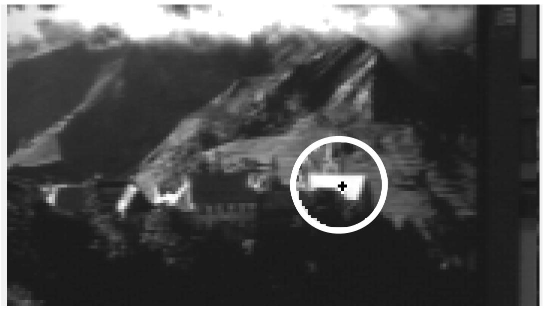
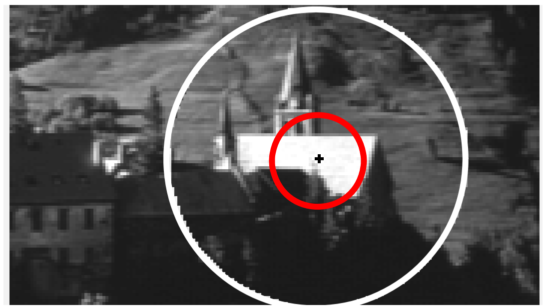
Overview

- Introduction to local features
- Harris interest points + SSD, ZNCC, SIFT
- **Scale & affine invariant interest point detectors**
- Evaluation and comparison of different detectors
- Region descriptors and their performance

Scale invariance - motivation

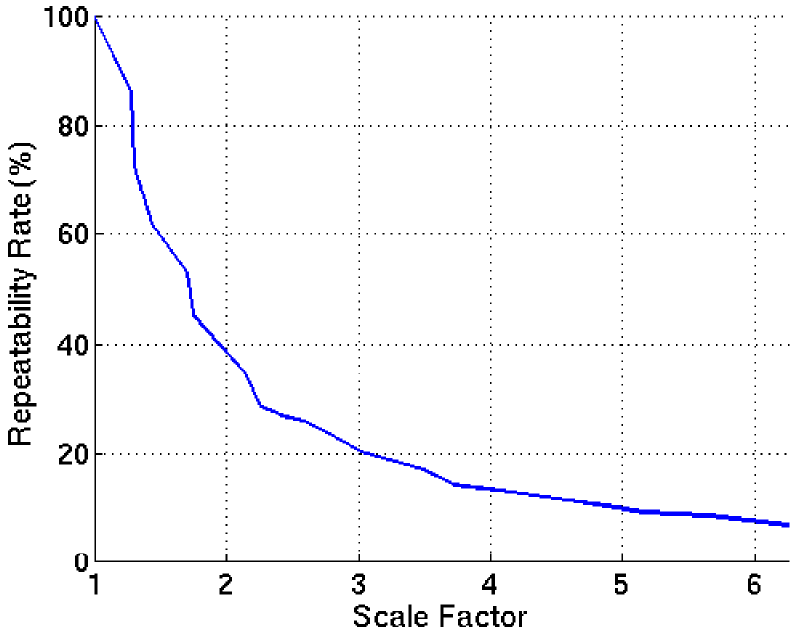
- Description regions have to be adapted to scale changes

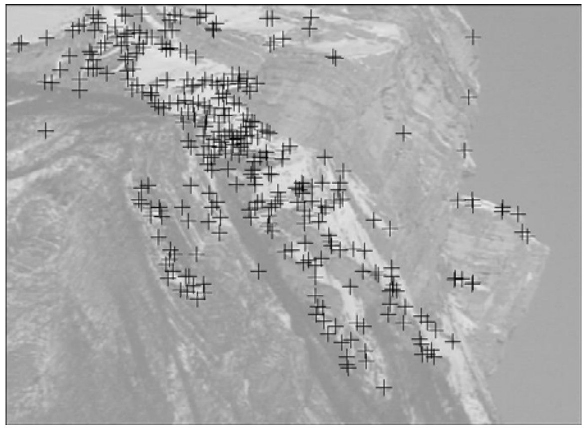


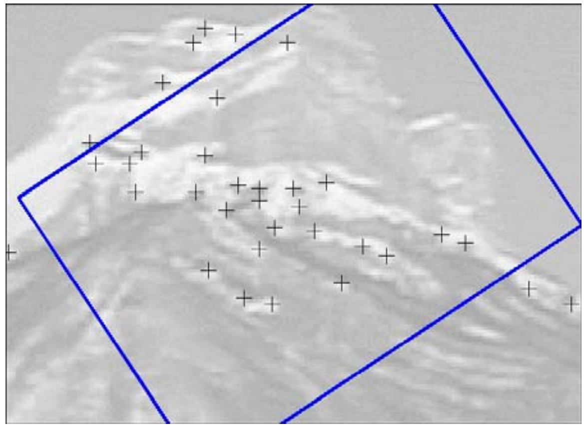


- Interest points have to be repeatable for scale changes

Harris detector + scale changes







Repeatability rate

$$R(\varepsilon) = \frac{|\{(\mathbf{a}_i, \mathbf{b}_i) \mid dist(H(\mathbf{a}_i), \mathbf{b}_i) < \varepsilon\}|}{\max(|\mathbf{a}_i|, |\mathbf{b}_i|)}$$

Scale adaptation

Scale change between two images

$$I_1\begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = I_2\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = I_2\begin{pmatrix} sx_1 \\ sy_1 \end{pmatrix}$$

Scale adapted derivative calculation

Scale adaptation

Scale change between two images

$$I_1\begin{pmatrix}x_1\\y_1\end{pmatrix}=I_2\begin{pmatrix}x_2\\y_2\end{pmatrix}=I_2\begin{pmatrix}sx_1\\sy_1\end{pmatrix}$$

Scale adapted derivative calculation

$$I_1\begin{pmatrix}x_1\\y_1\end{pmatrix}\otimes G_{i_1\ldots i_n}(\sigma)=\boldsymbol{s}^{\boldsymbol{n}}I_2\begin{pmatrix}x_2\\y_2\end{pmatrix}\otimes G_{i_1\ldots i_n}(\boldsymbol{s\sigma})$$

Scale adaptation

$$G(\widetilde{\sigma}) \otimes \begin{bmatrix} L_x^2(\sigma) & L_x L_y(\sigma) \\ L_x L_y(\sigma) & L_y^2(\sigma) \end{bmatrix}$$

where $L_i(\sigma)$ are the derivatives with Gaussian convolution

Scale adaptation

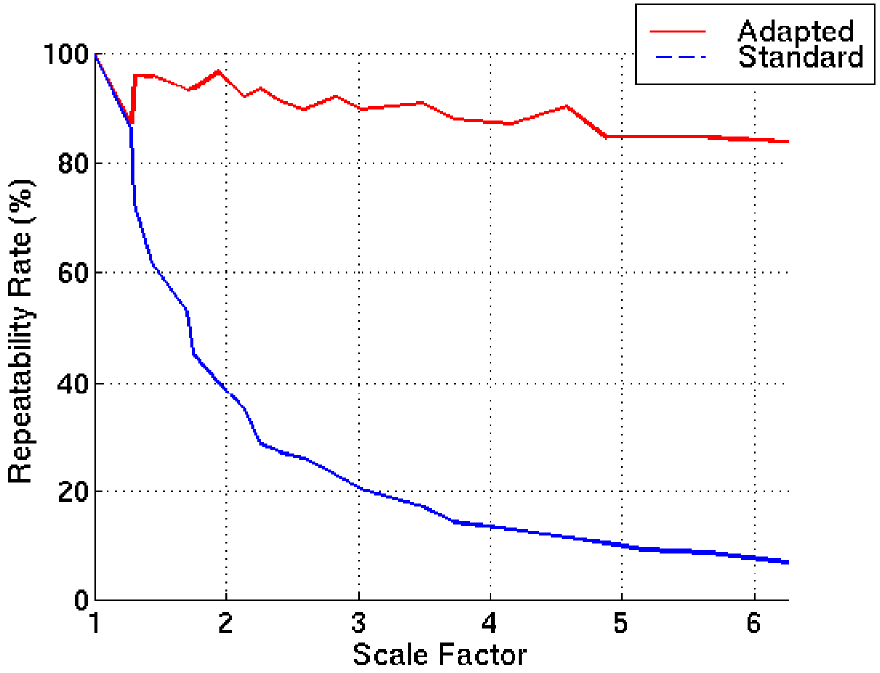
$$G(\widetilde{\sigma}) \otimes \begin{bmatrix} L_x^2(\sigma) & L_x L_y(\sigma) \\ L_x L_y(\sigma) & L_y^2(\sigma) \end{bmatrix}$$

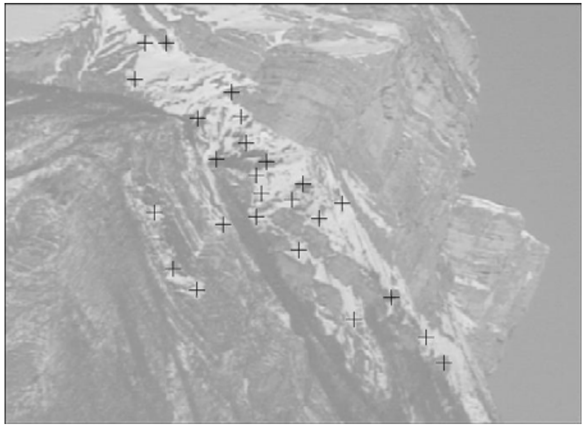
where $L_i(\sigma)$ are the derivatives with Gaussian convolution

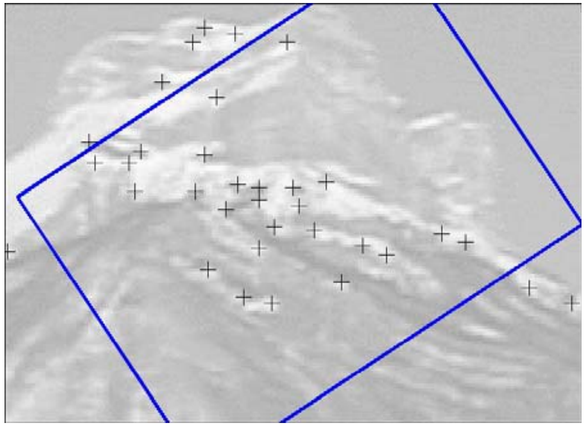
Scale adapted auto-correlation matrix

$$s^2 G(s\widetilde{\sigma}) \otimes \begin{bmatrix} L_x^2(s\sigma) & L_x L_y(s\sigma) \\ L_x L_y(s\sigma) & L_y^2(s\sigma) \end{bmatrix}$$

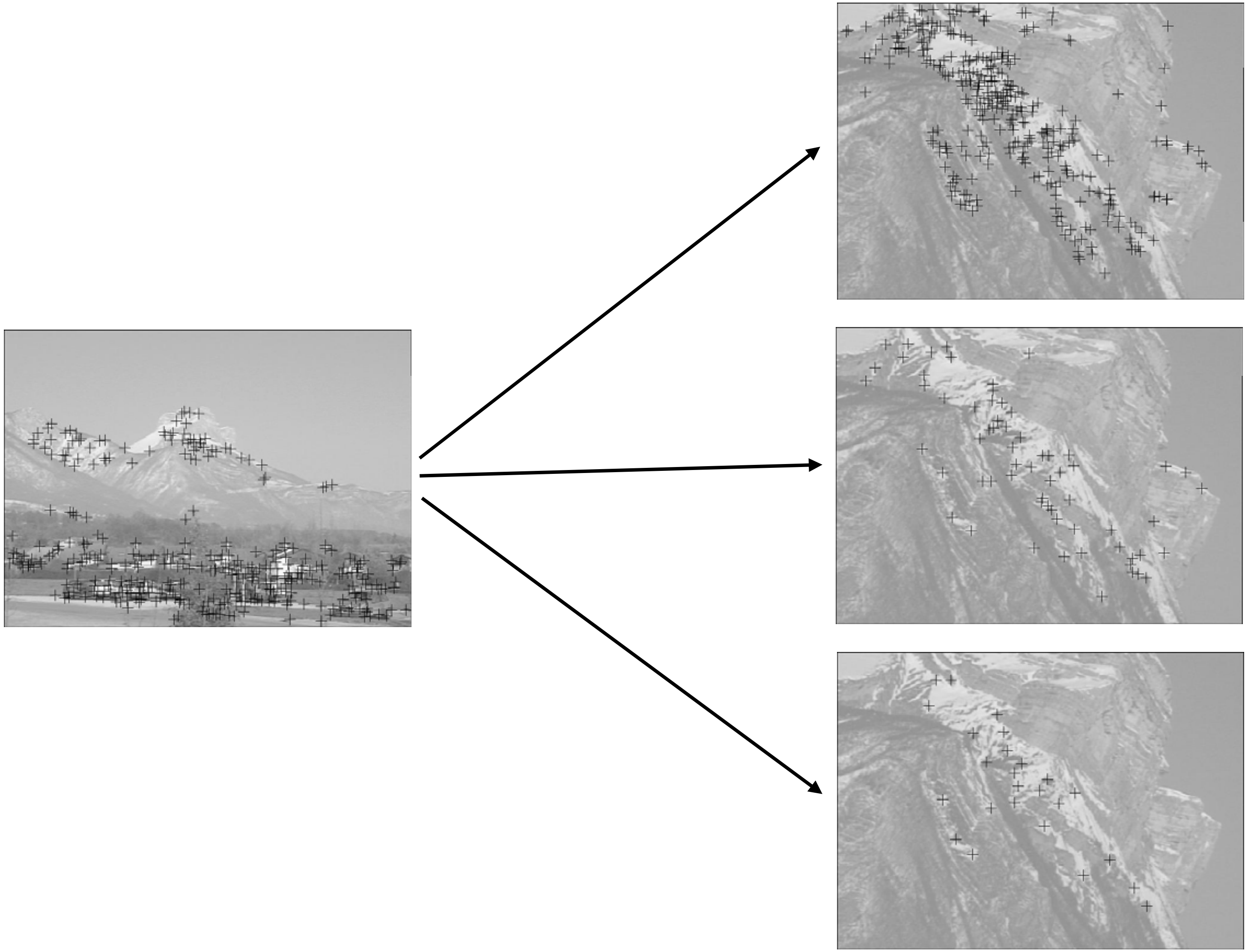
Harris detector – adaptation to scale







Multi-scale matching algorithm

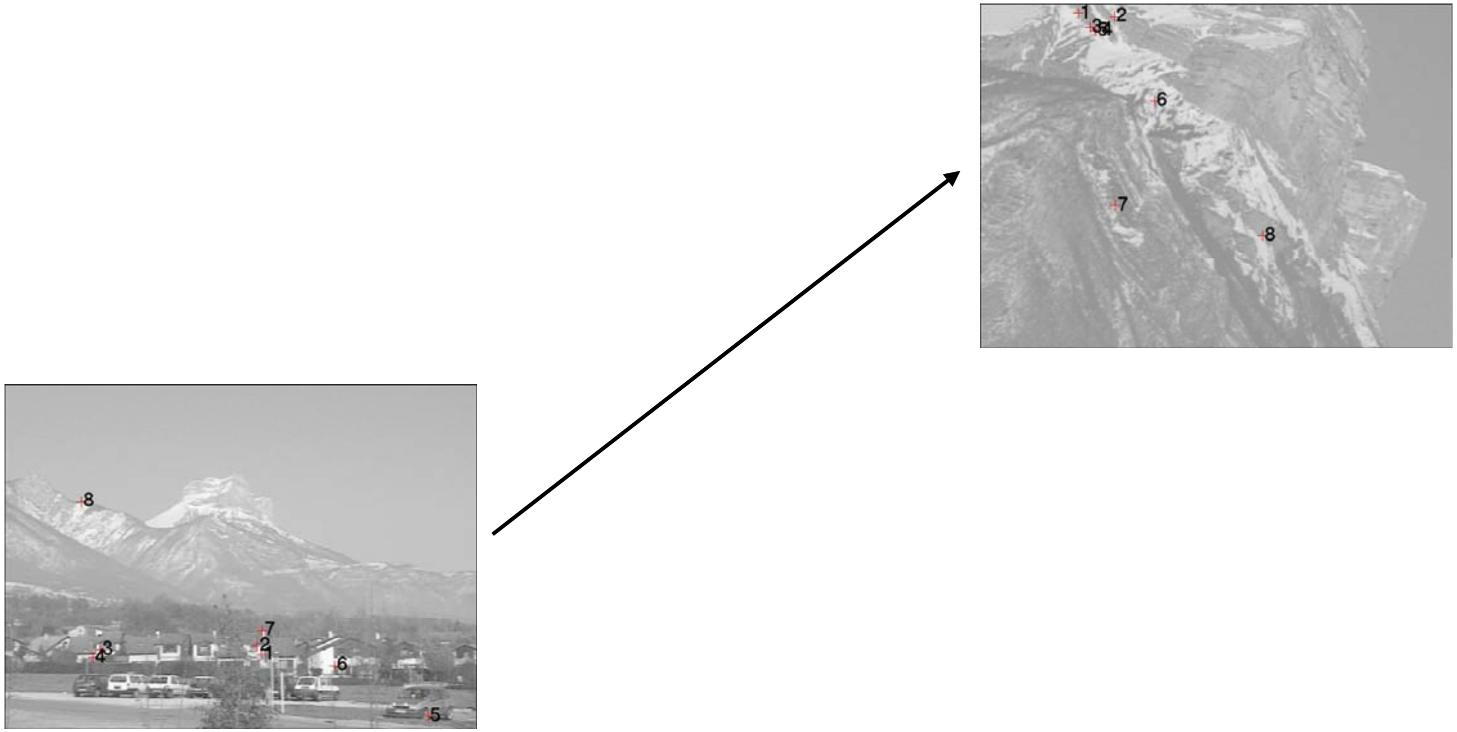


$s = 1$

$s = 3$

$s = 5$

Multi-scale matching algorithm

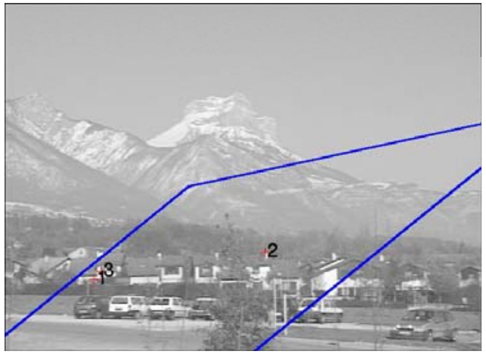


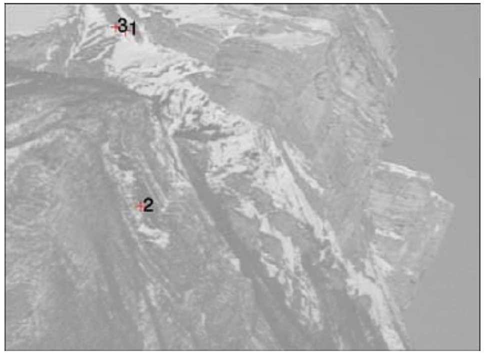
$s = 1$

8 matches

Multi-scale matching algorithm

Robust estimation of a global affine transformation

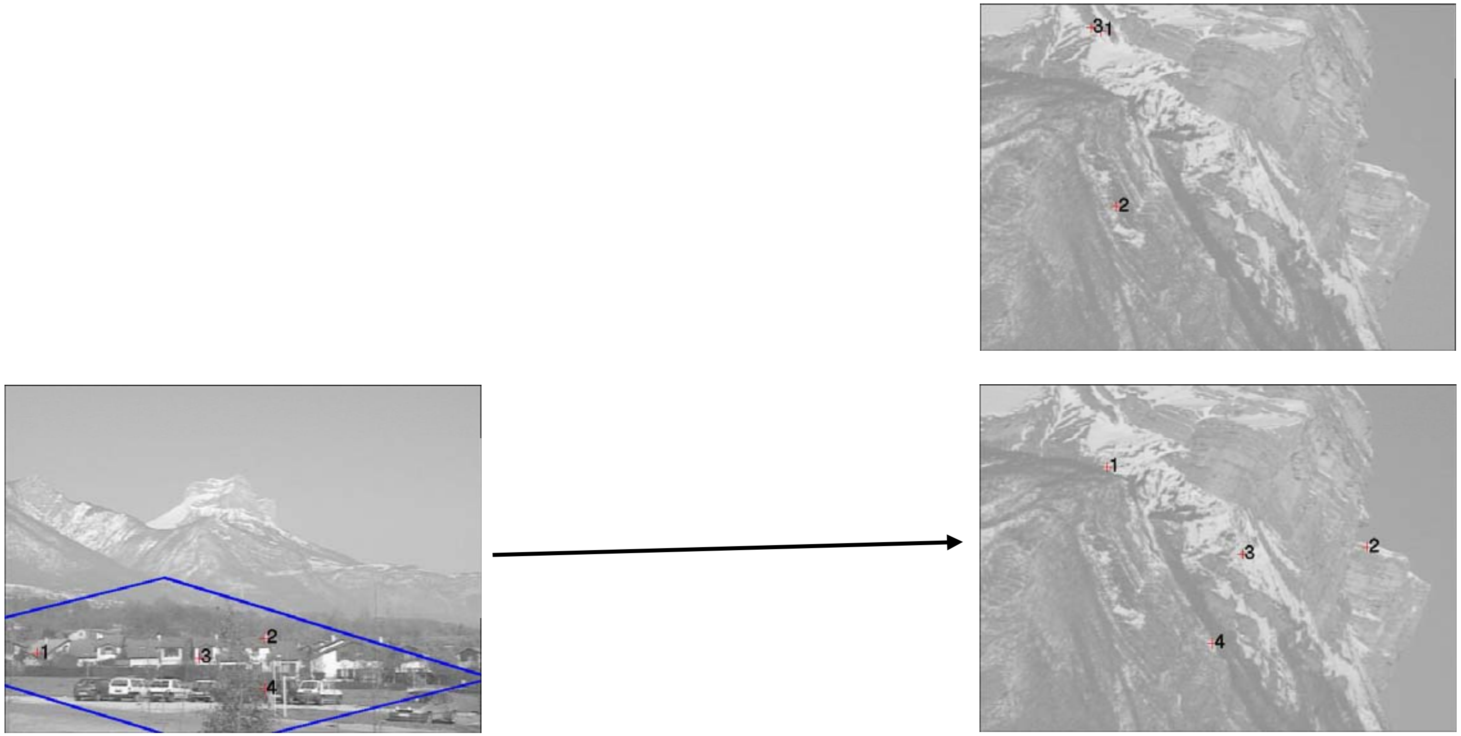




$s = 1$

3 matches

Multi-scale matching algorithm



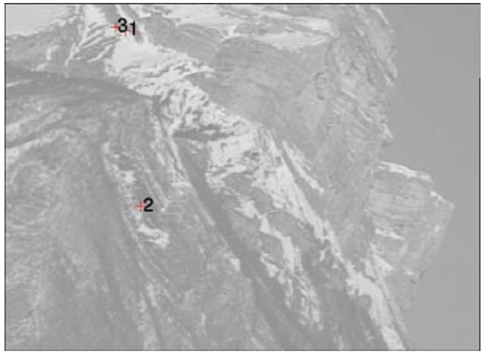
$s = 1$

3 matches

$s = 3$

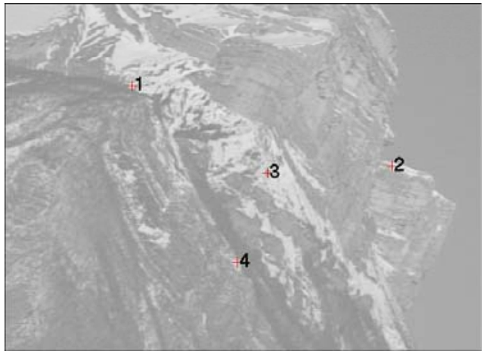
4 matches

Multi-scale matching algorithm



$s = 1$

3 matches

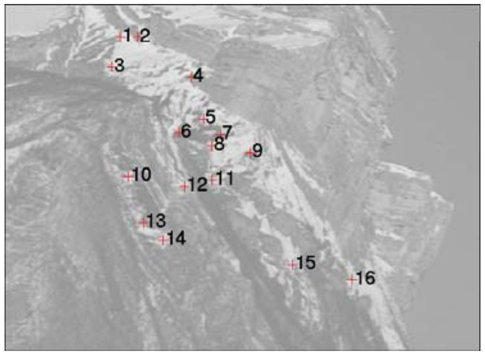


$s = 3$

4 matches

highest number of matches

correct scale

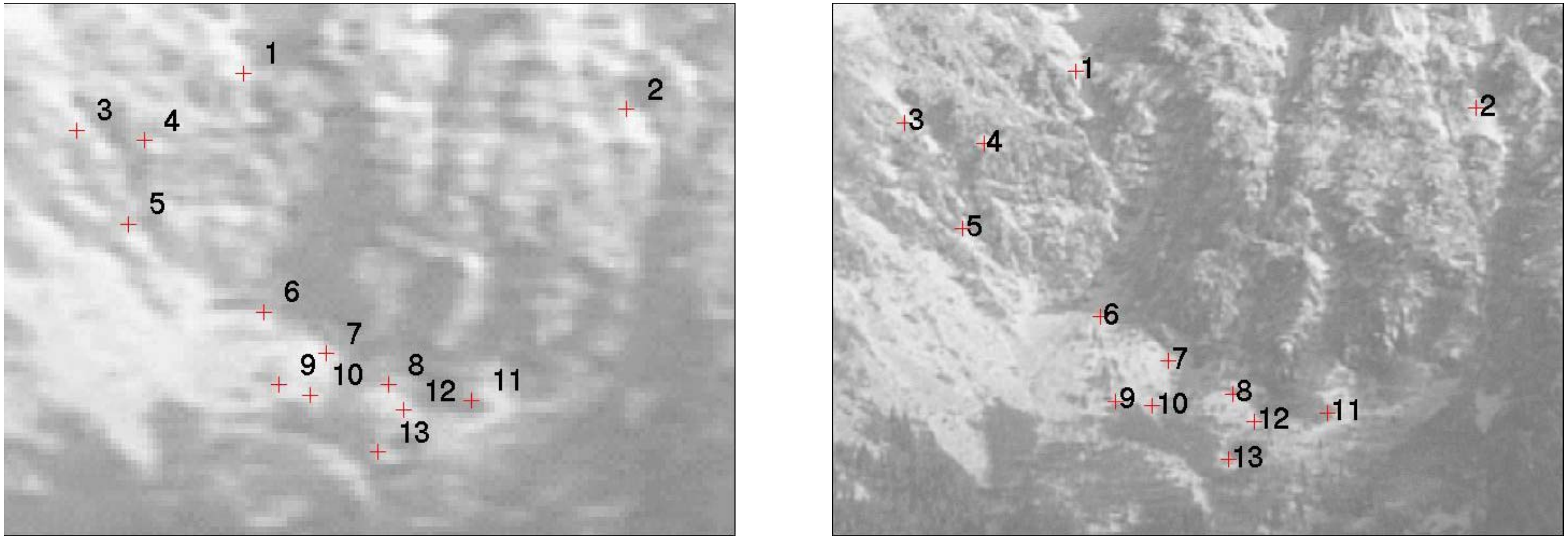


$\boxed{s = 5 \quad \text{16 matches}}$

Matching results

Scale change of 5.7

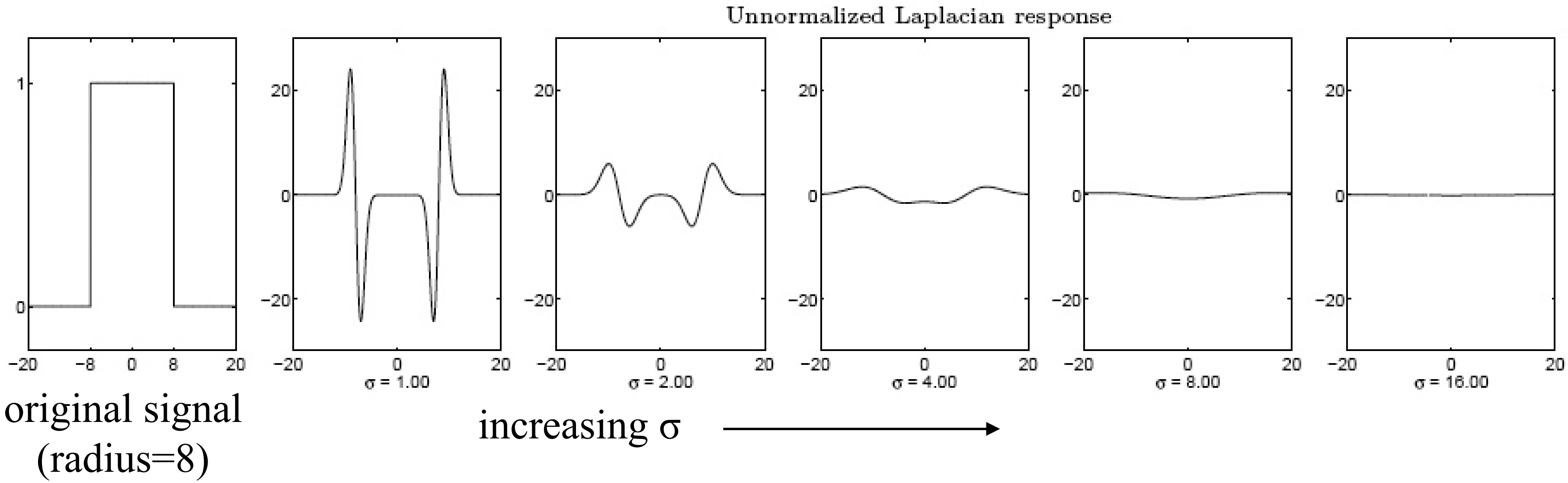
Matching results



100% correct matches (13 matches)

Scale selection

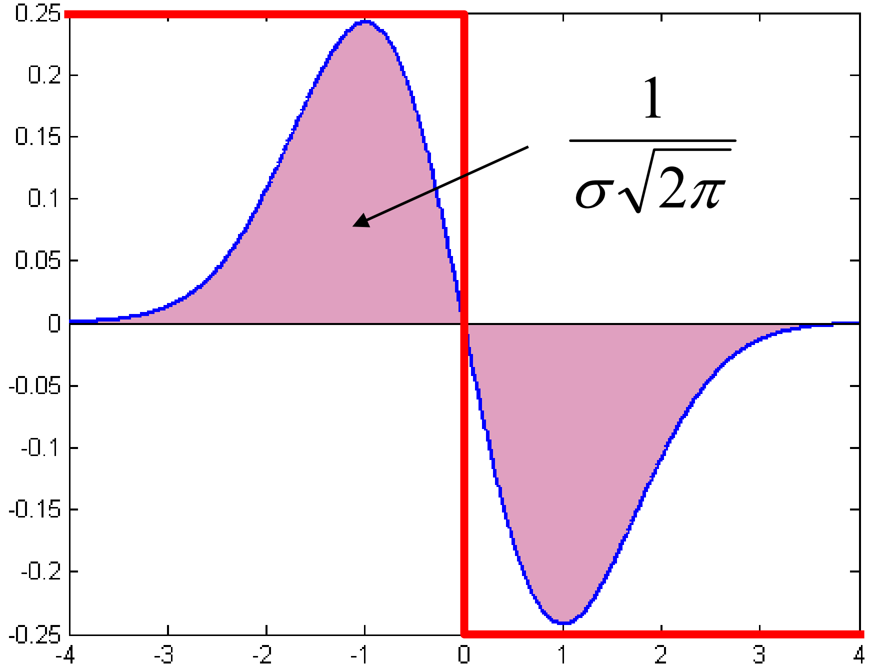
- We want to find the characteristic scale of the blob by convolving it with Laplacians at several scales and looking for the maximum response
- However, Laplacian response decays as scale increases:



Why does this happen?

Scale normalization

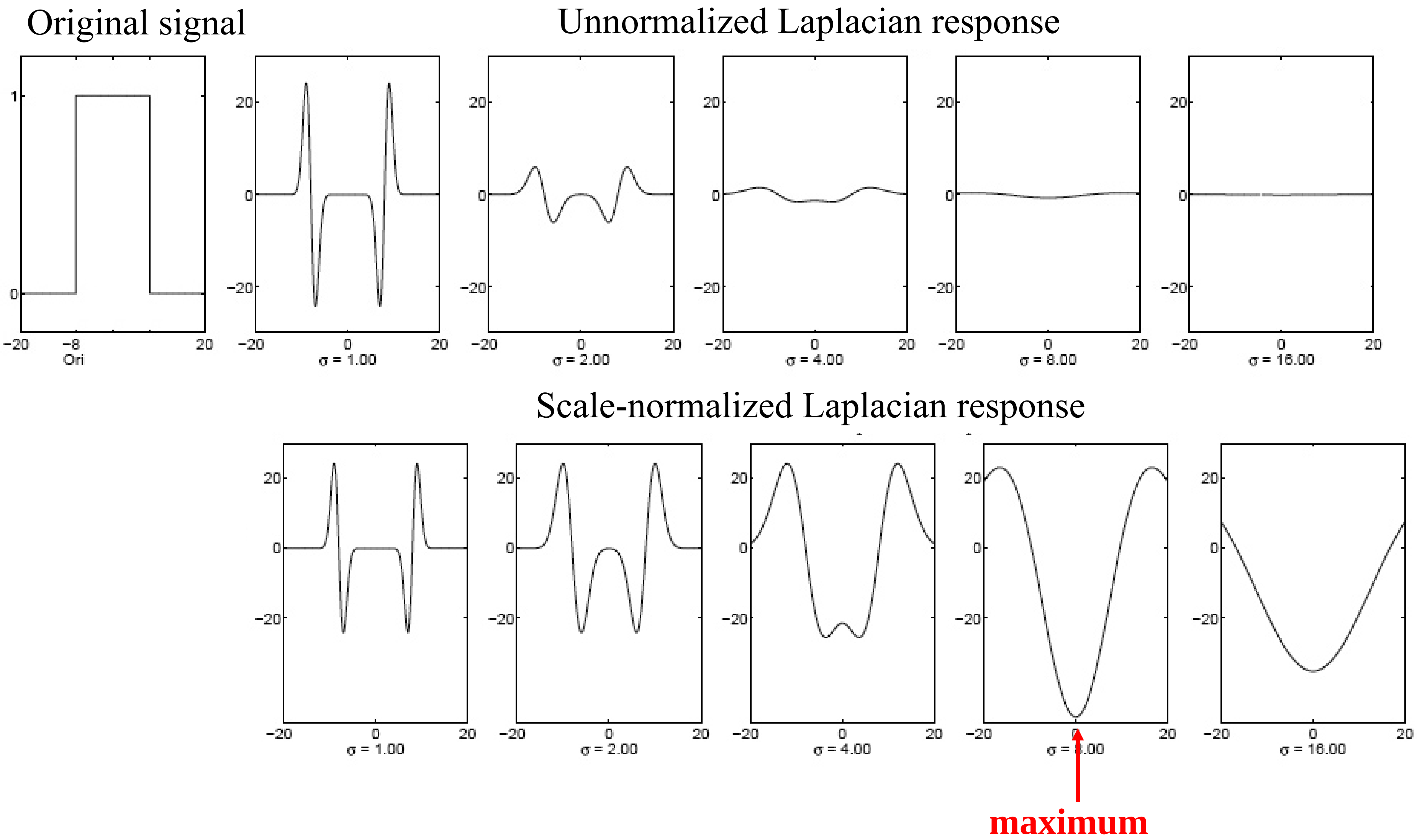
- The response of a derivative of Gaussian filter to a perfect step edge decreases as σ increases



Scale normalization

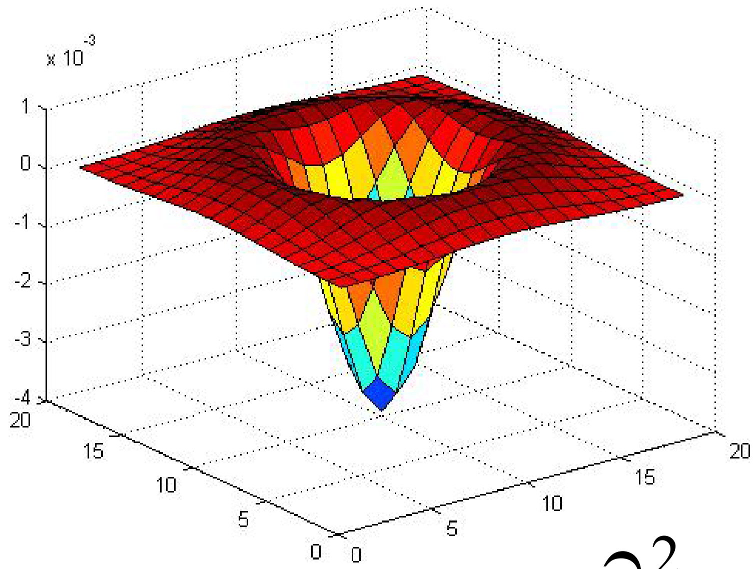
- The response of a derivative of Gaussian filter to a perfect step edge decreases as σ increases
- To keep response the same (scale-invariant), must multiply Gaussian derivative by σ
- Laplacian is the second Gaussian derivative, so it must be multiplied by σ^2

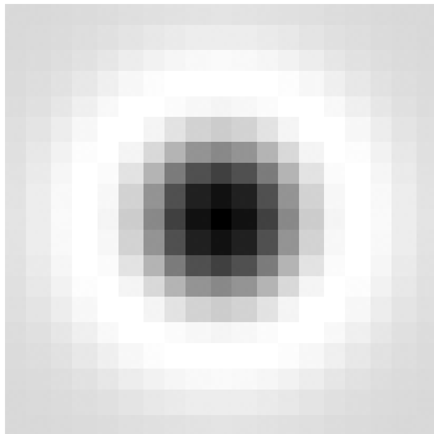
Effect of scale normalization



Blob detection in 2D

- Laplacian of Gaussian: Circularly symmetric operator for blob detection in 2D

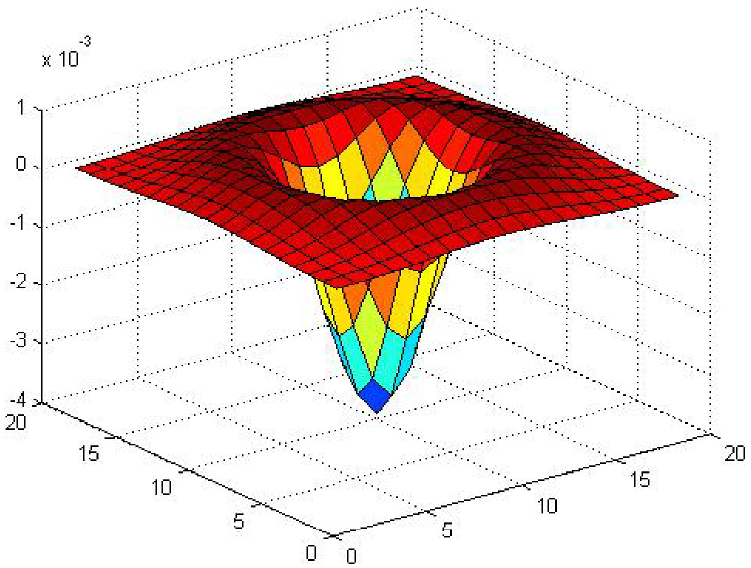


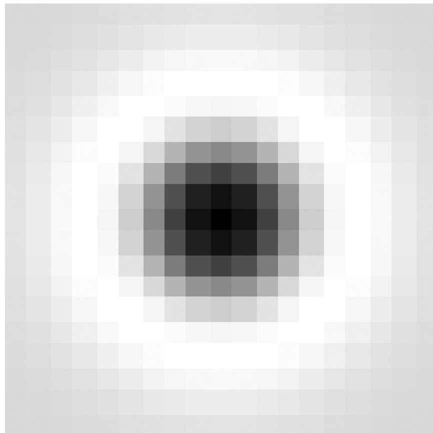


$$\nabla^2 g = \frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}$$

Blob detection in 2D

- Laplacian of Gaussian: Circularly symmetric operator for blob detection in 2D





Scale-normalized: $$\nabla^2_{\text{norm}} g = \sigma^2 \left(\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2} \right)$$

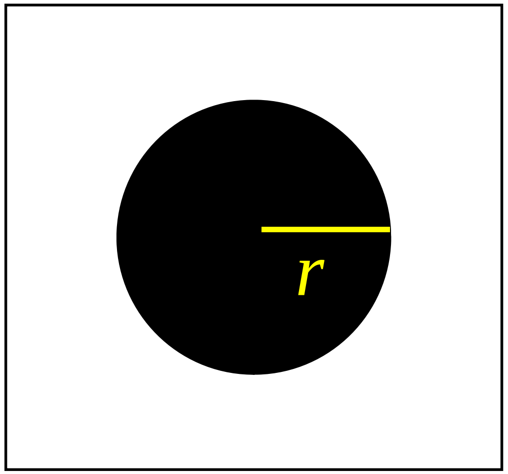
Scale selection

- The 2D Laplacian is given by

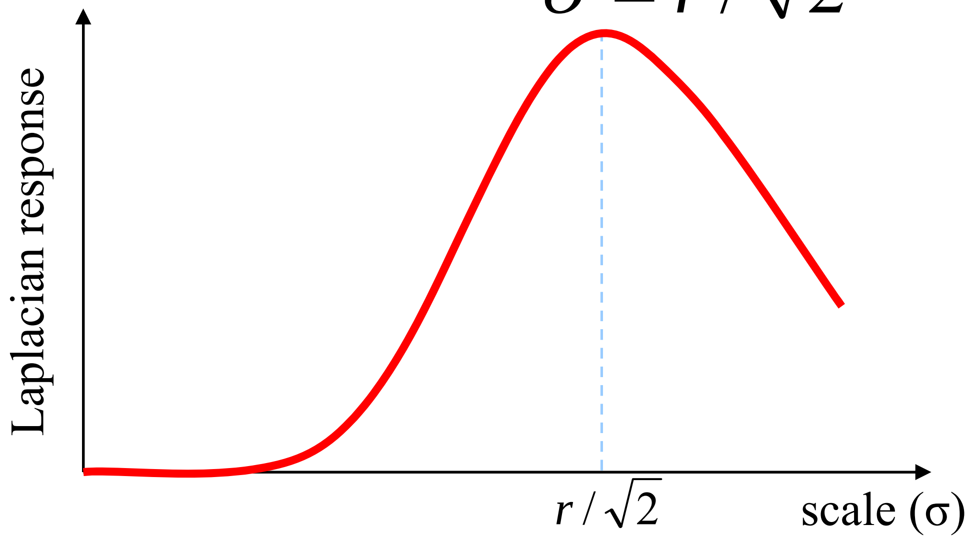
$$(x^2 + y^2 - 2\sigma^2)\, e^{-(x^2+y^2)/2\sigma^2} \quad \text{(up to scale)}$$

- For a binary circle of radius r, the Laplacian achieves a maximum at

$$\sigma = r/\sqrt{2}$$

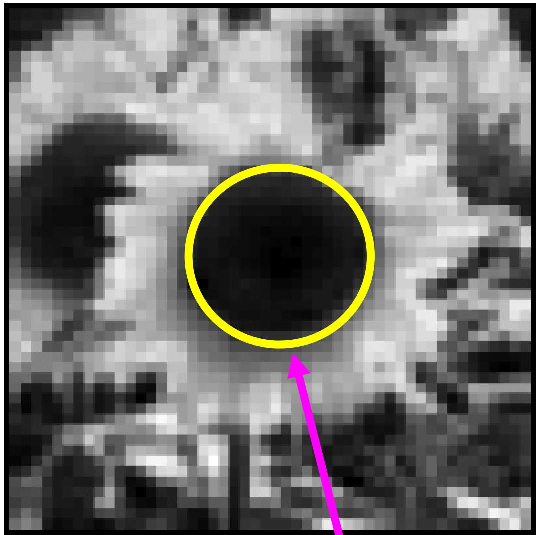


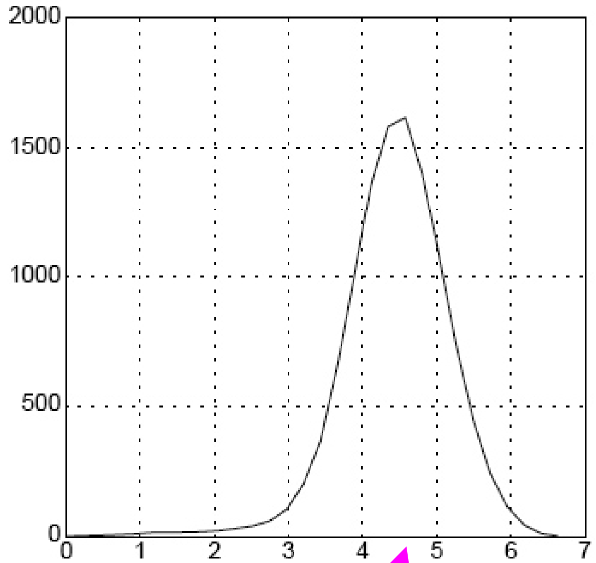
image



Characteristic scale

- We define the characteristic scale as the scale that produces peak of Laplacian response





characteristic scale

T. Lindeberg (1998). Feature detection with automatic scale selection. *International Journal of Computer Vision* **30** (2): pp 77--116.

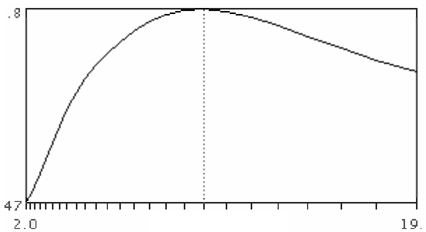
Scale selection

- For a point compute a value (gradient, Laplacian etc.) at several scales
- Normalization of the values with the scale factor

  e.g. Laplacian $| s^2 (L_{xx} + L_{yy}) |$

- Select scale s^* at the maximum $\rightarrow$ characteristic scale

$| s^2 (L_{xx} + L_{yy}) |$

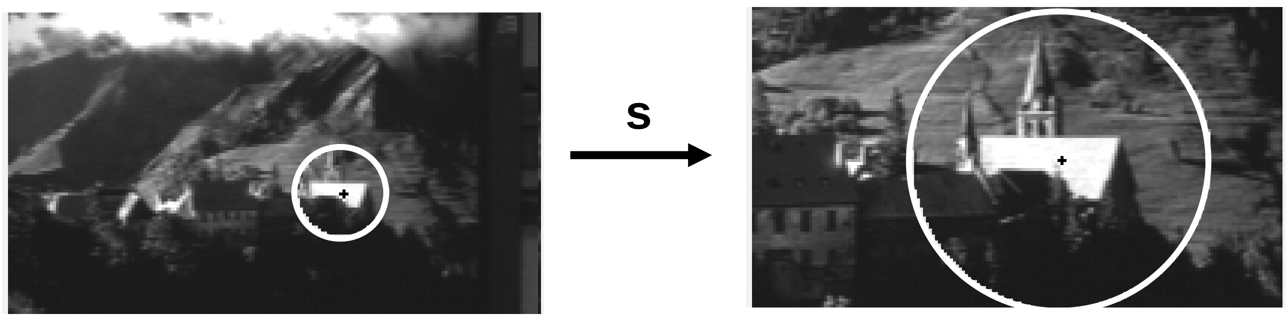


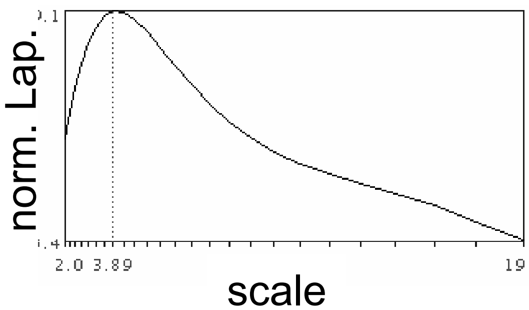
scale

- Exp. results show that the Laplacian gives best results

Scale selection

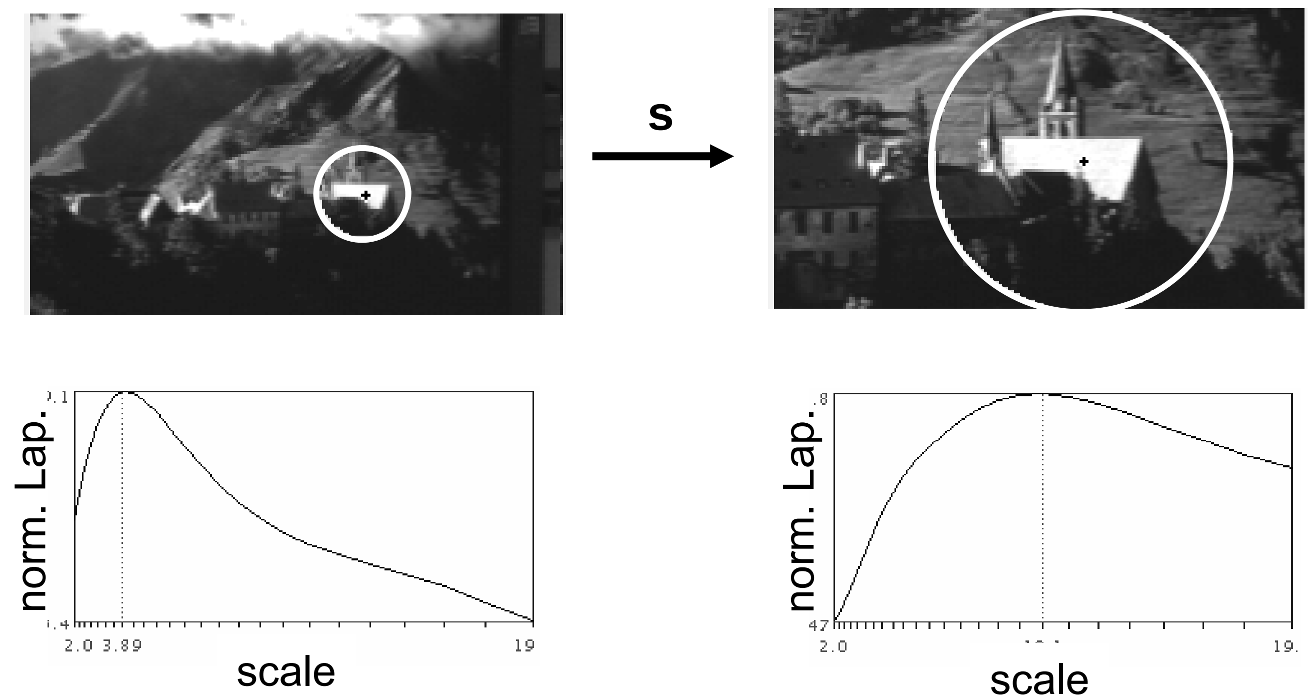
- Scale invariance of the characteristic scale





Scale selection

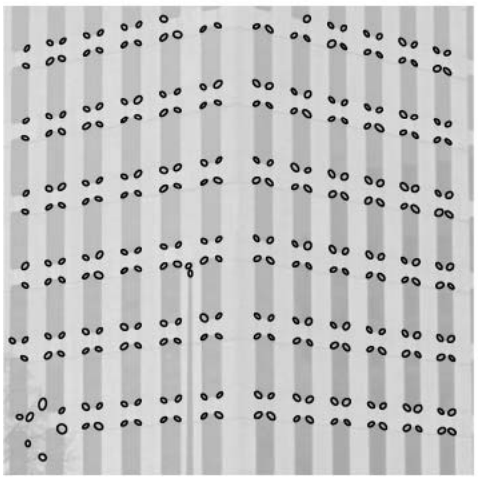
- Scale invariance of the characteristic scale



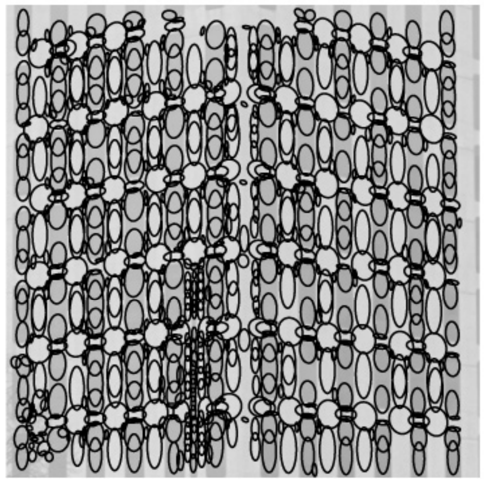
- Relation between characteristic scales $s \cdot s_1^{*} = s_2^{*}$

Scale-invariant detectors

- Harris-Laplace (Mikolajczyk & Schmid'01)
- Laplacian detector (Lindeberg'98)
- Difference of Gaussian (Lowe'99)



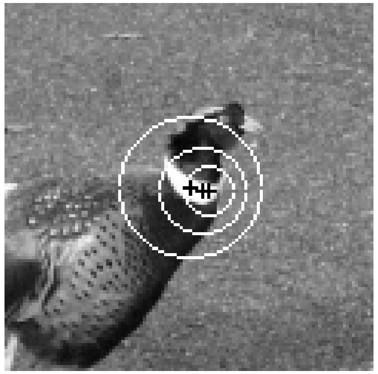
Harris-Laplace

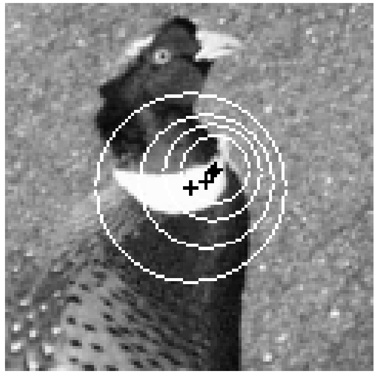


Laplacian

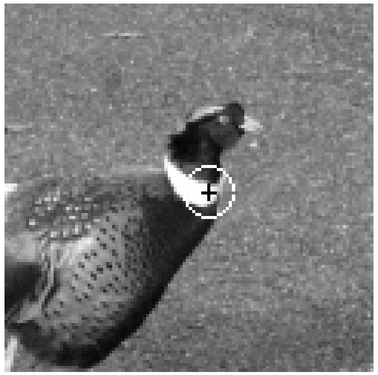
Harris-Laplace

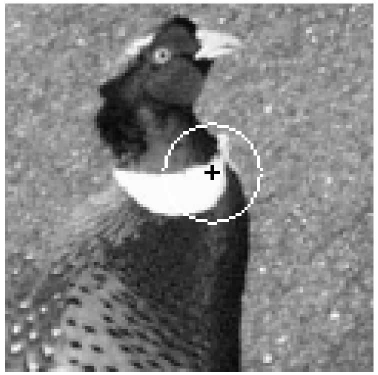
multi-scale Harris points





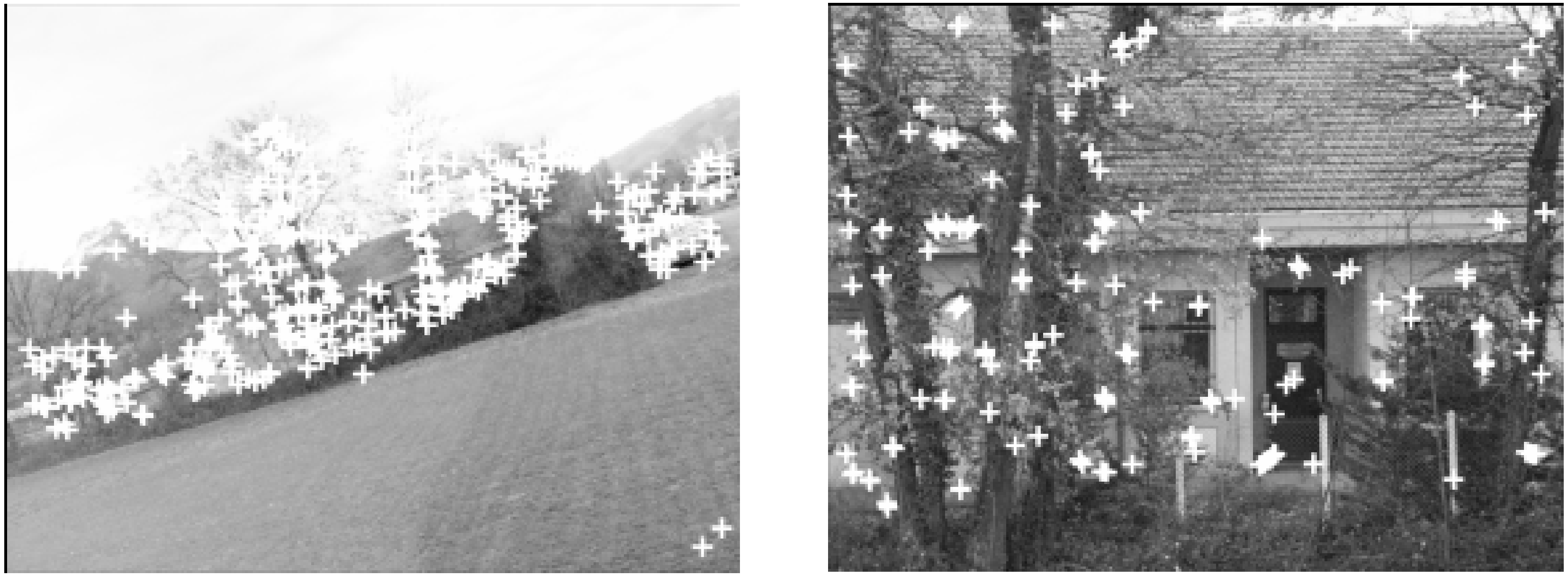
selection of points at maximum of Laplacian





➡ invariant points + associated regions [Mikolajczyk & Schmid’01]

Matching results



213 / 190 detected interest points

Matching results

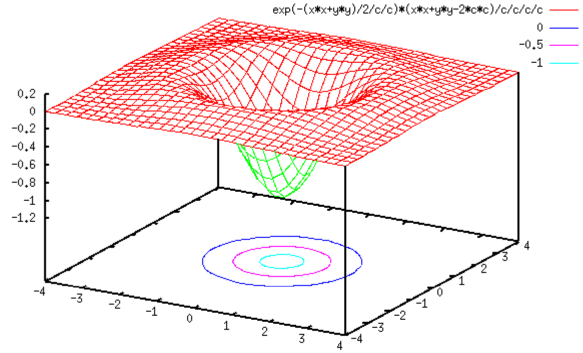
58 points are initially matched

Matching results

32 points are matched after verification – all correct

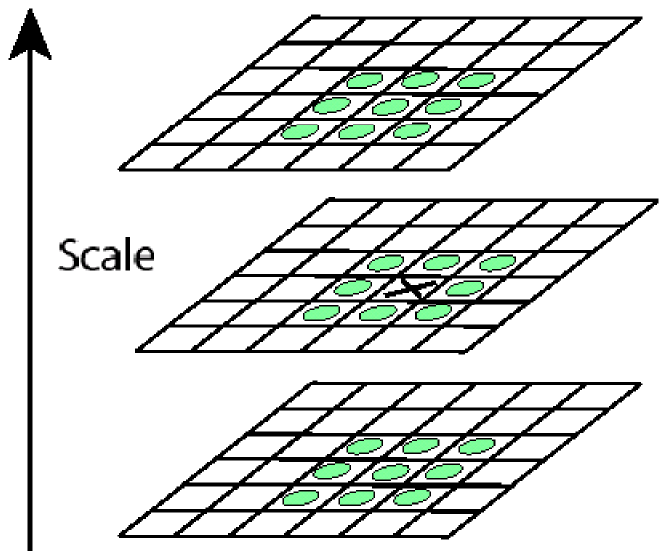
LOG detector

Convolve image with scale-normalized Laplacian at several scales



$$LOG = s^2 (G_{xx}(\sigma) + G_{yy}(\sigma))$$

Detection of maxima and minima of Laplacian in scale space



Hessian detector

Hessian matrix $$H(x) = \begin{bmatrix} L_{xx} & L_{xy} \\ L_{xy} & L_{yy} \end{bmatrix}$$

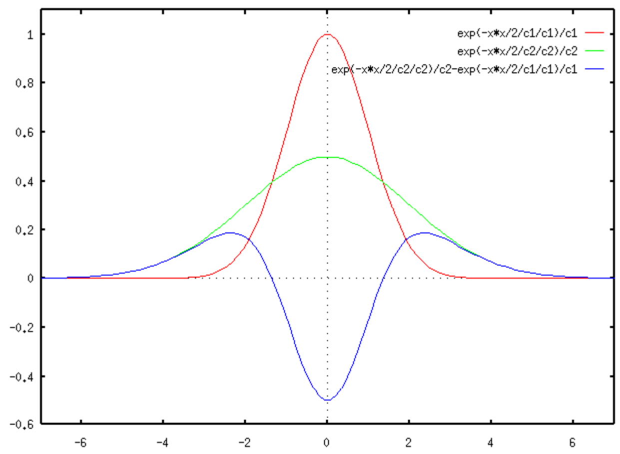
Determinant of Hessian matrix $$DET = L_{xx} L_{yy} - L_{xy}{}^2$$

Penalizes/eliminates long structures

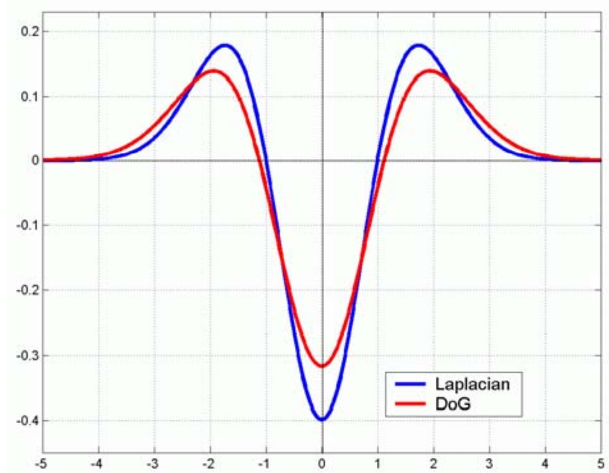
- with small derivative in a single direction

Efficient implementation

- Difference of Gaussian (DOG) approximates the Laplacian $DOG = G(k\sigma) - G(\sigma)$

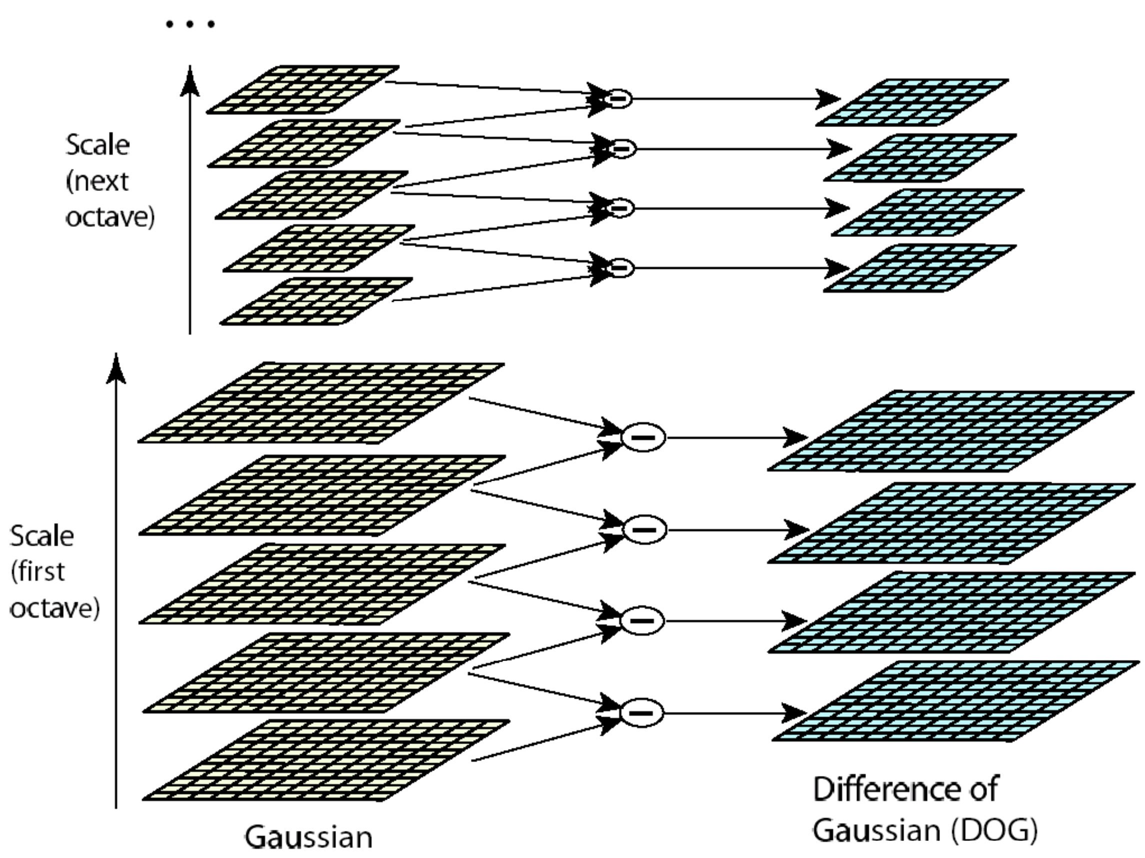


- Error due to the approximation



DOG detector

- Fast computation, scale space processed one octave at a time



David G. Lowe. "Distinctive image features from scale-invariant keypoints."I*JCV* 60 (2).

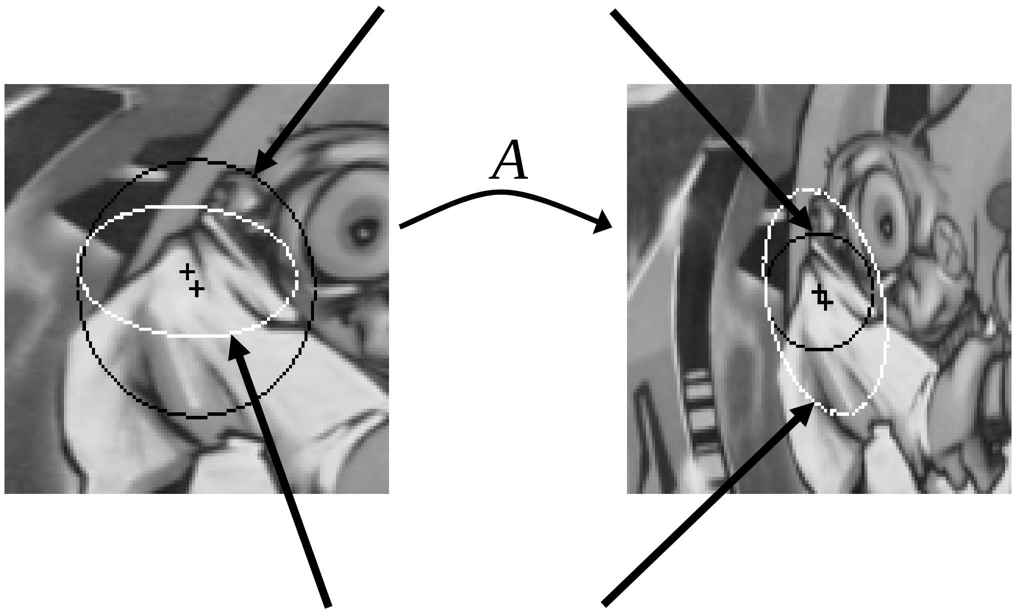
Local features - overview

- Scale invariant interest points
- ***Affine invariant interest points***
- Evaluation of interest points
- Descriptors and their evaluation

Affine invariant regions - Motivation

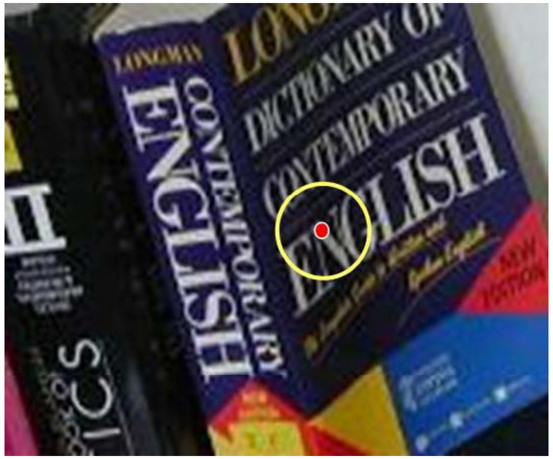
- Scale invariance is not sufficient for large baseline changes

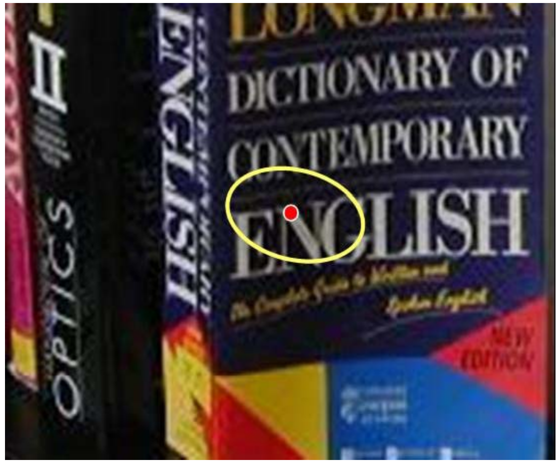
detected scale invariant region



projected regions, viewpoint changes can locally be approximated by an affine transformation A

Affine invariant regions - Motivation





Affine invariant regions - Example

Harris/Hessian/Laplacian-Affine

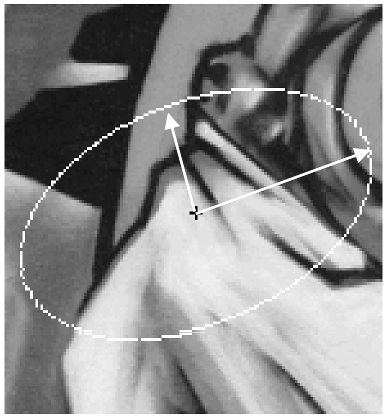
- Initialize with scale-invariant Harris/Hessian/Laplacian points
- Estimation of the affine neighbourhood with the second moment matrix [Lindeberg'94]
- Apply affine neighbourhood estimation to the scale-invariant interest points [Mikolajczyk & Schmid'02, Schaffalitzky & Zisserman'02]
- Excellent results in a comparison [Mikolajczyk et al.'05]

Affine invariant regions

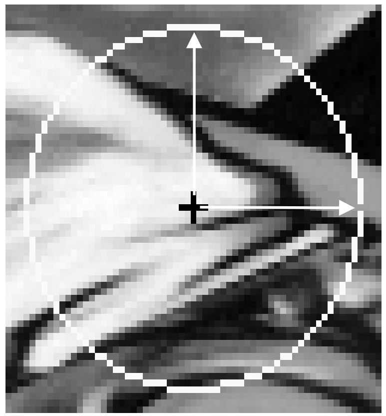
- Based on the second moment matrix (Lindeberg'94)

$$M = \mu(\mathbf{x}, \sigma_I, \sigma_D) = \sigma_D^{\ 2} G(\sigma_I) \otimes \begin{bmatrix} L_x^{\ 2}(\mathbf{x}, \sigma_D) & L_x L_y(\mathbf{x}, \sigma_D) \\ L_x L_y(\mathbf{x}, \sigma_D) & L_y^{\ 2}(\mathbf{x}, \sigma_D) \end{bmatrix}$$

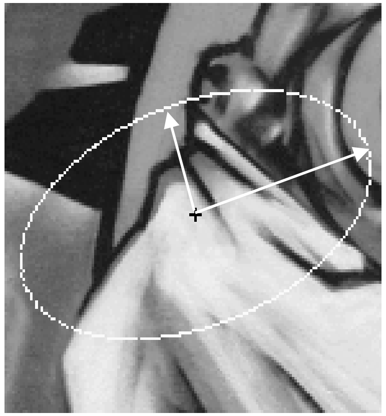
- Normalization with eigenvalues/eigenvectors



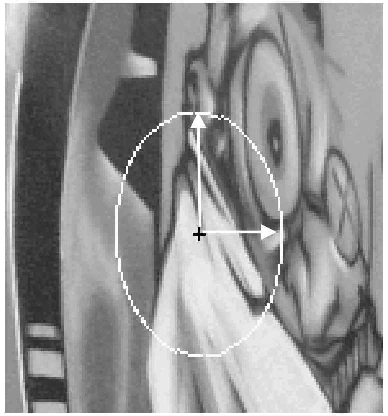
$$\mathrm{x}' = M^{\frac{1}{2}}\mathrm{x}$$



Affine invariant regions

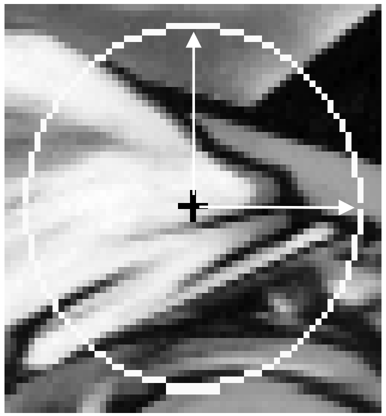


$$\mathrm{x}_{\mathrm{R}} = A\mathrm{x}_{\mathrm{L}}$$

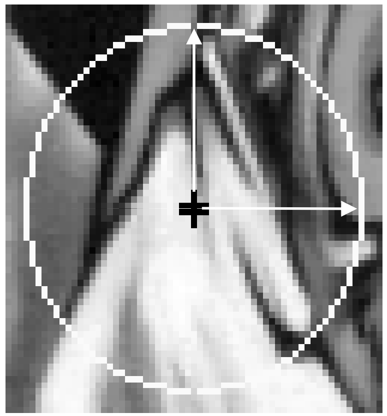


$$\mathrm{x}_{\mathrm{L}}' = M_L^{\frac{1}{2}}\mathrm{x}_{\mathrm{L}}$$

$$\mathrm{x}_{\mathrm{R}}' = M_R^{\frac{1}{2}}\mathrm{x}_{\mathrm{R}}$$



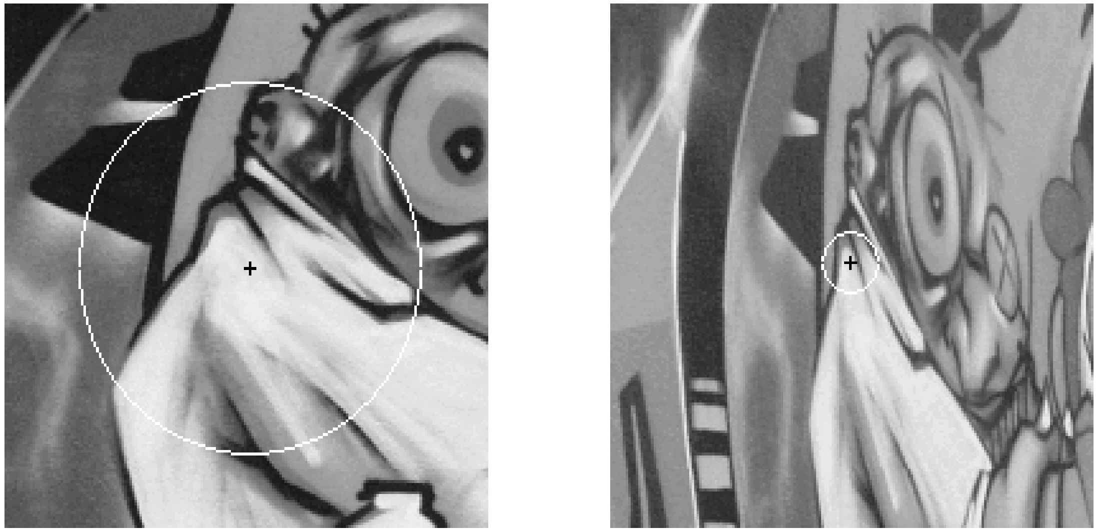
$$\mathrm{x}_R' = R\mathrm{x}_L'$$



Isotropic neighborhoods related by image rotation

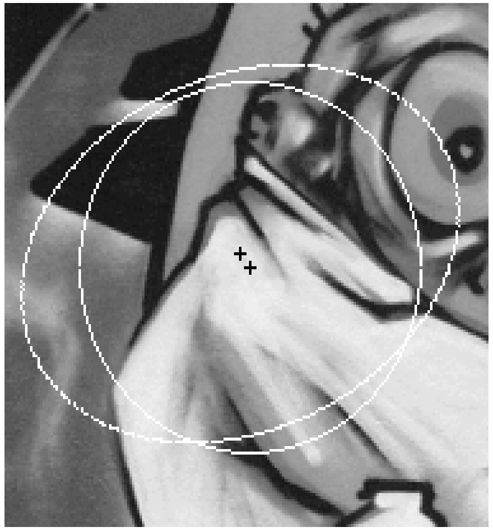
Affine invariant regions - Estimation

- Iterative estimation – initial points



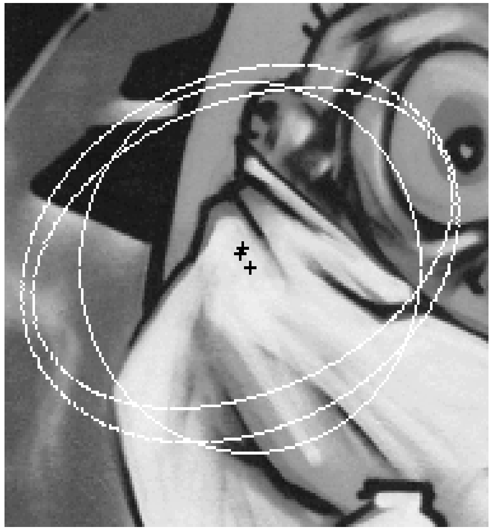
Affine invariant regions - Estimation

- Iterative estimation – iteration #1



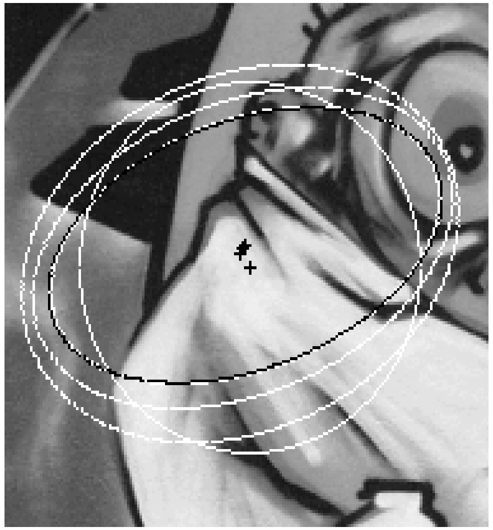
Affine invariant regions - Estimation

- Iterative estimation – iteration #2

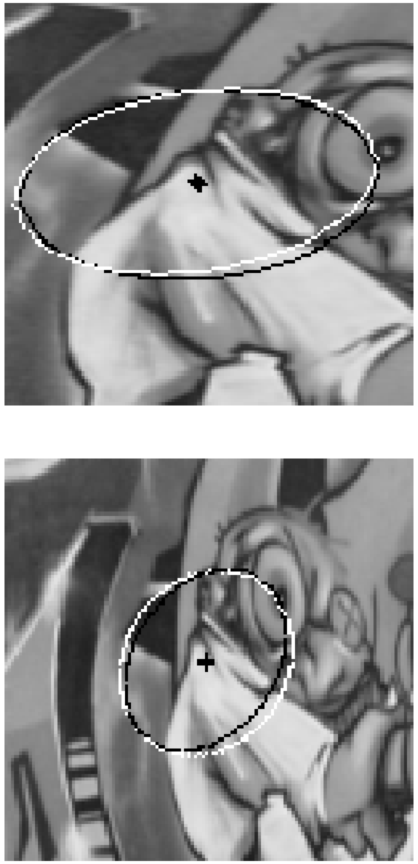


Affine invariant regions - Estimation

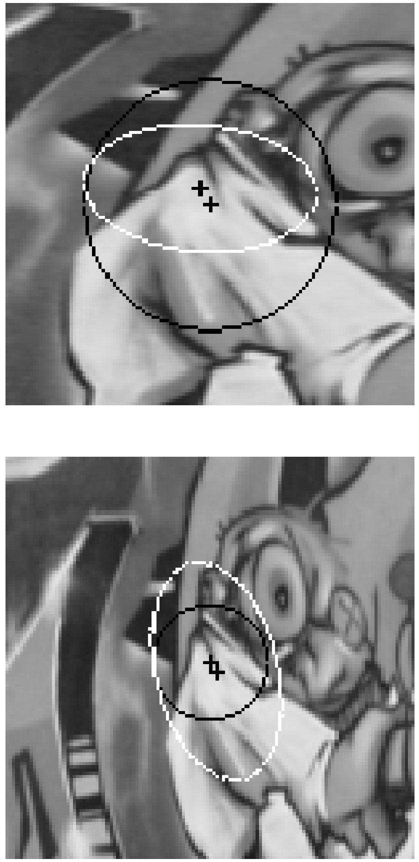
- Iterative estimation – iteration #3, #4



Harris-Affine versus Harris-Laplace

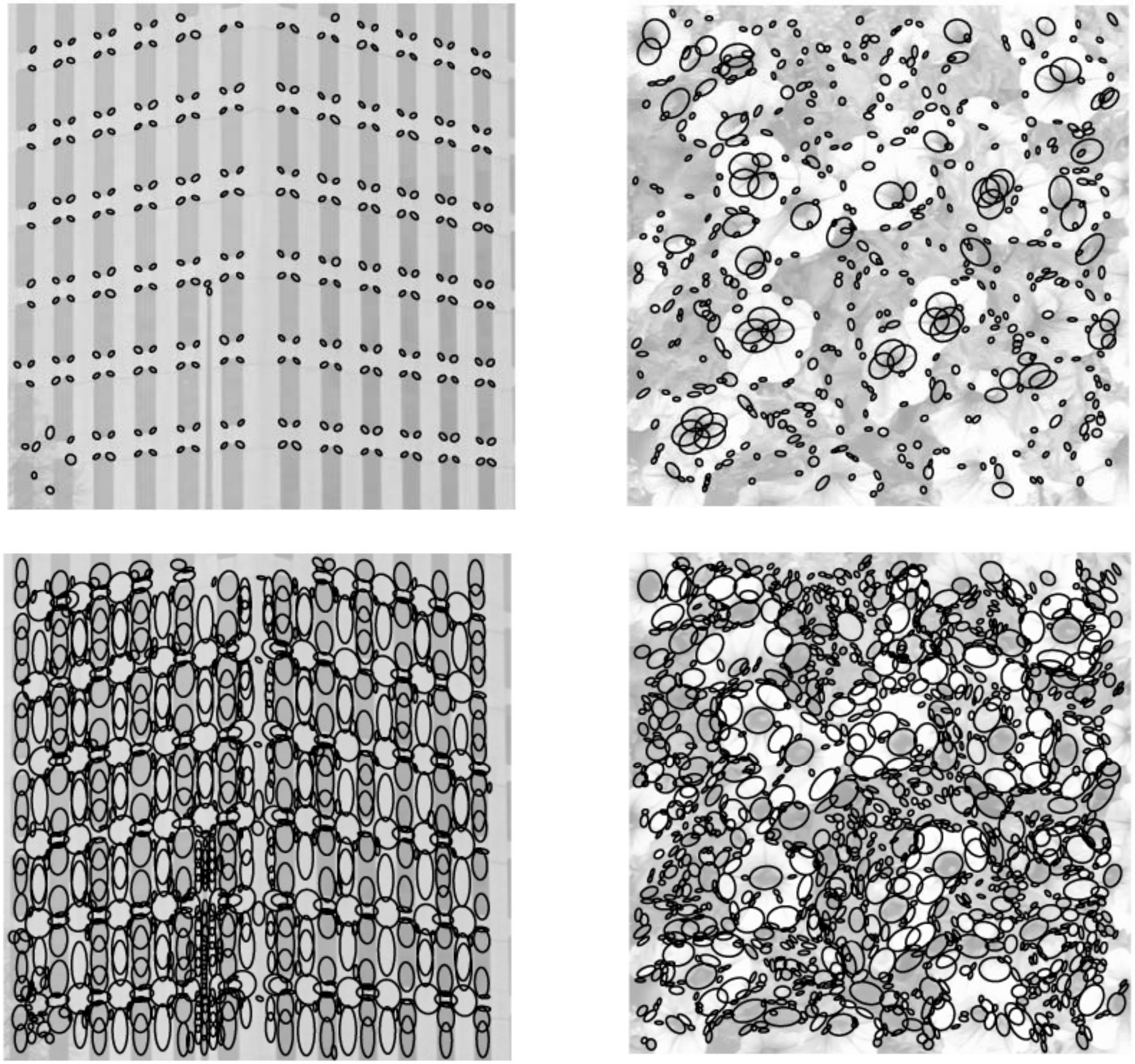


Harris-Affine



Harris-Laplace

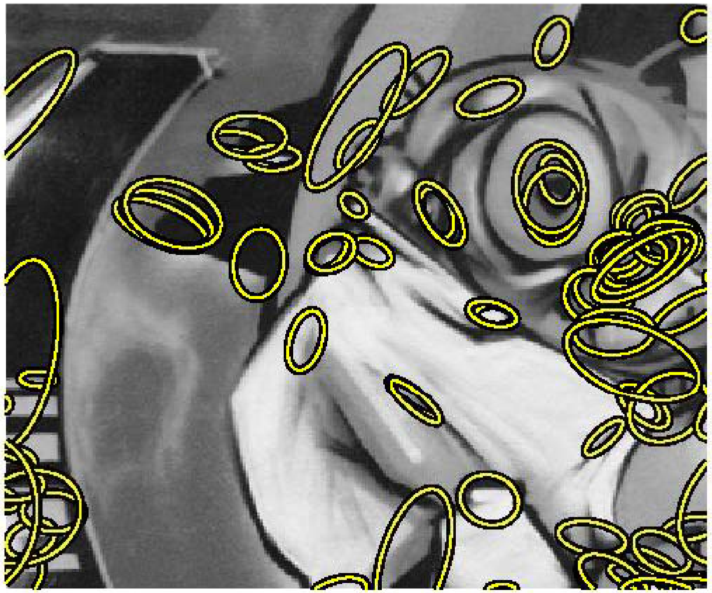
Harris/Hessian-Affine



Harris-Affine

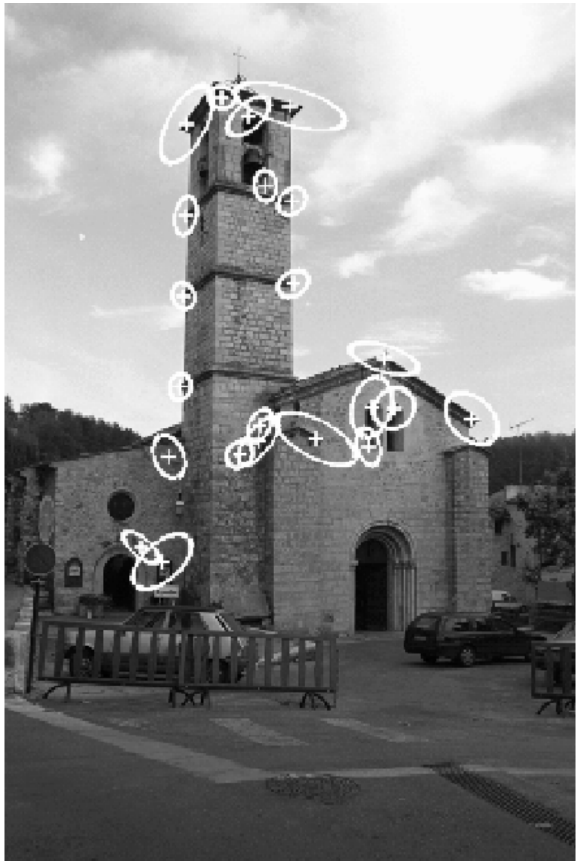
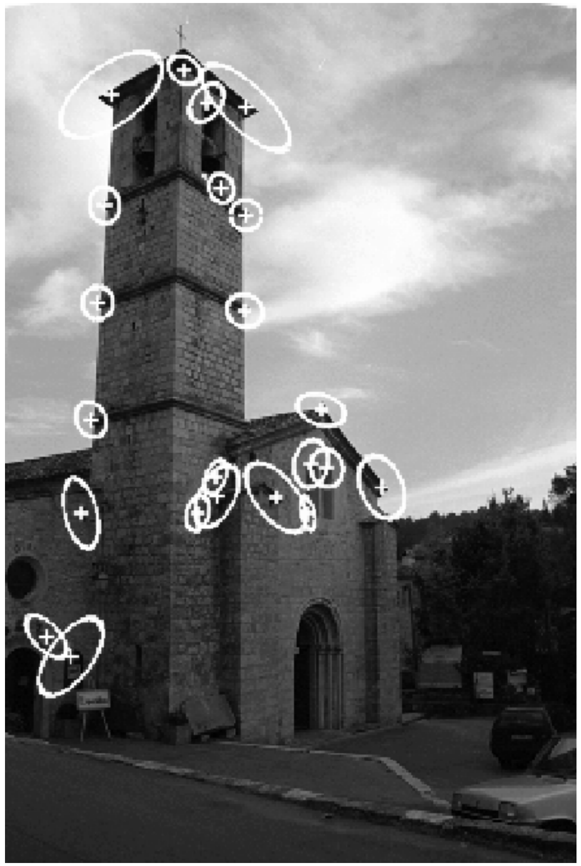
Hessian-Affine

Harris-Affine

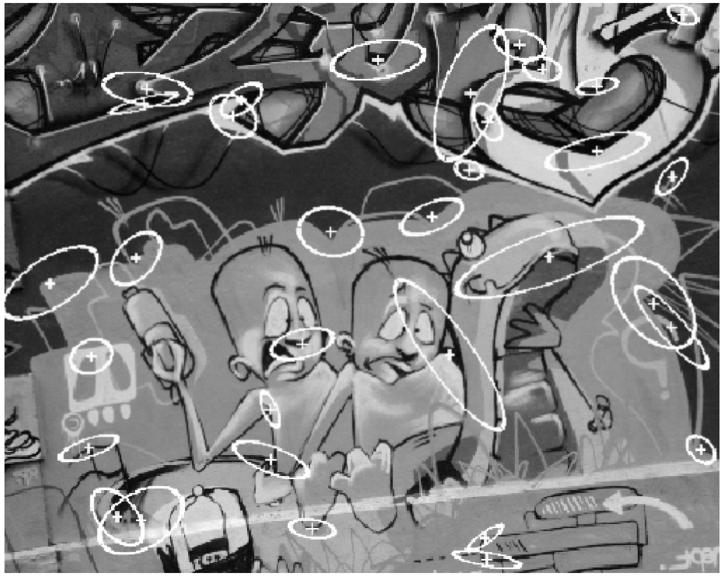
Hessian-Affine

Matches

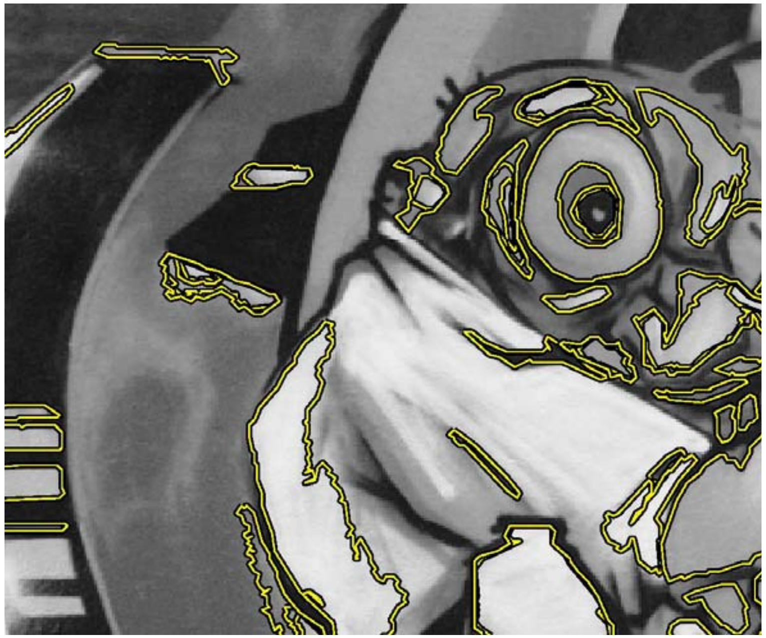
22 correct matches

Matches



33 correct matches

Maximally stable extremal regions (MSER) [Matas'02]



- Based on the idea of region segmentation
- State of the art results

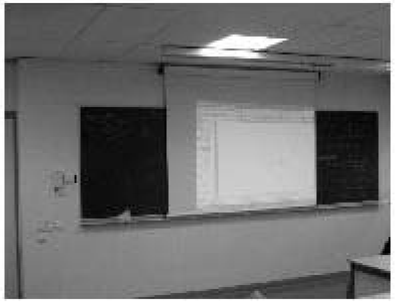
Maximally stable extremal regions (MSER) [Matas'02]

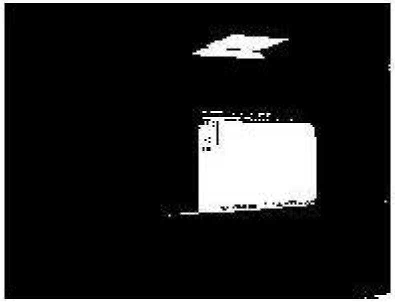
- Extremal regions: connected components in a thresholded image (all pixels above/below a threshold)

- Maximally stable: minimal change of the component (area) for a change of the threshold, i.e. region remains stable for a change of threshold

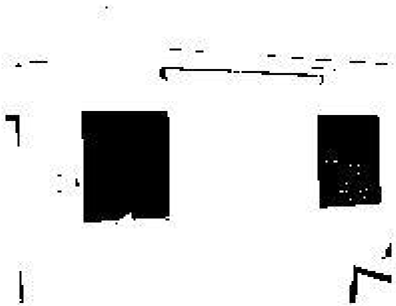
Maximally stable extremal regions (MSER)

Examples of thresholded images



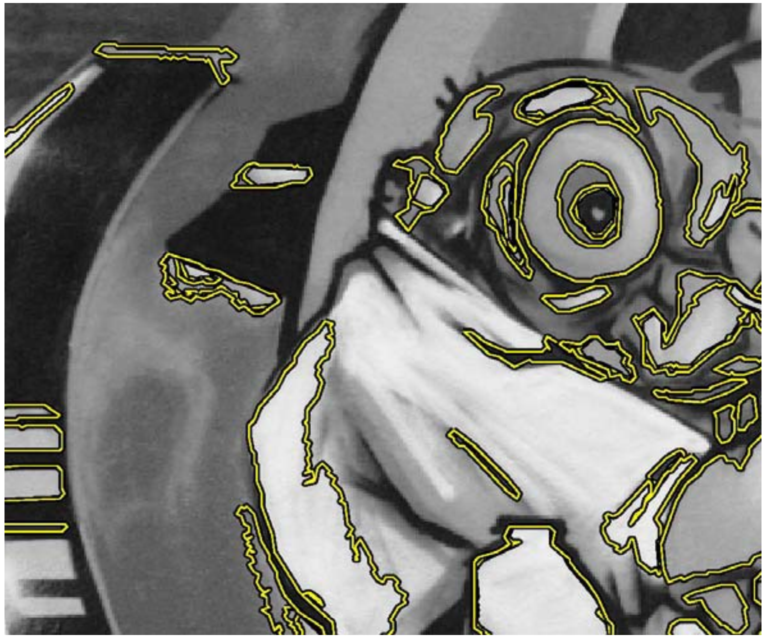


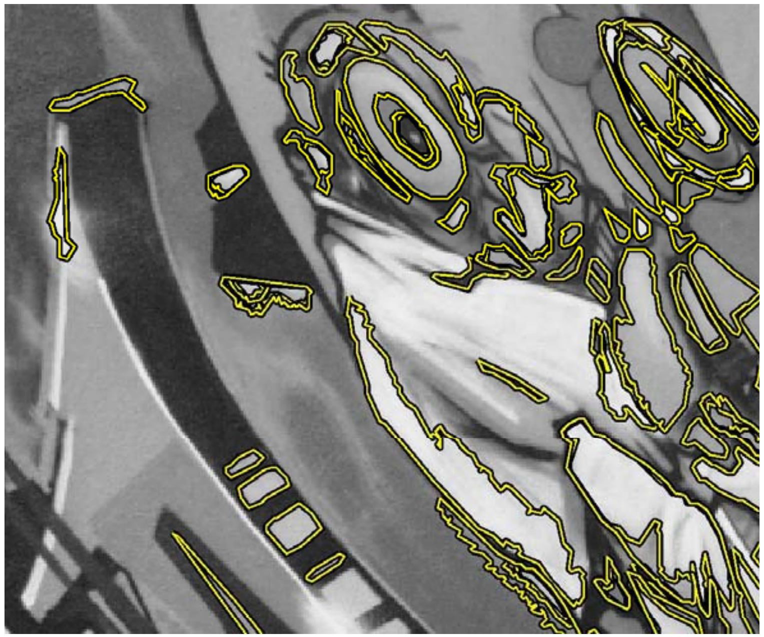
high threshold



low threshold

MSER





Overview

- Introduction to local features
- Harris interest points + SSD, ZNCC, SIFT
- Scale & affine invariant interest point detectors
- **Evaluation and comparison of different detectors**
- Region descriptors and their performance

Evaluation of interest points

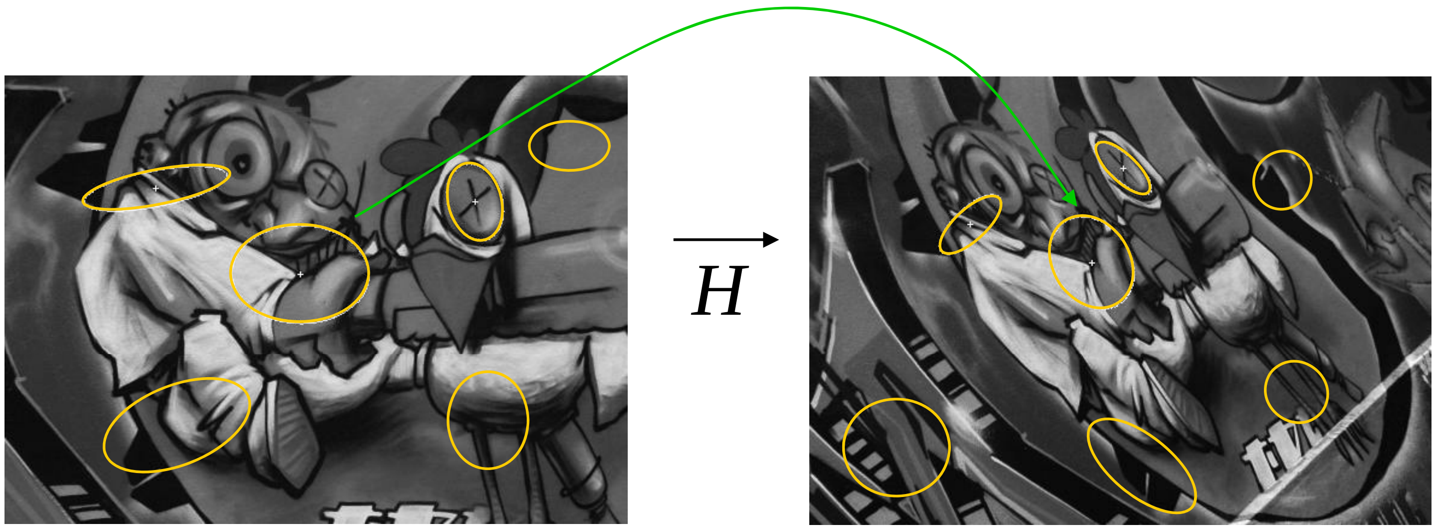
- Quantitative evaluation of interest point/region detectors
  - points / regions at the same relative location and area

- Repeatability rate : percentage of corresponding points

- Two points/regions are corresponding if
  - location error small
  - area intersection large

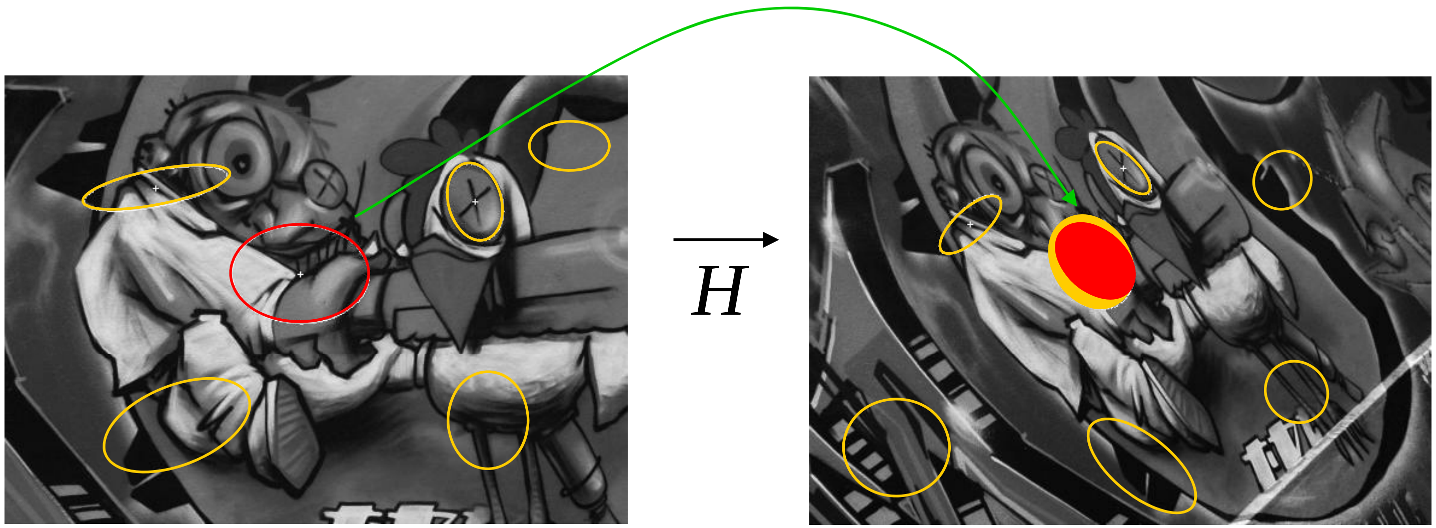
- [K. Mikolajczyk, T. Tuytelaars, C. Schmid, A. Zisserman, J. Matas, F. Schaffalitzky, T. Kadir & L. Van Gool '05]

Evaluation criterion



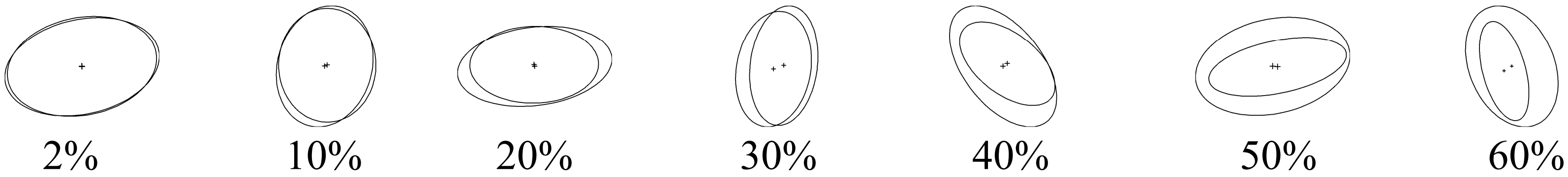
$$repeatability = \frac{\#\, corresponding\ regions}{\#\, detected\ regions} \cdot 100\%$$

Evaluation criterion



$$repeatability = \frac{\#\,corresponding\ regions}{\#\,detected\ regions} \cdot 100\%$$

$$overlap\ error = (1 - \frac{intersection}{union}) \cdot 100\%$$



Dataset

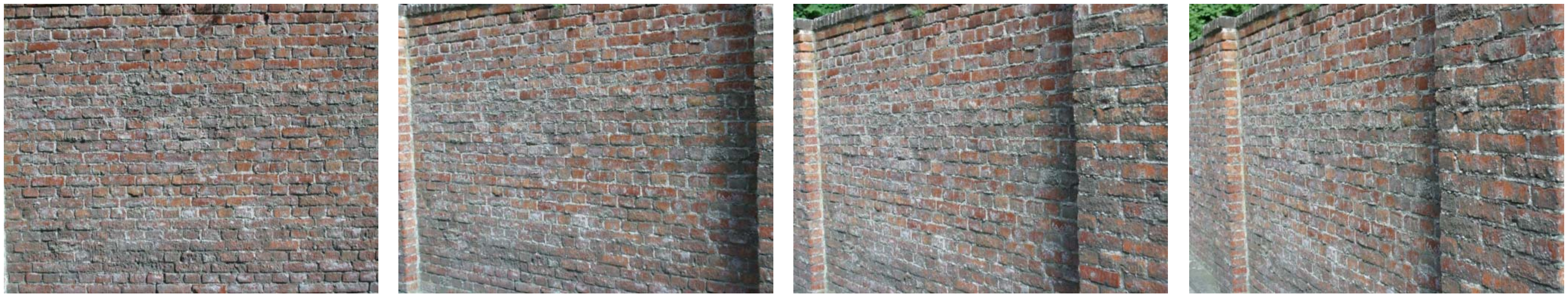
- Different types of transformation
  - Viewpoint change
  - Scale change
  - Image blur
  - JPEG compression
  - Light change

- Two scene types
  - Structured
  - Textured

- Transformations within the sequence (homographies)
  - Independent estimation

Viewpoint change (0-60 degrees)

structured scene



textured scene

Zoom + rotation (zoom of 1-4)

structured scene

textured scene

Blur, compression, illumination

blur - structured scene

blur - textured scene

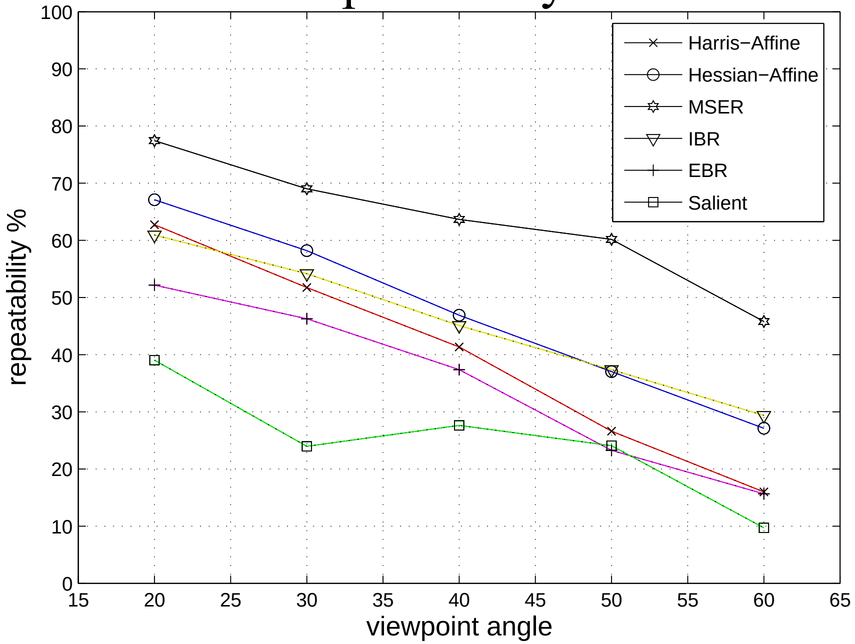
light change - structured scene

jpeg compression - structured scene

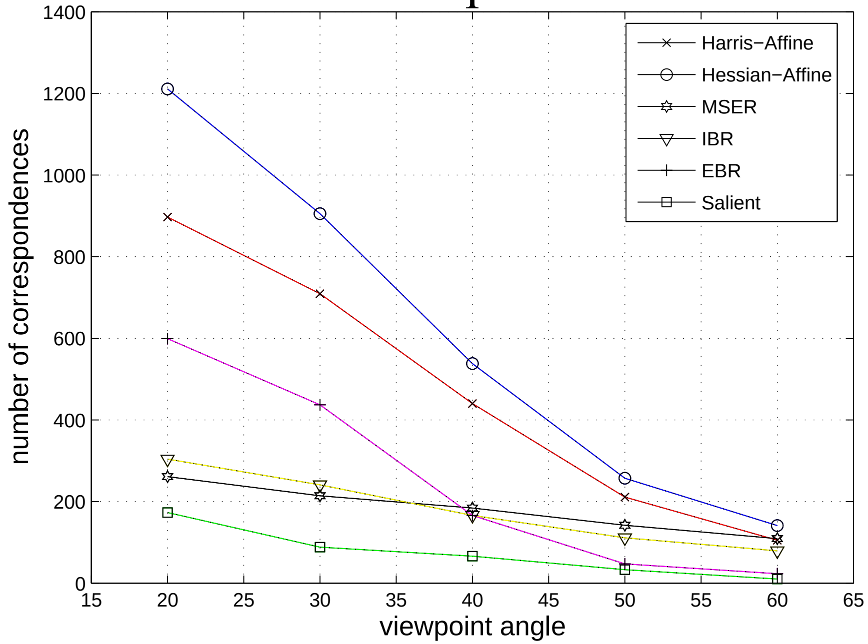
Comparison of affine invariant detectors

Viewpoint change - structured scene

repeatability %



correspondences



reference image

20

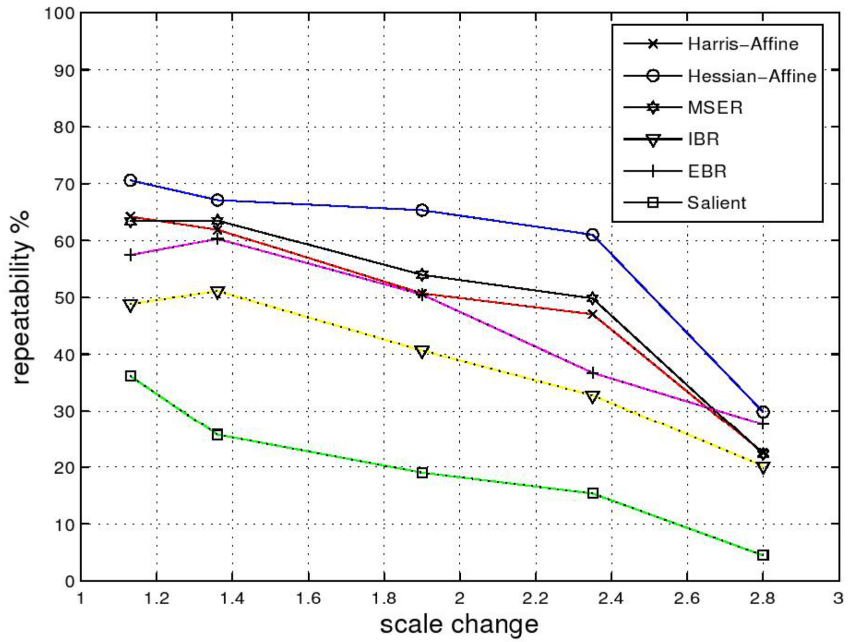
40

60

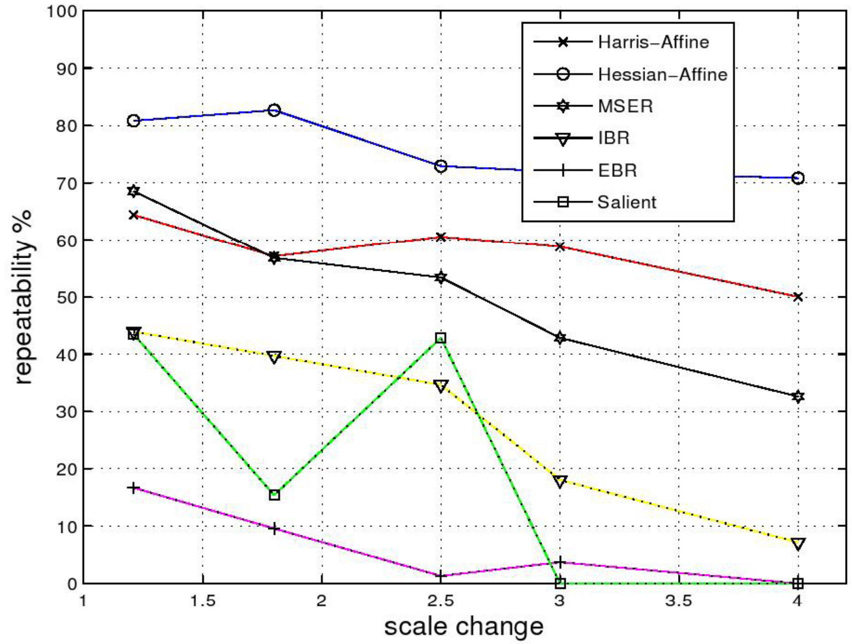
Comparison of affine invariant detectors

Scale change

repeatability %



repeatability %



reference image

2.8

reference image

4

Conclusion - detectors

- Good performance for large viewpoint and scale changes
- Results depend on transformation and scene type, no one best detector
- Detectors are complementary
  - MSER adapted to structured scenes
  - Harris and Hessian adapted to textured scenes
- Performance of the different scale invariant detectors is very similar (Harris-Laplace, Hessian, LoG and DOG)
- Scale-invariant detector sufficient up to 40 degrees of viewpoint change

Overview

- Introduction to local features

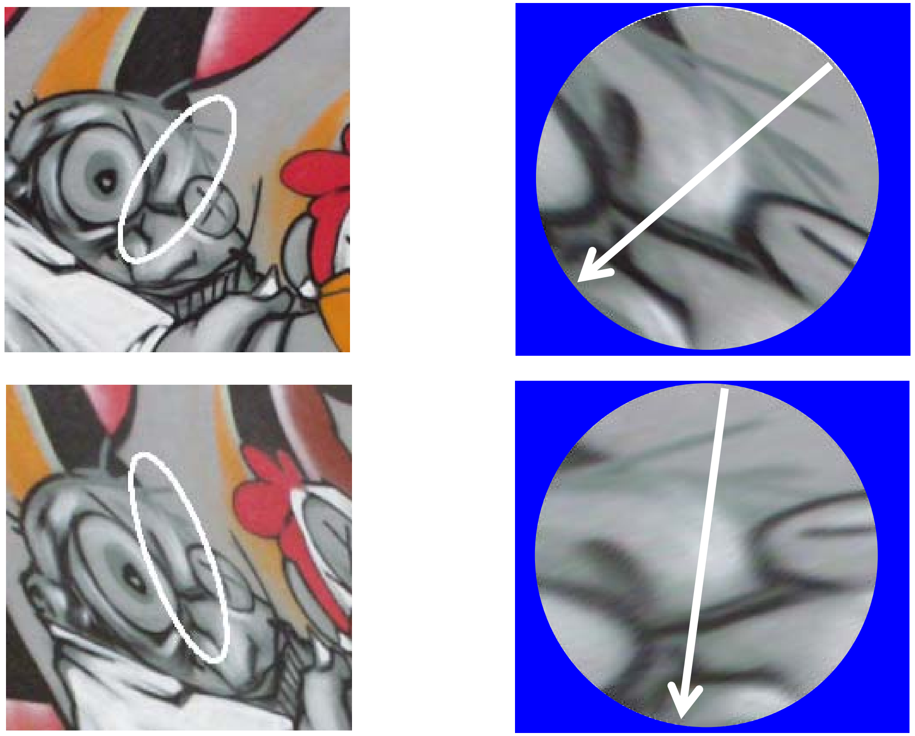
- Harris interest points + SSD, ZNCC, SIFT

- Scale & affine invariant interest point detectors

- Evaluation and comparison of different detectors

- **Region descriptors and their performance**

Region descriptors



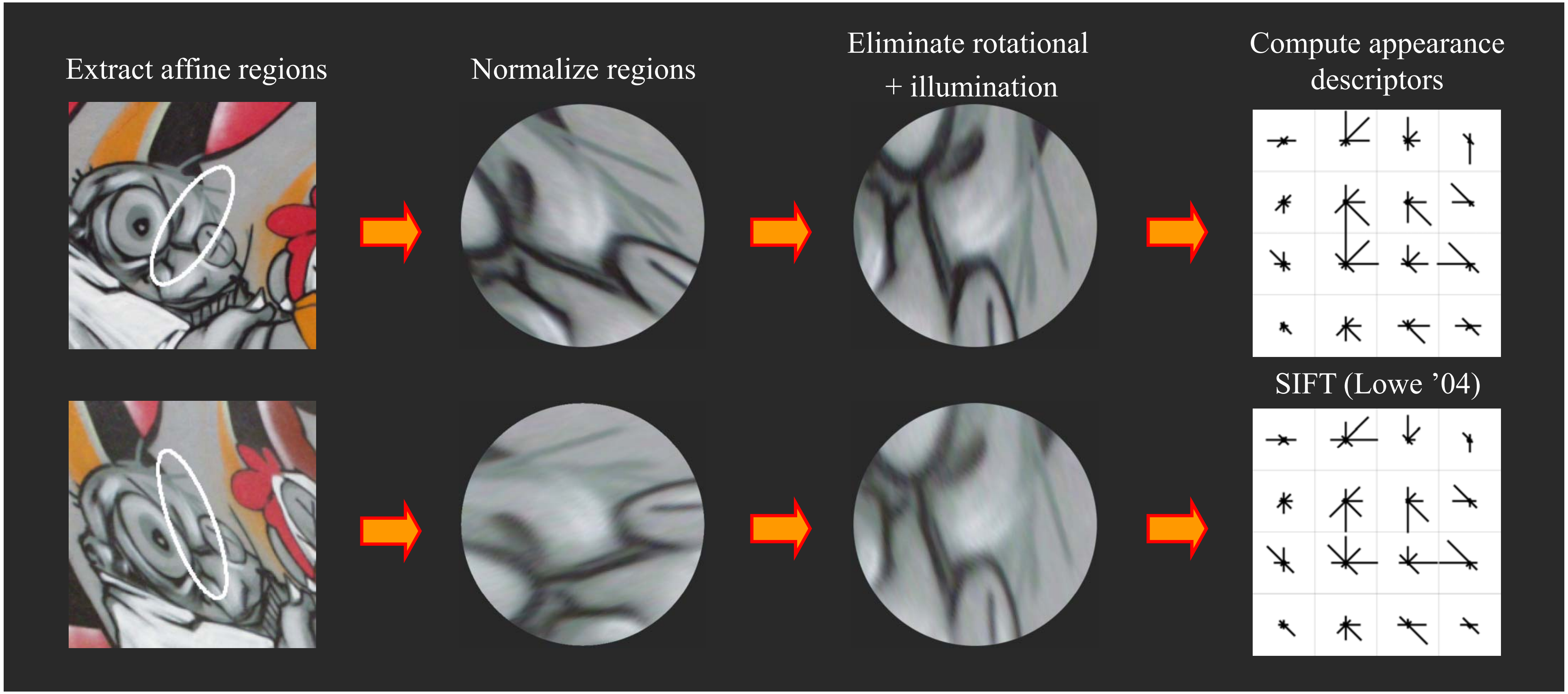
- Normalized regions are
  - invariant to geometric transformations except rotation
  - not invariant to photometric transformations

Descriptors

- Regions invariant to geometric transformations except rotation
  - rotation invariant descriptors
  - **normalization with dominant gradient direction**

- Regions not invariant to photometric transformations
  - invariance to affine photometric transformations
  - **normalization with mean and standard deviation of the image patch**

Descriptors



Descriptors

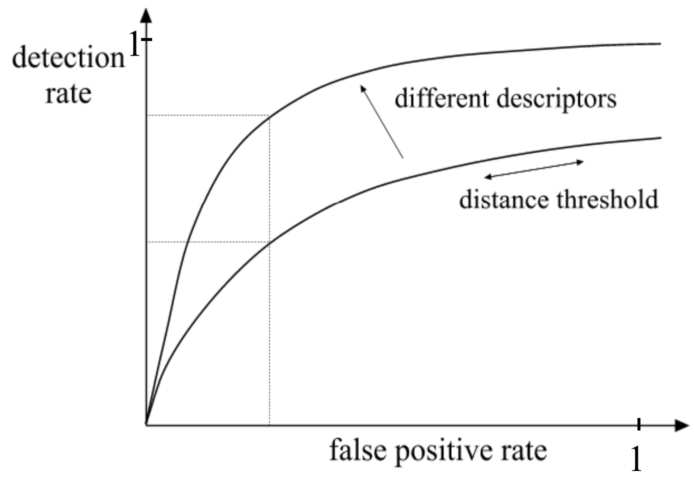
- Gaussian derivative-based descriptors
  - Differential invariants (*Koenderink and van Doorn'87*)
  - Steerable filters (*Freeman and Adelson'91*)

- SIFT (*Lowe'99)*
- Moment invariants [Van Gool et al.'96]
- Shape context [Belongie et al.'02]
- SIFT with PCA dimensionality reduction
- Gradient PCA [Ke and Sukthankar'04]
- SURF descriptor [Bay et al.'08]
- DAISY descriptor [Tola et al.'08, Windler et al'09]

Comparison criterion

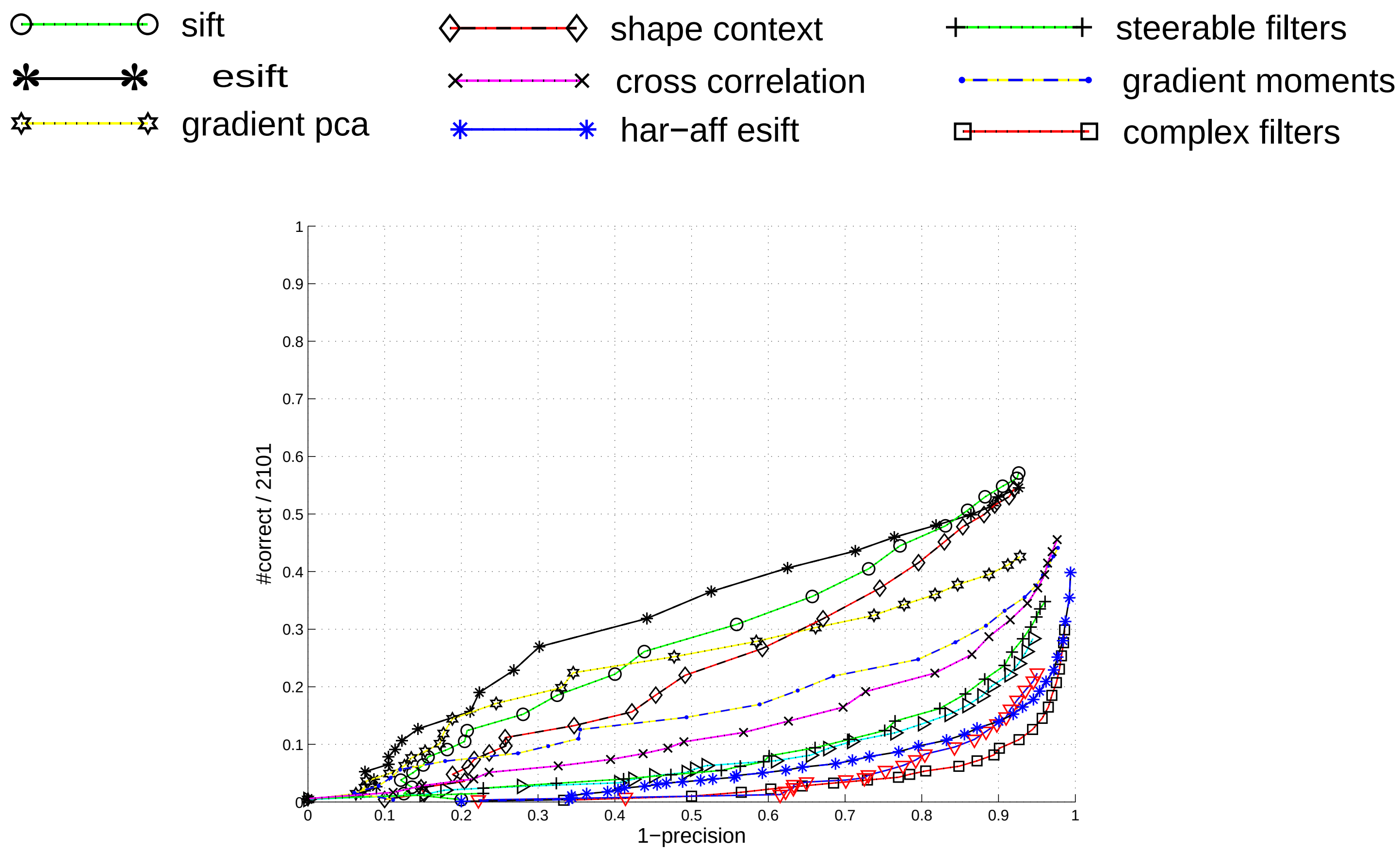
- Descriptors should be
  - Distinctive
  - Robust to changes on viewing conditions as well as to errors of the detector

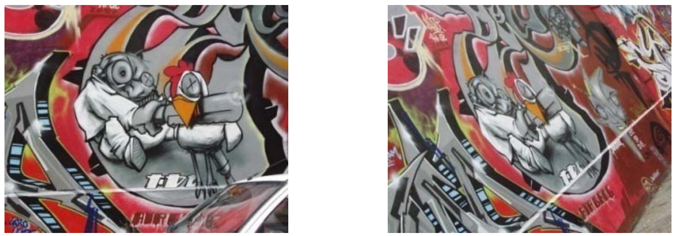
- Detection rate (recall)
  - #correct matches / #correspondences
- False positive rate
  - #false matches / #all matches
- Variation of the distance threshold
  - distance (d1, d2) < threshold



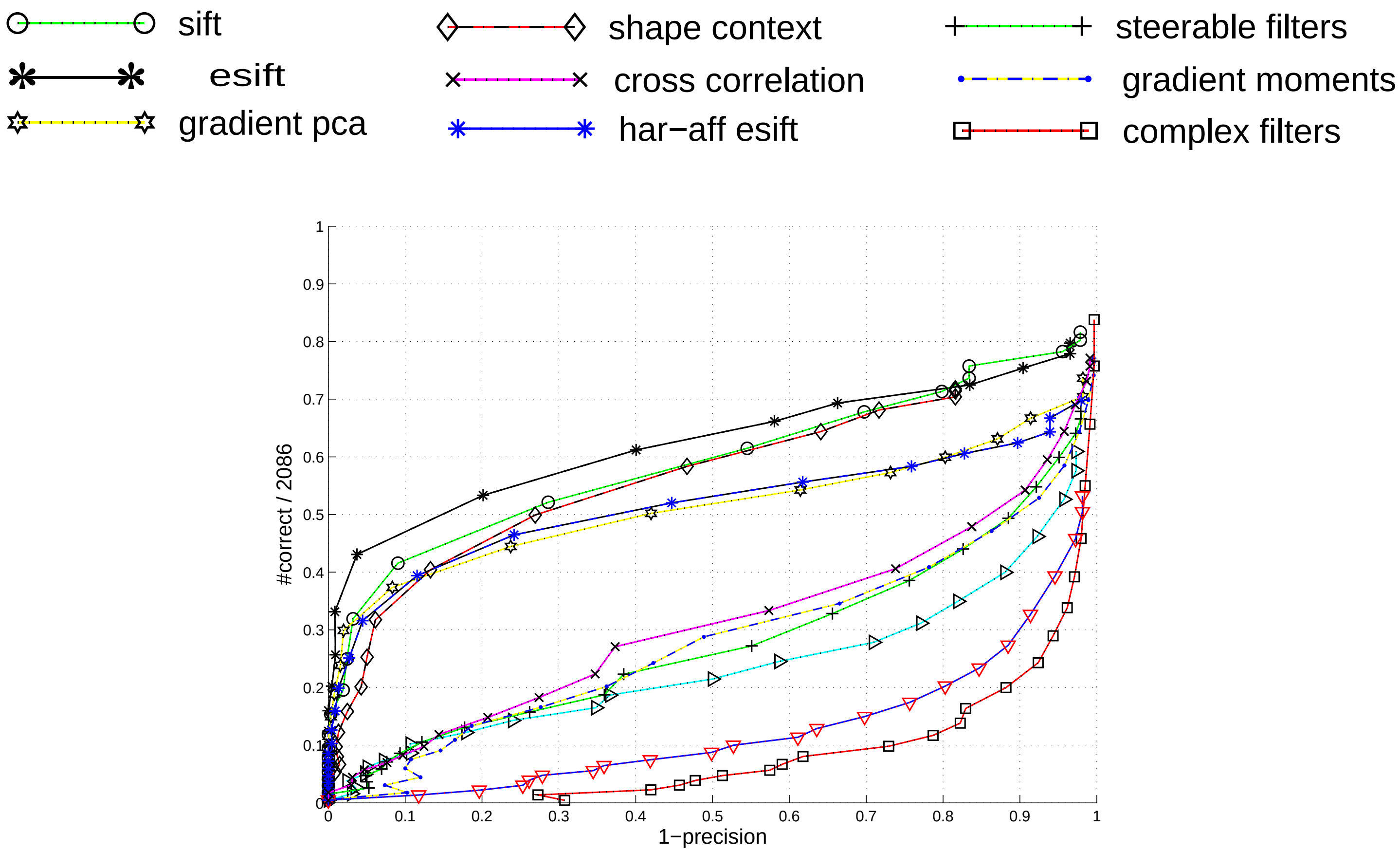
[K. Mikolajczyk & C. Schmid, PAMI'05]

Viewpoint change (60 degrees)





Scale change (factor 2.8)



Conclusion - descriptors

- SIFT based descriptors perform best
- Significant difference between SIFT and low dimension descriptors as well as cross-correlation
- Robust region descriptors better than point-wise descriptors
- Performance of the descriptor is relatively independent of the detector

Available on the internet

http://lear.inrialpes.fr/software

- Binaries for detectors and descriptors
  - *Building blocks for recognition systems*

- Carefully designed test setup
  - Dataset with transformations
  - Evaluation code in matlab
  - *Benchmark for new detectors and descriptors*