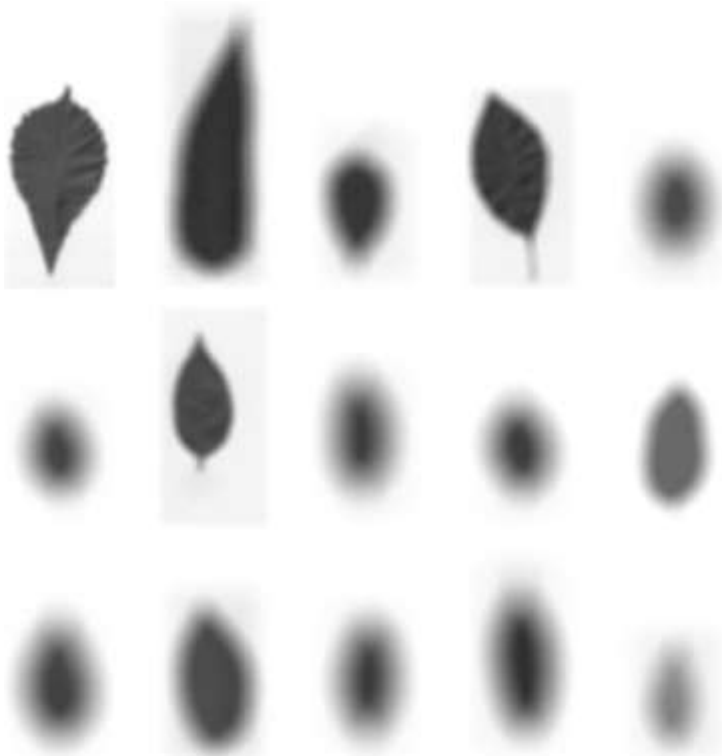




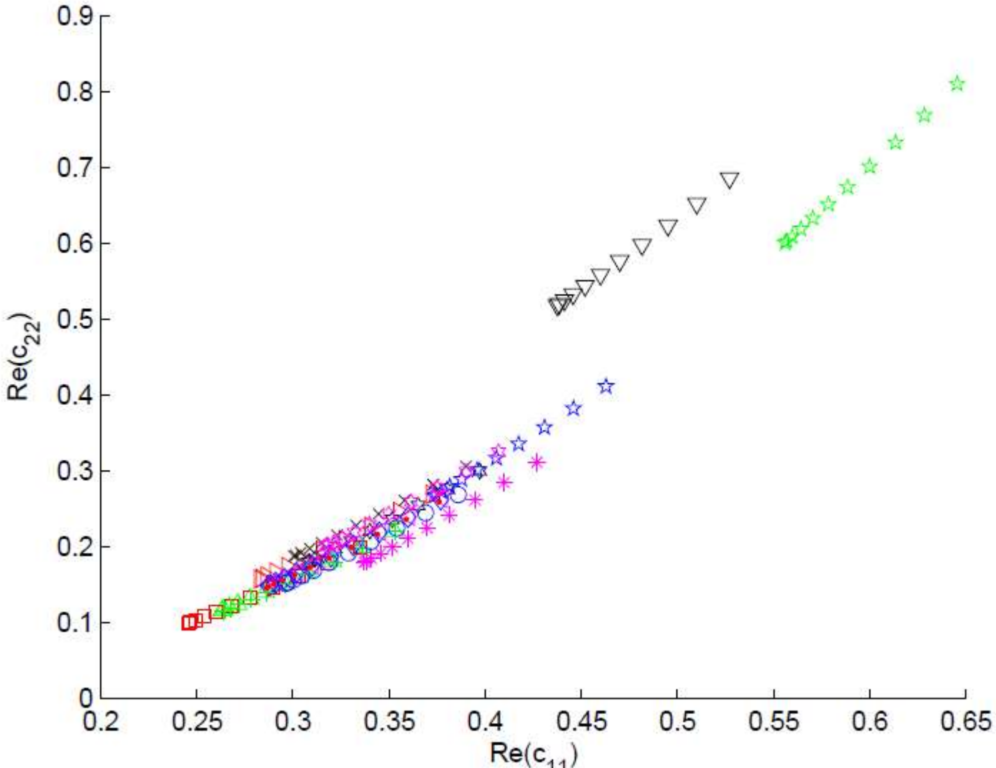
Leaf recognition system MEW2010

10 000 tree leaves
100 classes (species)
Recognition based solely on the contour

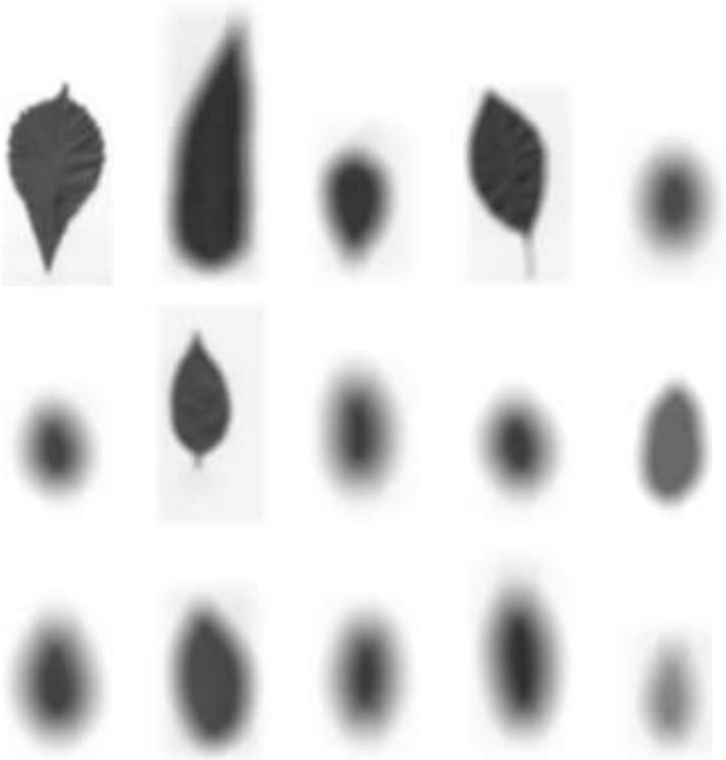
Leaf recognition system MEW2010



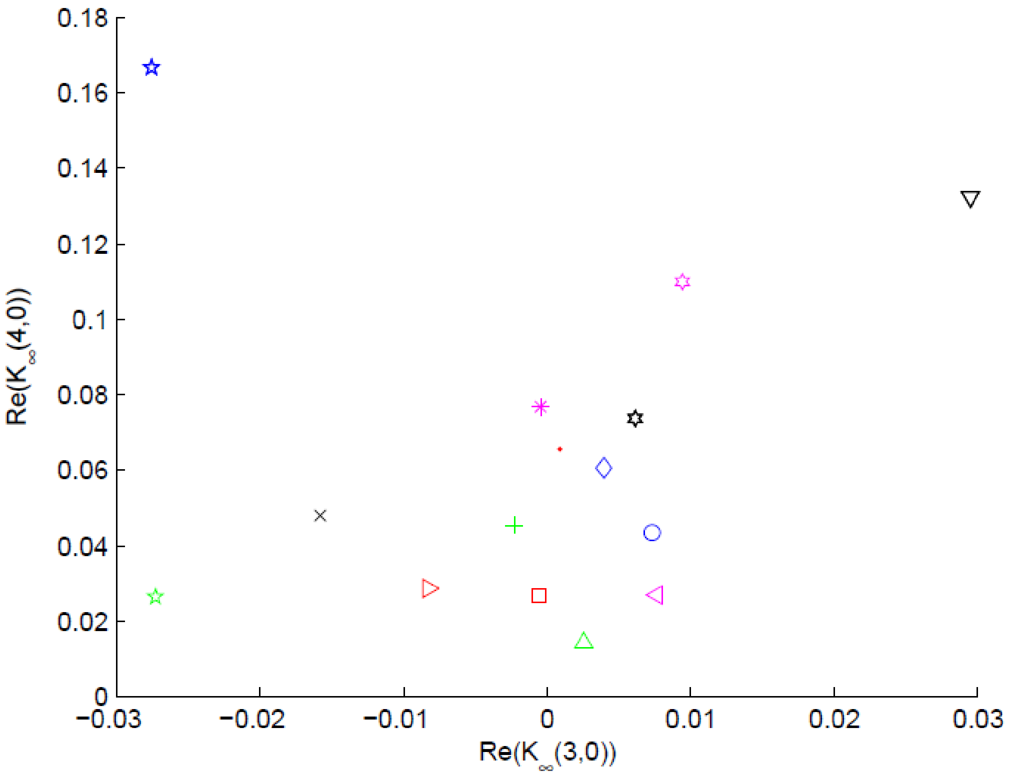
Plain moments



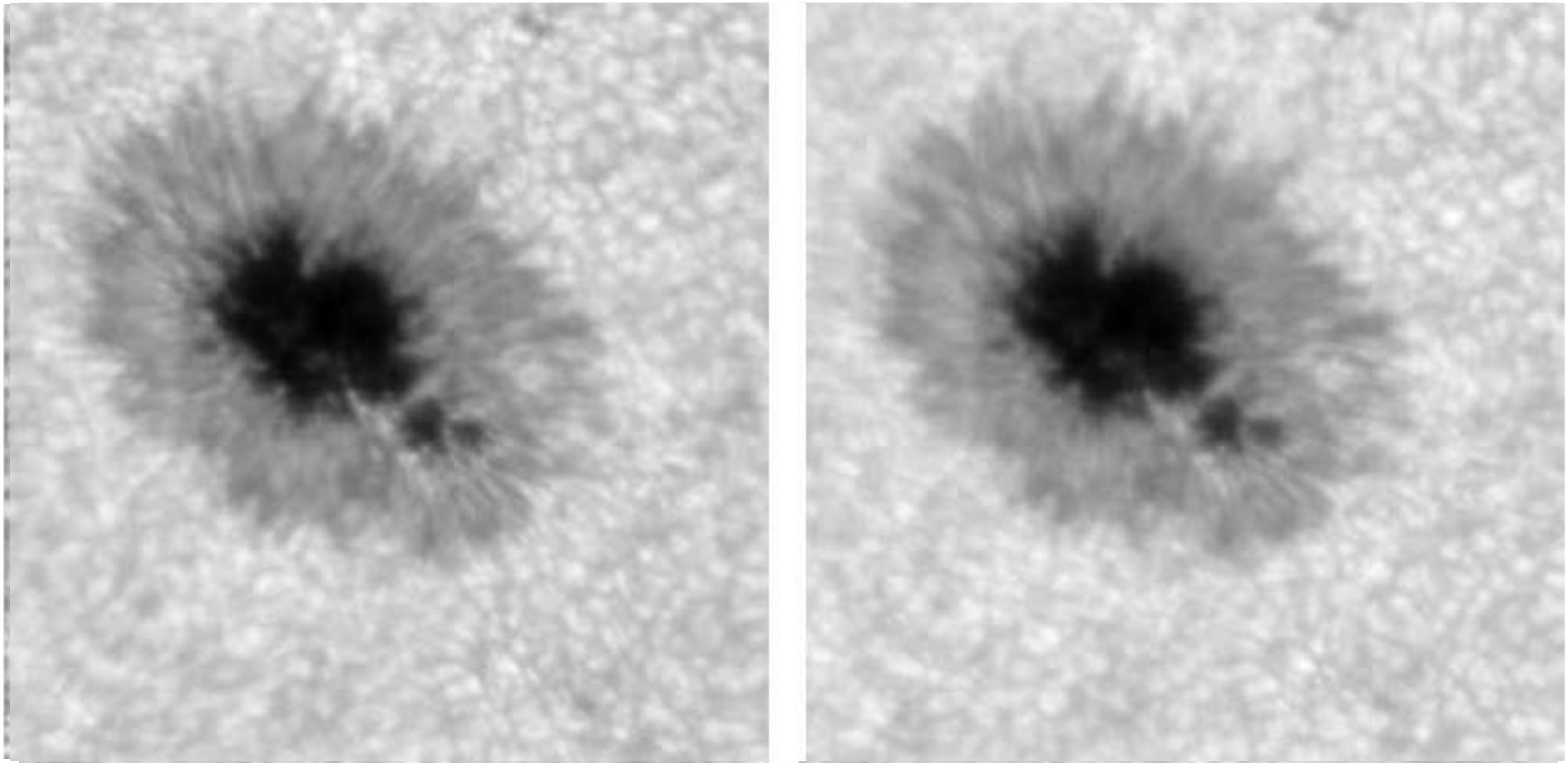
Leaf recognition system MEW2010



Invariants



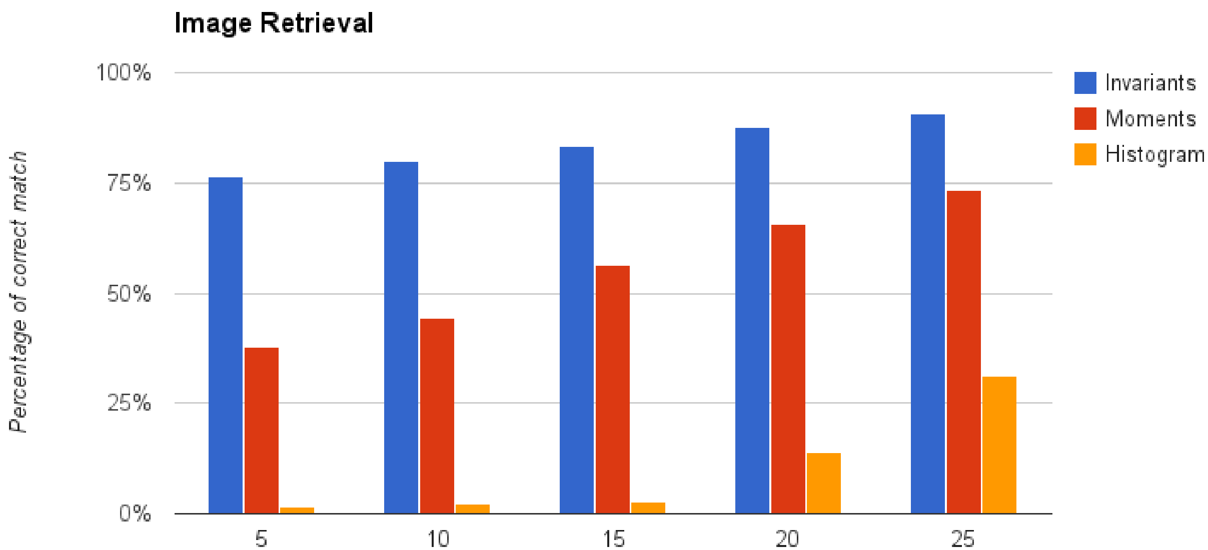
Recognition abilities of blur invariants



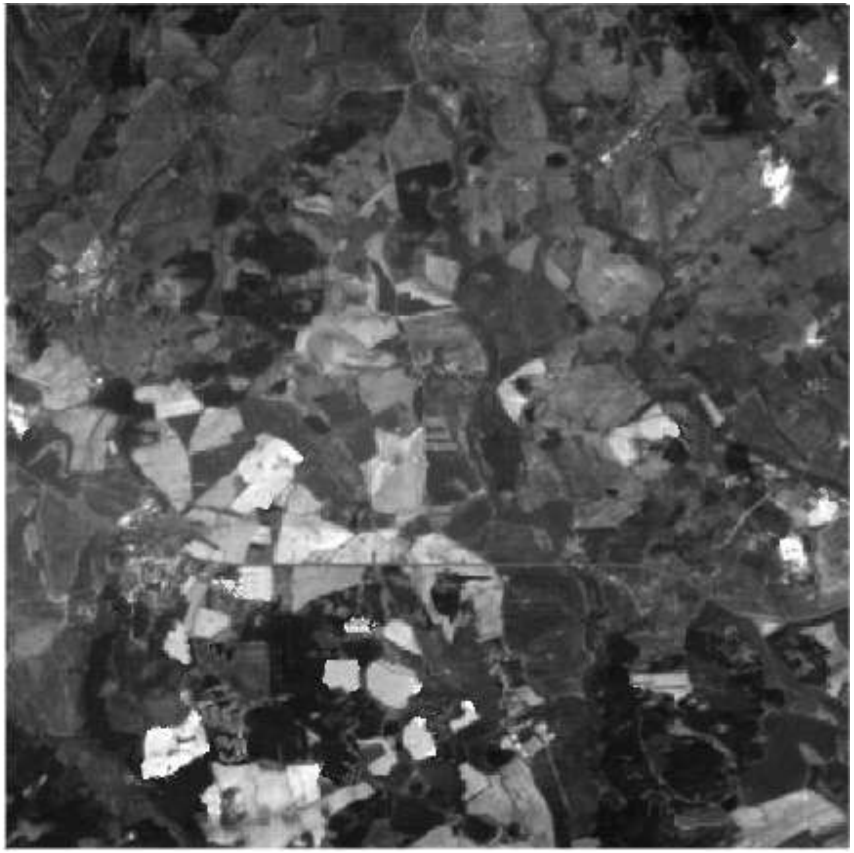
Recognition abilities of blur invariants

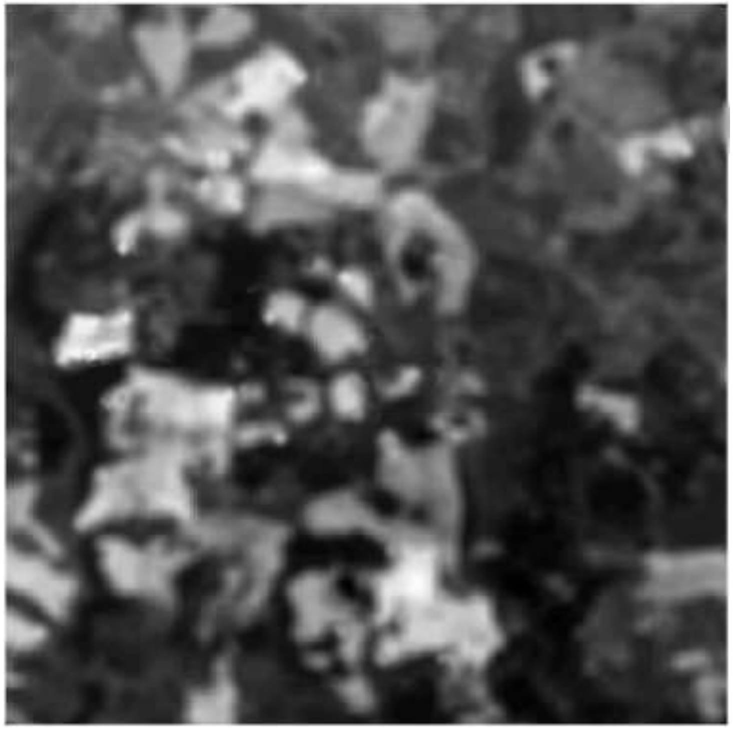
Image	Mean error	Standard deviation
	Cross-correlation	
(b)	7.30	3.82
(c)	7.29	3.81
(d)	7.28	3.80
	Gaussian blur invariants	
(b)	0.88	0.45
(c)	0.90	0.47
(d)	0.85	0.44

Blur invariants and CBIR

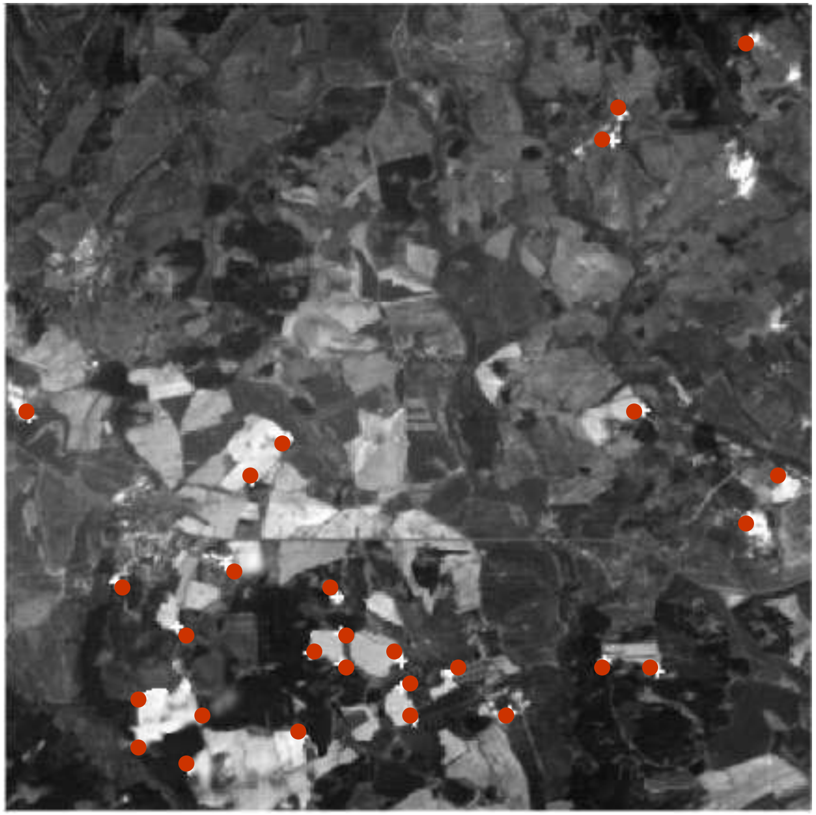


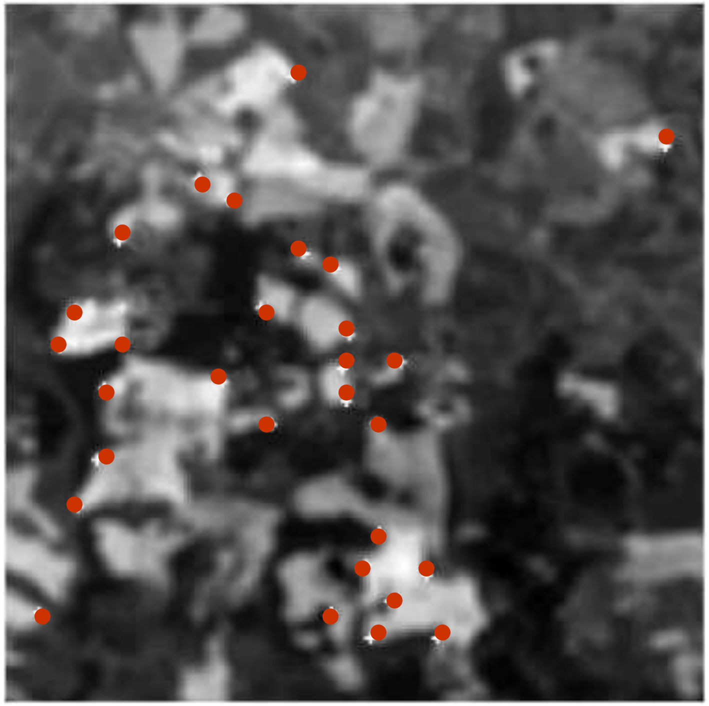
Satellite image registration by combined invariants





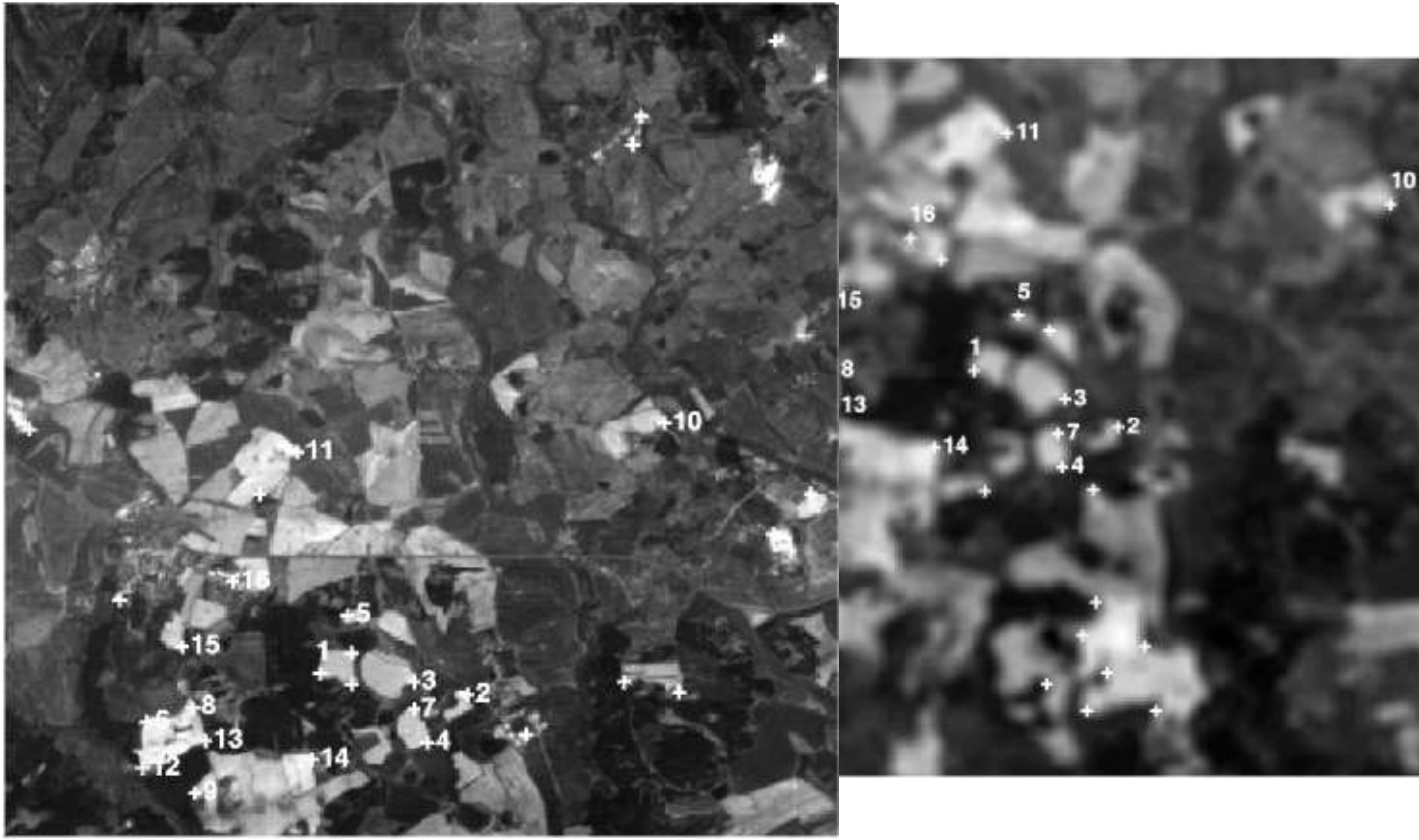
Control point detection



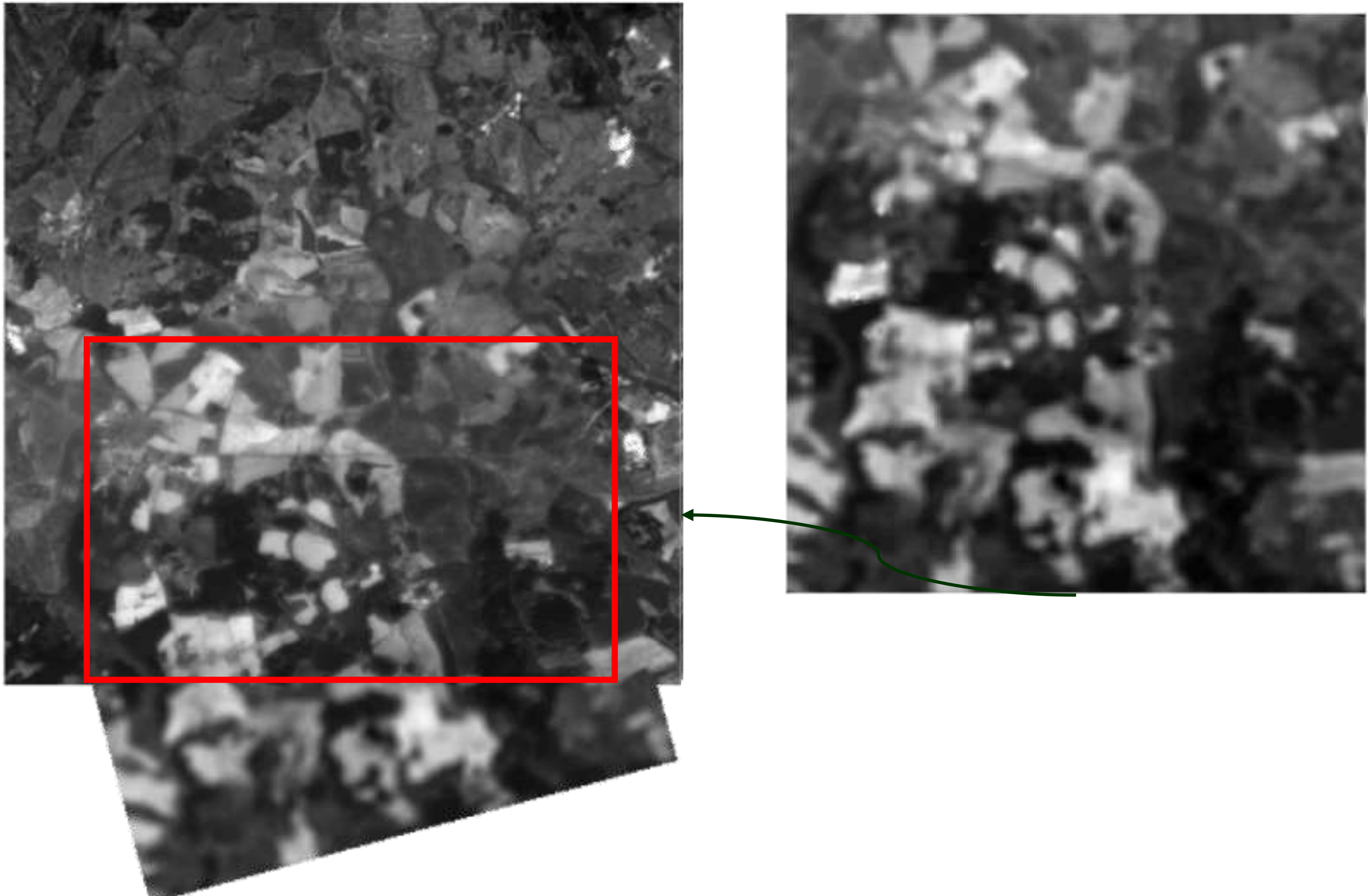


$$\min_{k,m} \text{distance}((\,v1_k, v2_k, v3_k, \ldots\,), (\,v1_m, v2_m, v3_m, \ldots\,))$$

Control point matching



Registration result



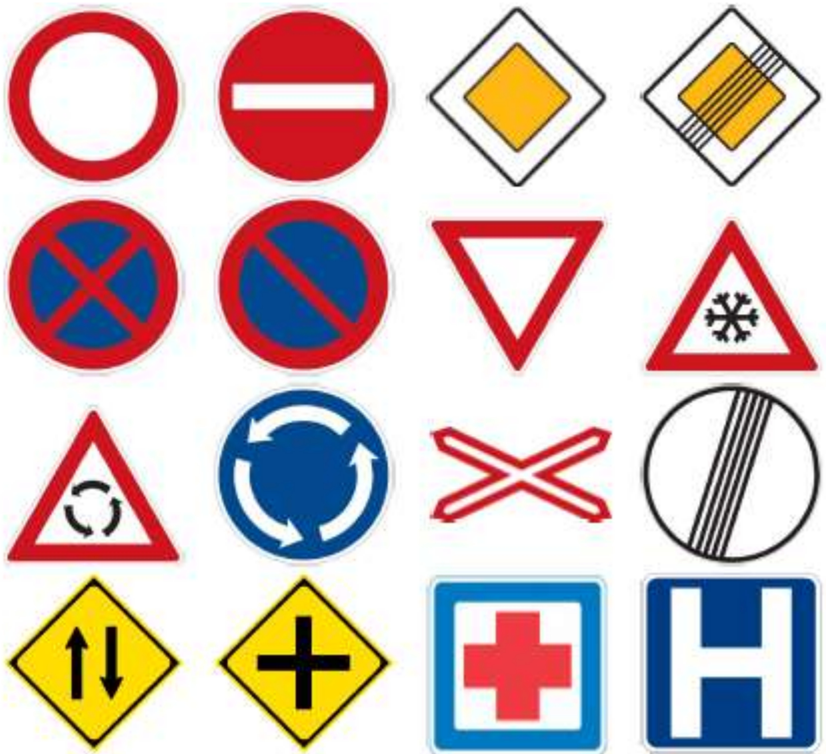
Multichannel blind deconvolution

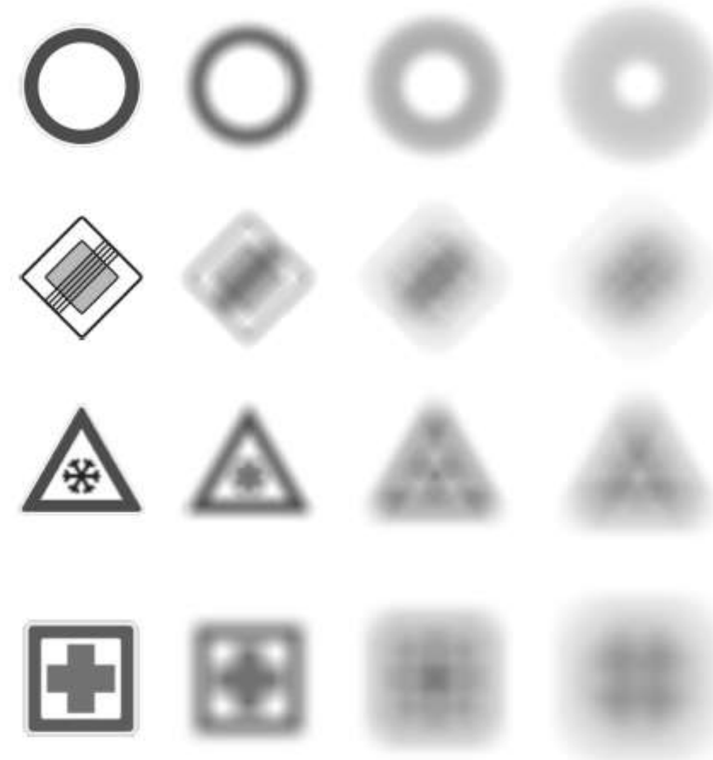
Multichannel blind deconvolution

The Poor Fisherman, Paul Gauguin, 1896

Detecting forgeries

Recognition of symmetric objects

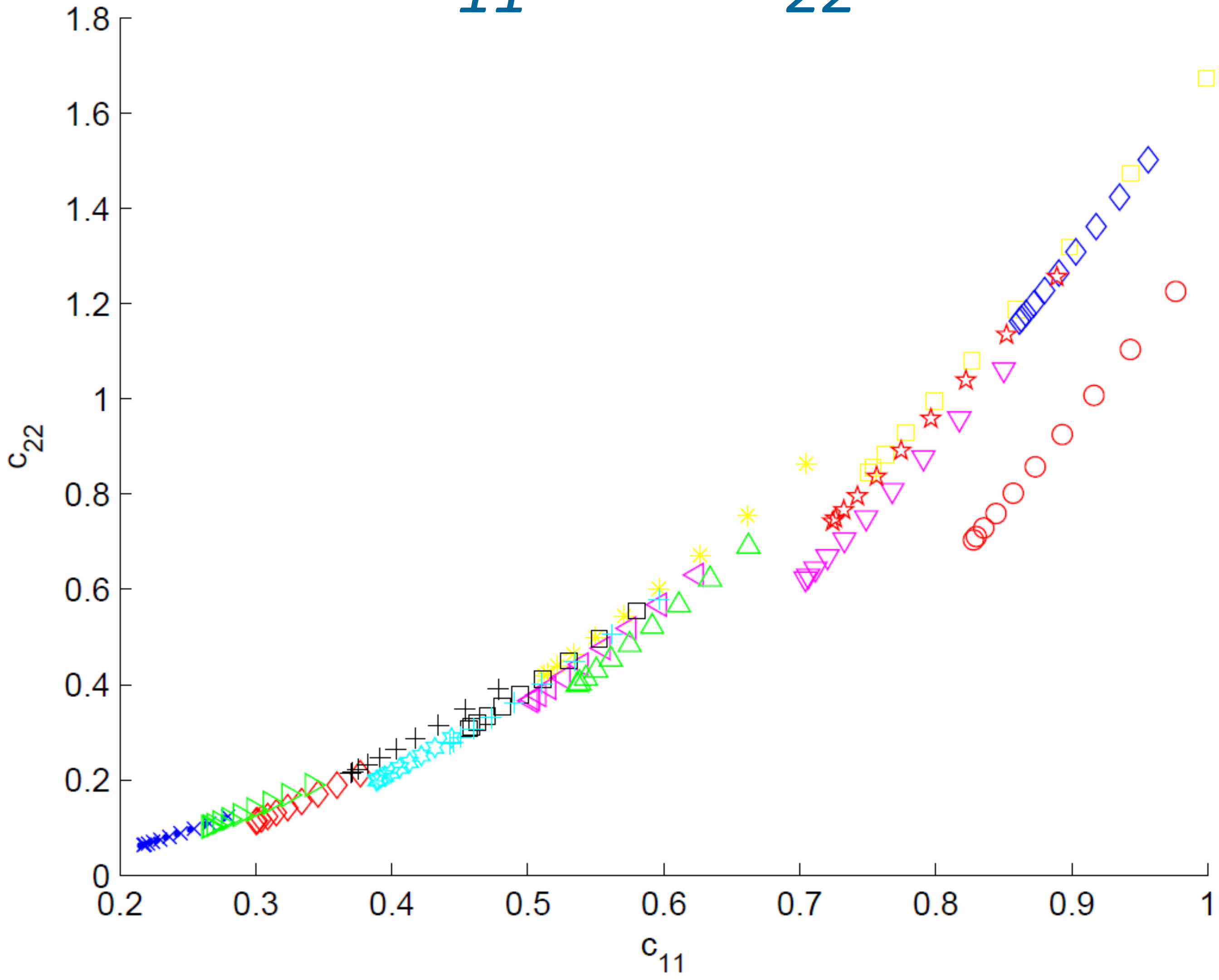




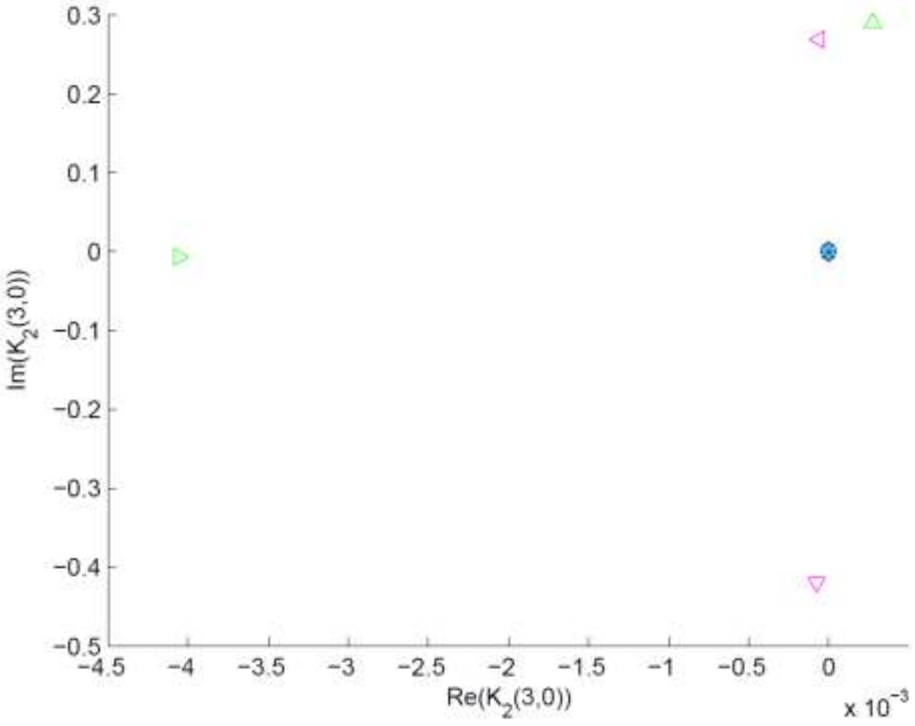
7 signs of 2-FRS
4 signs of 4-FRS

4 signs of 3-FRS
1 sign having ∞-FRS

Recognition of symmetric objects c_{11} and c_{22}



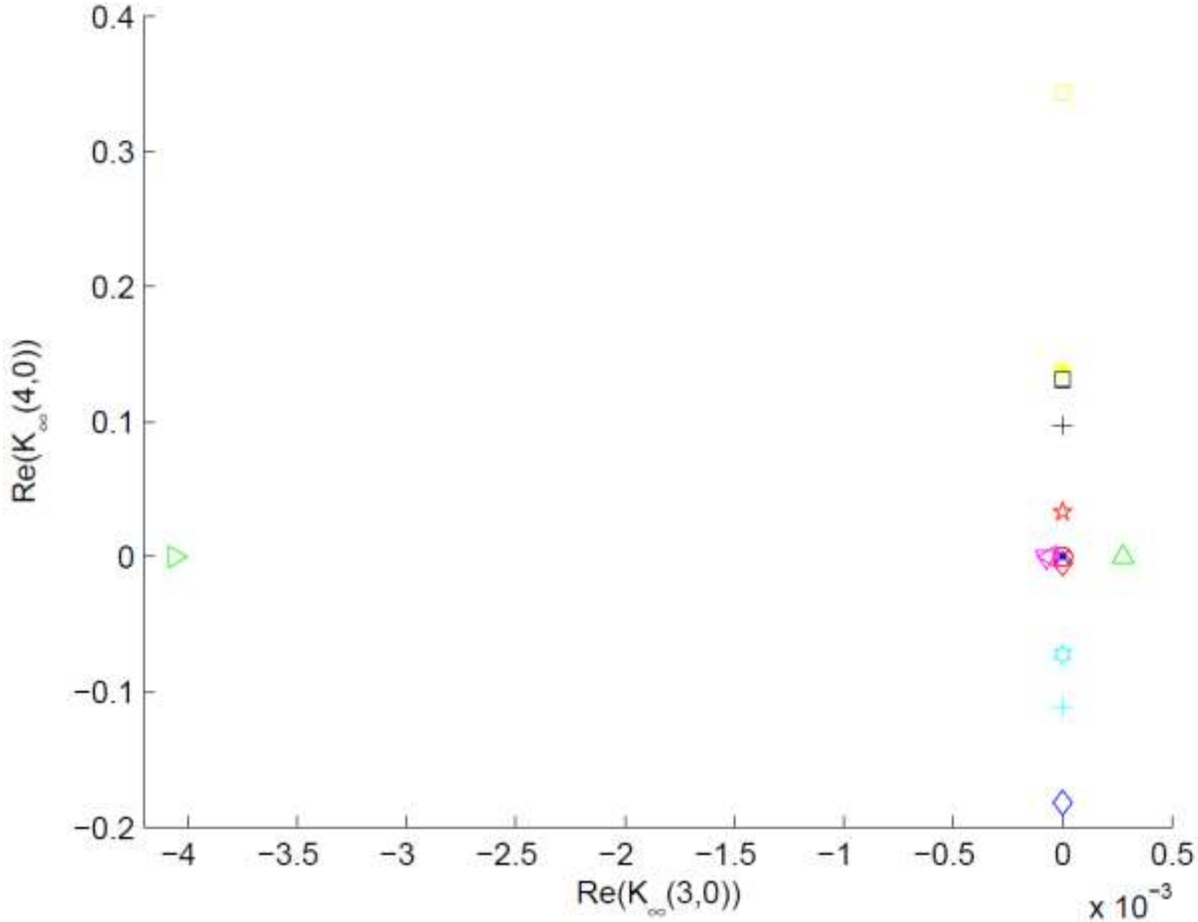
Recognition of symmetric objects
Real and Im of $K_2(3,0)$



signs with even-fold symmetry lie in its nullspace

Recognition of symmetric objects

Real and Im of $K_\infty(3,0)$



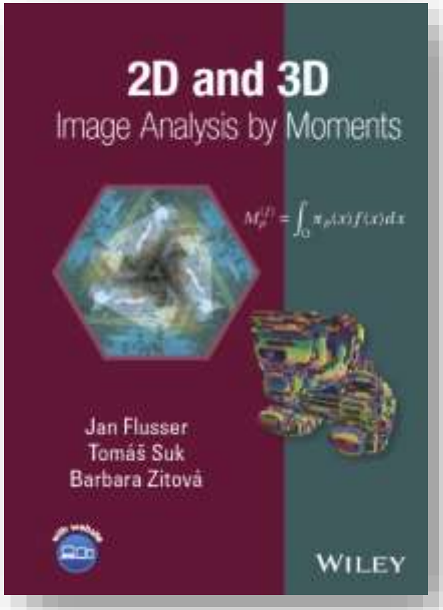
Reconstruction versus Invariants

- Whole image is needed - >

  reconstruction

- Scene analysis, object detection ->

  invariants



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Thank you…