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Recovering Scene Geometry via TIP: the Transfer of Invariant Parameters

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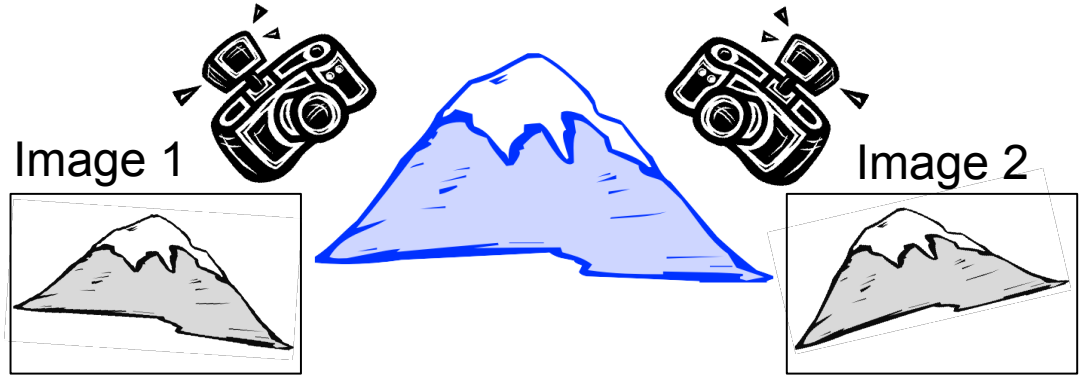
Context: 3D Scene Geometry from 2D Images

- The 3D geometry of a scene can be recovered from two or more images of the scene.
- Applications: 3D modeling, ego motion, …



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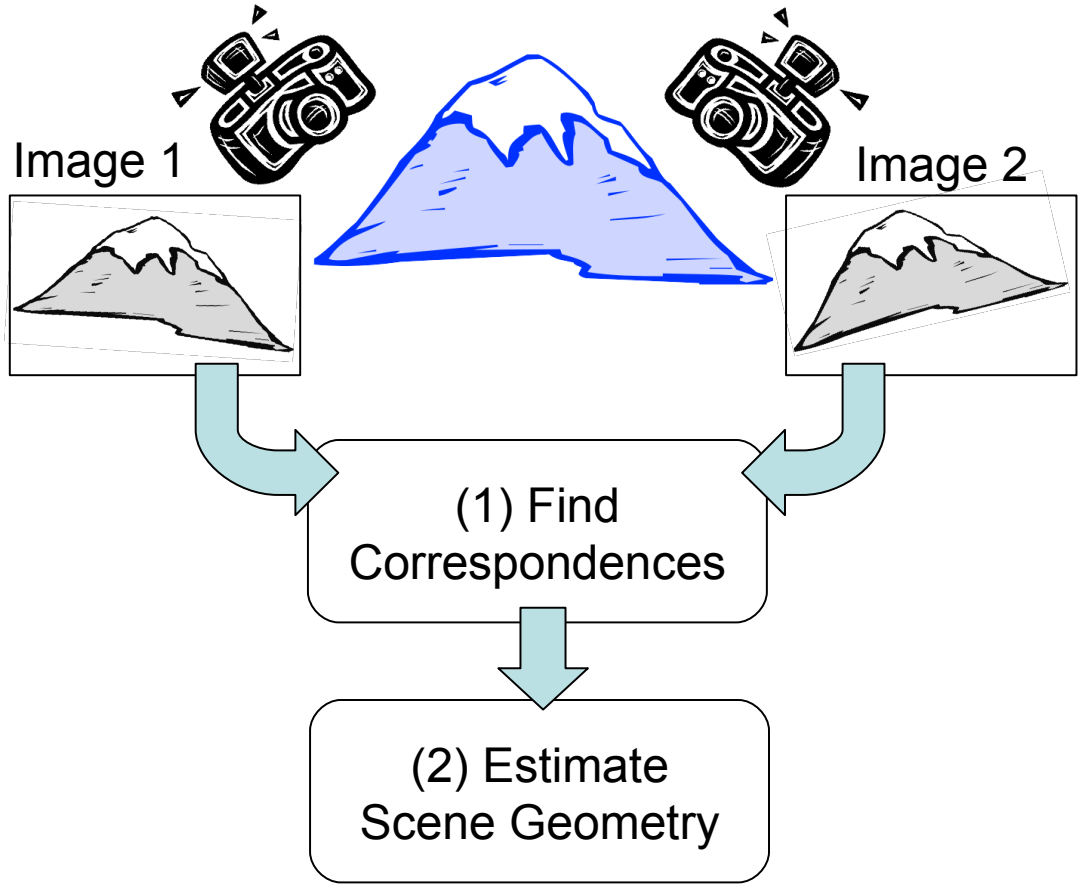

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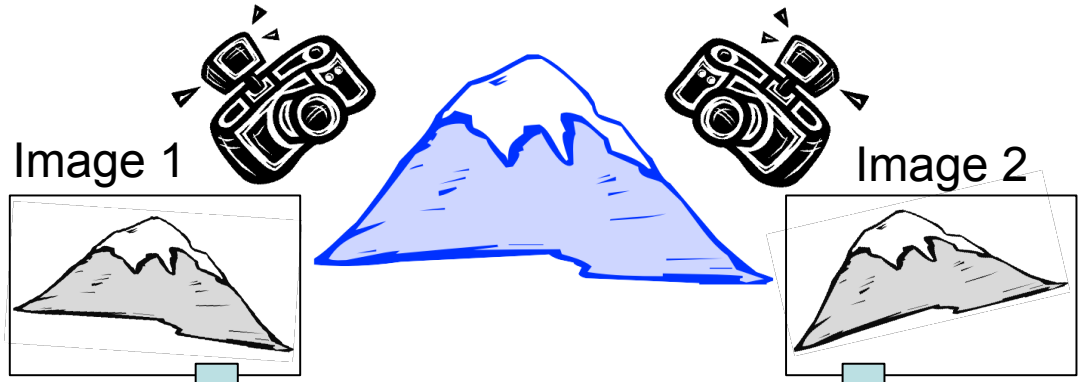
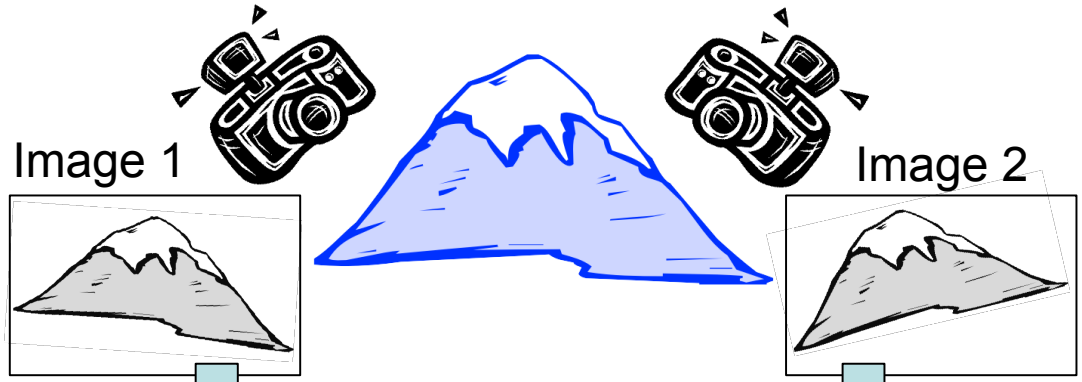


(1) Find Correspondences

Feature Matching
Point-to-point
Invariant features
i.e. SIFT

(2) Estimate Scene Geometry

Context: 3D Scene Geometry from 2D Images



(1) Find Correspondences

(2) Estimate Scene Geometry

Epipolar geometry
Fundamental matrix
Point-based algorithms
i.e. the 8-point algorithm

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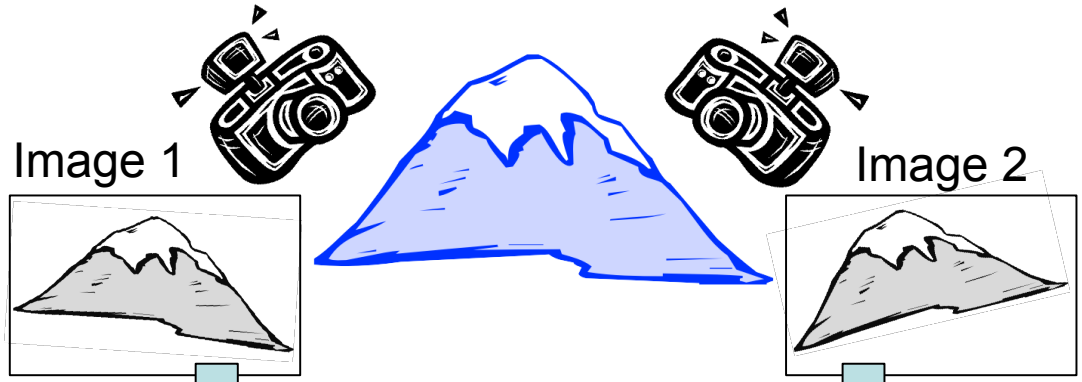
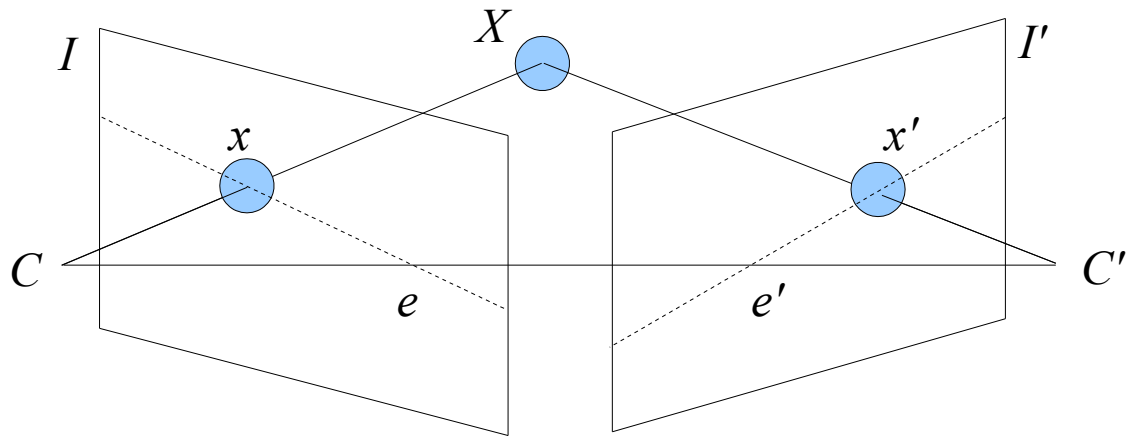


(1) Find Correspondences

(2) Estimate Scene Geometry

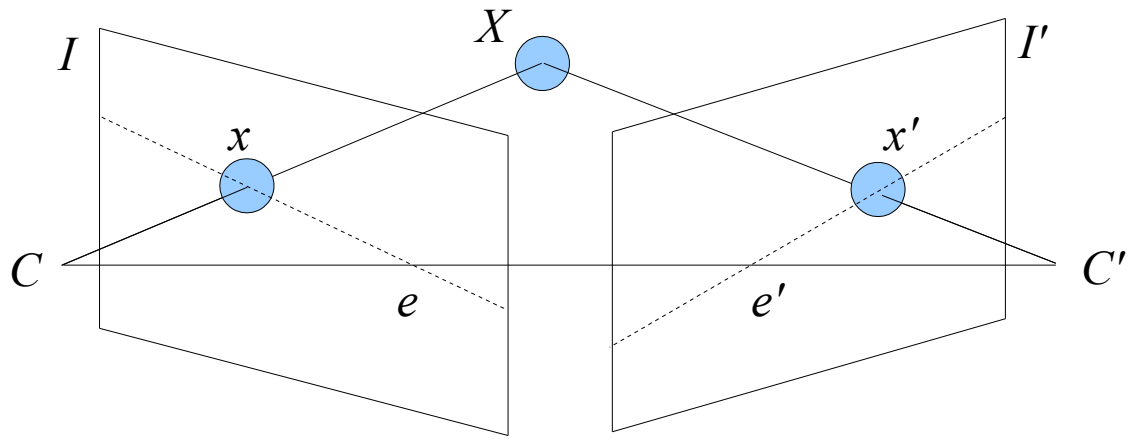
(3) **The TIP method:**
- Invariant feature correspondences
- Point-based geometry estimation

Scene Geometry



- Epipolar geometry
  - Relates a point X in a 3D scene to it's projections x, x' in different images I, I' of the scene.
  - Recovering the 3D scene geometry requires estimating the epipolar geometry.

Scene Geometry



- Fundamental matrix (FM)
  - Describes the epipolar geometry of an uncalibrated 2-image system.
  - A *3*x*3*, rank *2* matrix F satisfying:

    $$x'^{T}Fx = 0 \text{ and } \det(F) = 0,$$

    where x and x' are corresponding points in I and I'.

Fundamental Matrix Estimation

- Point-based methods:
  - Point-to-point correspondences.
  - 8-point algorithm: linear solution, 8+ correspondences.
  - 7-point algorithm: cubic solution, 7 correspondences.
  - Widely used: Intel OpenCV, others…
- Difficulties
  - Quality of estimation dependent on number and accuracy of correspondences.
  - 8 point-to-point correspondences required for linear estimation.
  - Sparse or noisy correspondence = unstable estimation.

Fundamental Matrix Estimation

- Other methods:
  - Higher order correspondences, i.e. lines, curves, conics.
  - Typically involve finding roots of Kruppa's equations.
  - Less popular.

Image Correspondence

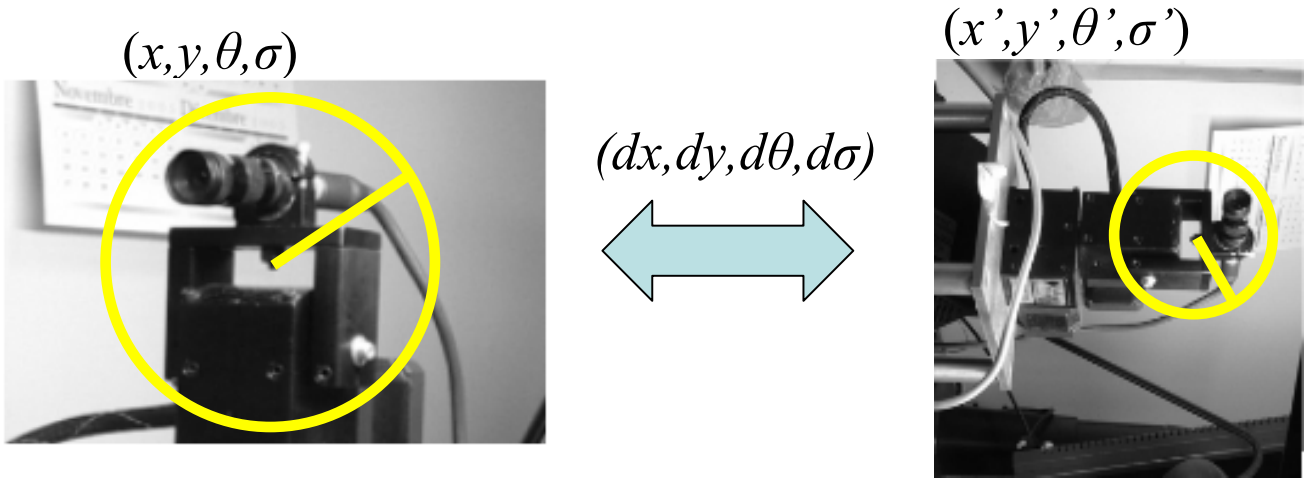
- Image correspondence
  - Identify points in different images arising from the same 3D world point.
- General approach
  - Consider informative image points that can be readily detected, and matched between images, e.g. corners.
- Difficulty
  - Detecting and matching points in the presence of image transformation arising from viewpoint change.

Invariant Feature Correspondence

- Invariant features
  - Image regions that are invariant under a transformation group, e.g. similarity transform, affine transform.
- Benefits
  - Robust to match over large changes in viewpoint.
  - Efficient to detect using image pyramids.
  - Generally applicable to many types of scenes.
  - Model a variety of image characteristics, i.e. edges, blobs, phase, entropy.
- Examples:
  - Similarity transform: scale-invariant features (SIFT, Lowe 2004)
  - Affine transform: affine-invariant features (Mikolajczyk, 2004).

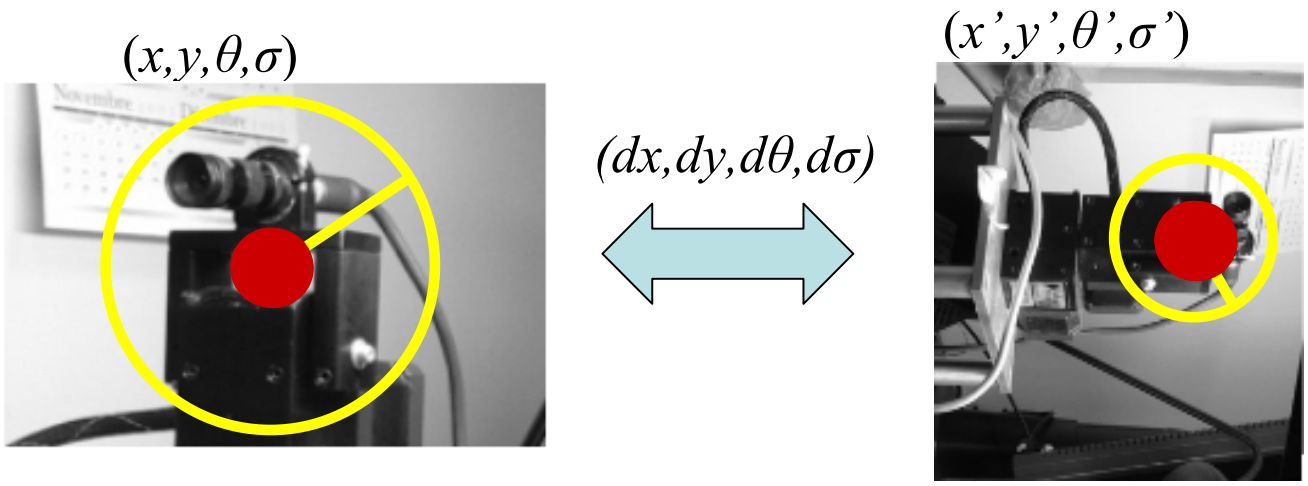
Invariant Feature Correspondence

- Invariant feature region:
  - Described by K parameters, e.g. location, orientation and scale (x,y,θ,σ).
- Invariant feature correspondence:
  - A K-parameter transform between two regions, i.e. $(dx,dy,d\theta,d\sigma)$.



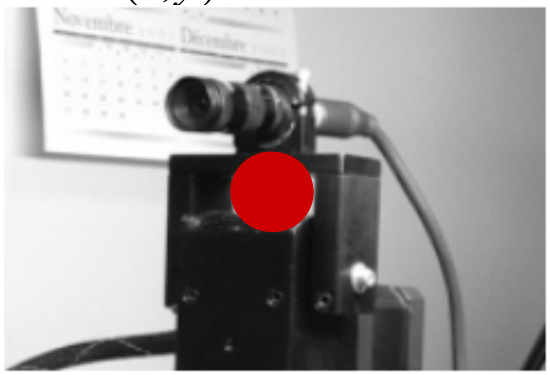
Invariant Features and FM Estimation

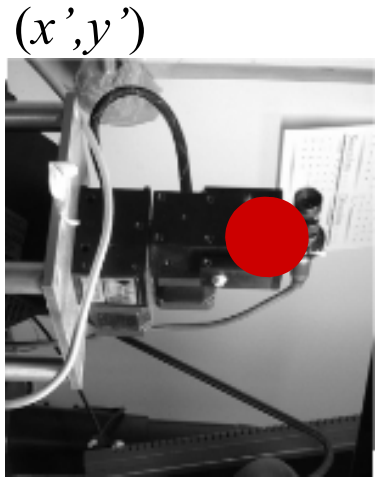
- Standard approach
  1) Use invariant region centers as point-to-point correspondences.
  2) Perform point-based FM estimation.



Invariant Features and FM Estimation

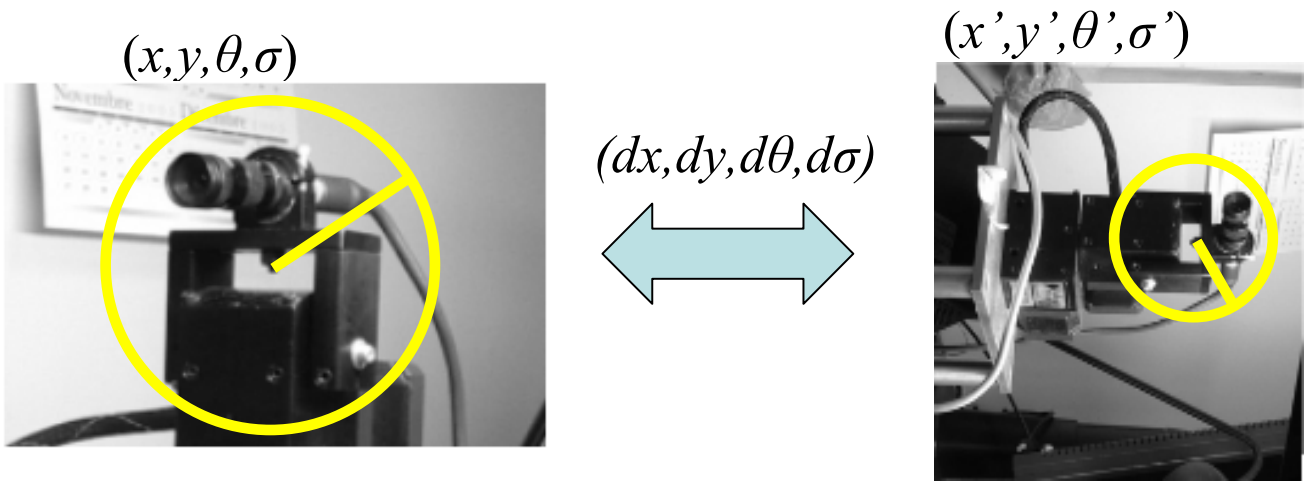
- Standard approach
  1) Use invariant region centers as point-to-point correspondences.
  2) Perform point-based FM estimation.
- Problem
  - Important geometrical information is thrown away!





Question

- Can additional geometrical information inherent to invariant feature correspondences be used to improve the quality of FM estimation?



Motivation

- 3D scene viewed as points

Motivation

- 3D scene viewed as invariant regions
  - More informative?

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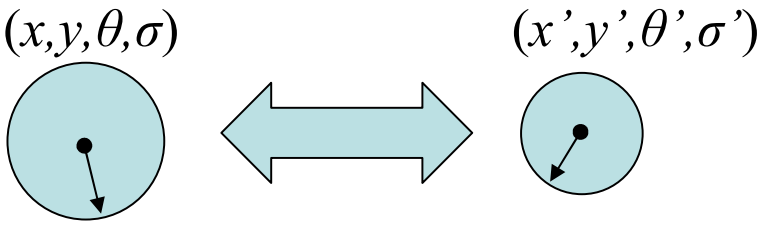
Motivation

- Original 3D scene

Transfer of Invariant Parameters (TIP)

- Each invariant feature correspondence represents a local geometric transform from one image to the next.



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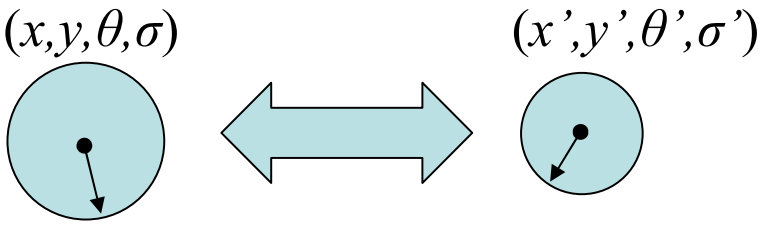

- This transform can be equivalently parameterized in terms of point-to-point matches: ***TIP matches***.

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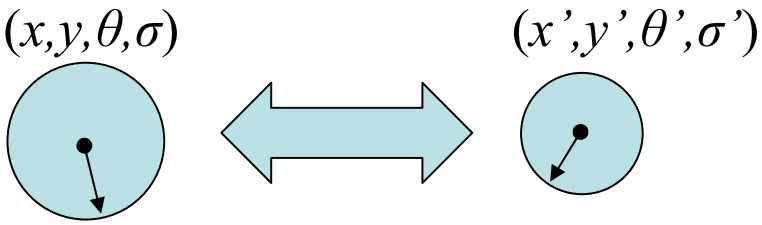

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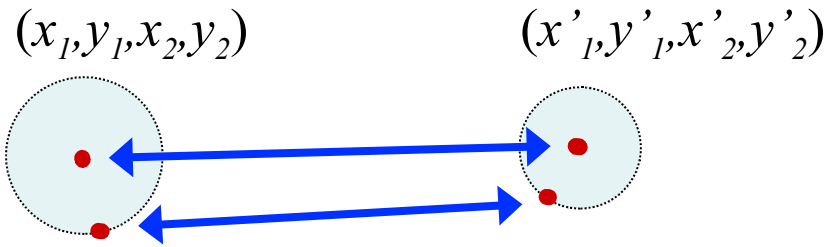
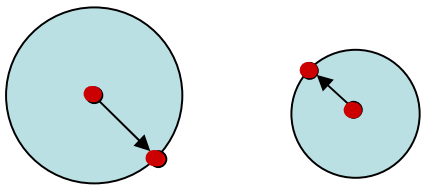
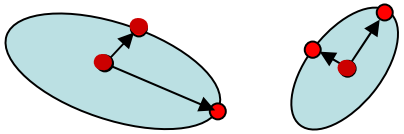


Transfer of Invariant Parameters (TIP)

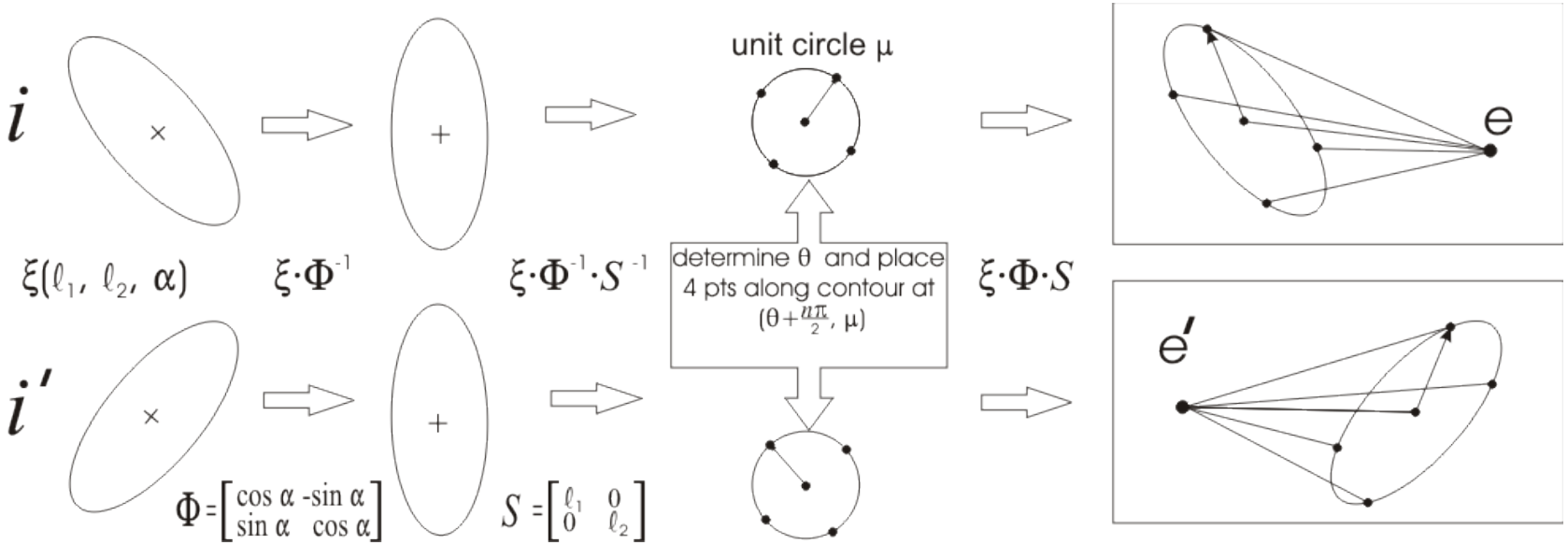
- TIP matches
  - Augment the number of point correspondences passed to FM estimation routines.
  - Improve robustness in the case of sparse correspondences.
  - Allow estimation from fewer than 8 invariant feature correspondences.
- How many additional TIP matches?
  - Determined by the number of parameters describing the invariant region K.

Transfer of Invariant Parameters (TIP)

Invariance	Parameters	K	Tip Matches	Invariant Corr. Req'd with TIP	Example TIP Matches
Translation	(x,y)	2	1	8 (*or* 7)	
Similarity (Scale)	(x,y,σ,θ)	4	2	4	
Affinity (Affine)	$(x,y,\theta,\alpha,\ell_1,\ell_2)$	6	3	3	

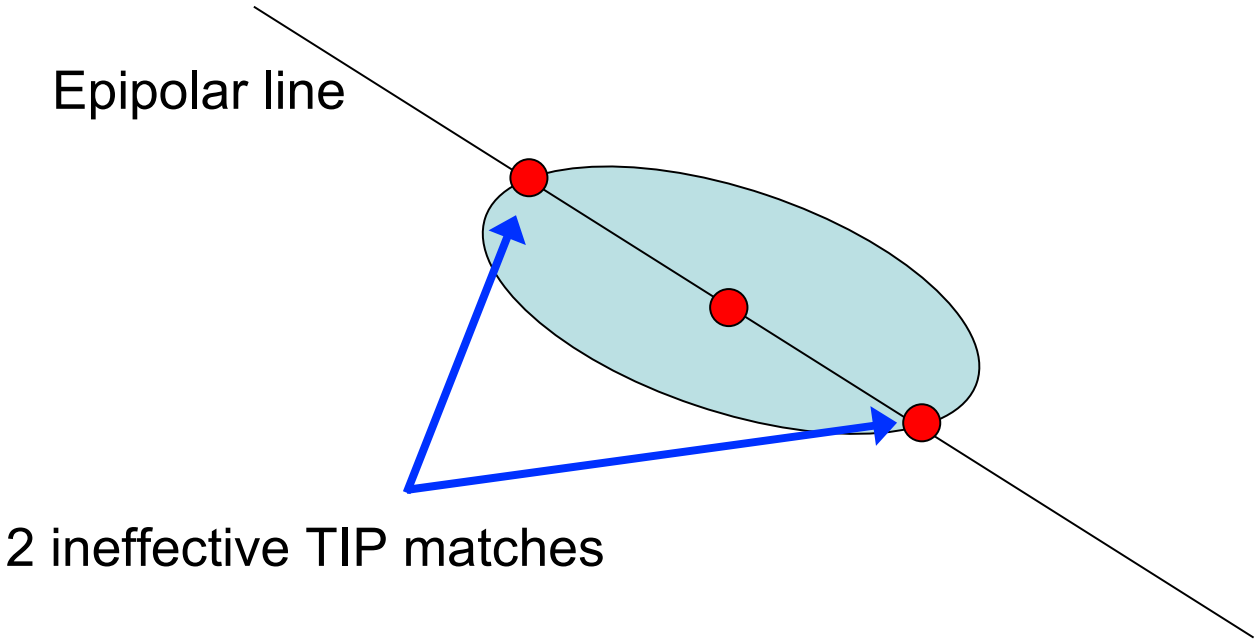
TIP with Affine Invariance

- Affine invariant correspondences
  - Elliptical invariant regions.
  - Good representation for locally planar surfaces, distant camera.
  - Add 5 TIP matches: 1 center + 4 along region boundaries.



TIP with Affine Invariance

- Why 5 TIP matches instead of 3?
  - Redundancy helps to avoid ineffective TIP matches.
  - For example, TIP matches lying along the same epipolar line.



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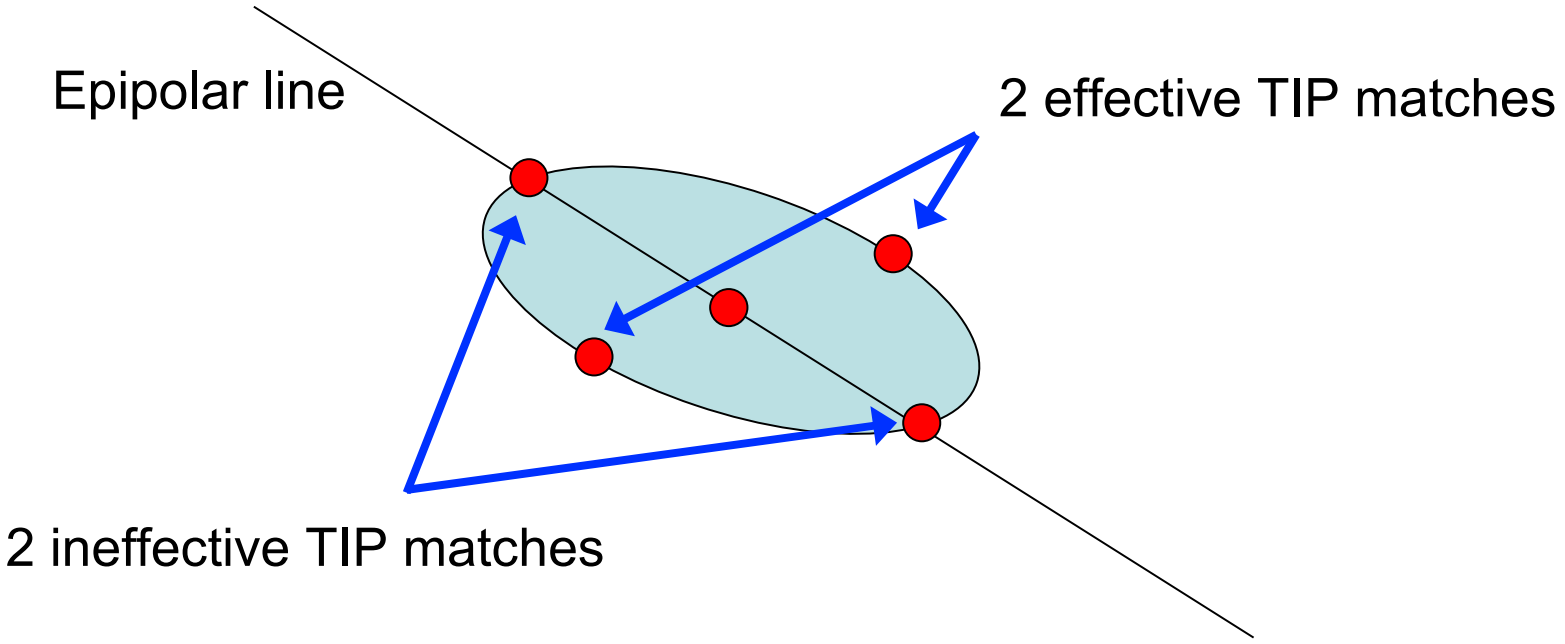
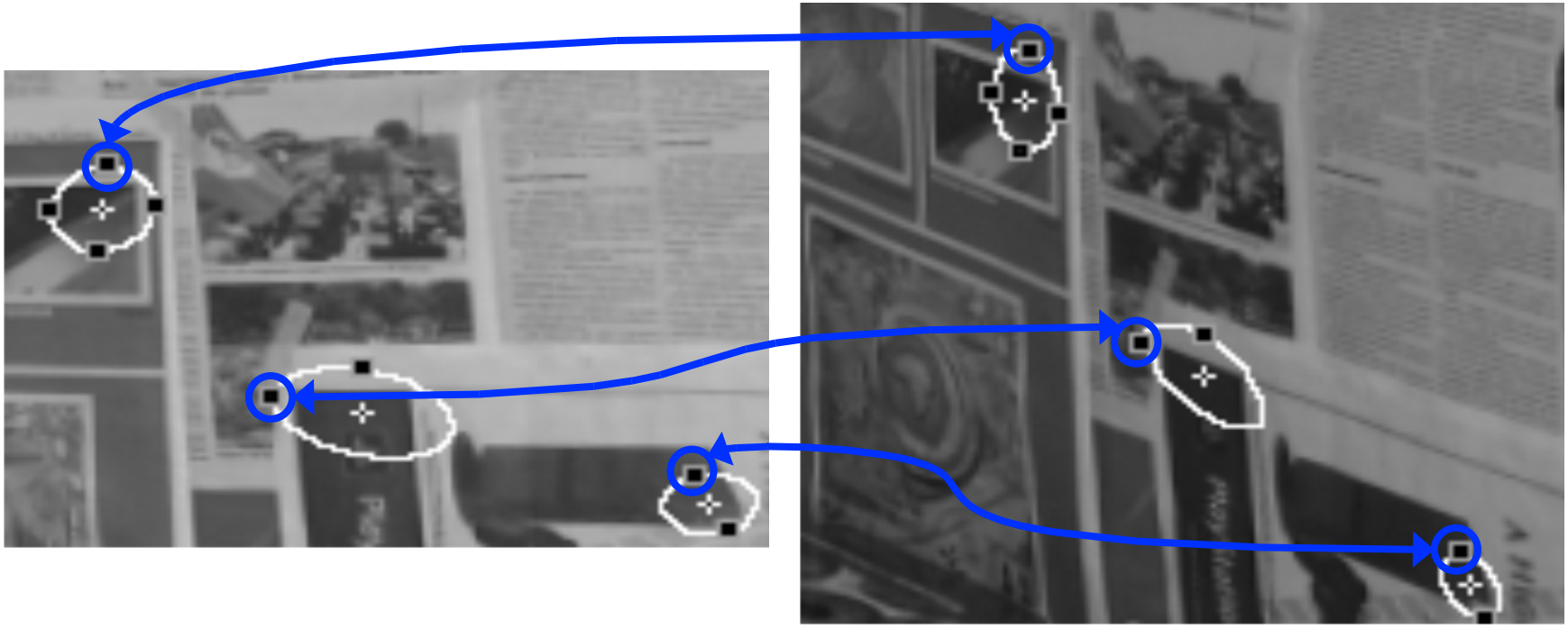


TIP with Affine Invariance

- Example: affine-invariant TIP matches



Experimentation

- Sample a set of *n* affine correspondences (inliers) between an image pair.
- For each correspondence set, estimate two FMs:

  F: estimated from feature centers for n = {20,...,7} using the 8-point algorithm, n = 7 using 7-point algorithm.

  F^{TIP}: estimated from TIP matches for n ={20,...,3} using the 8-point algorithm.

Note: F cannot be estimated for n ={6,...,3}

- Perform 100 random samples for each *n*.

Test Images

Error Measure

- Re-projection Error Distance (ε):
  - Pass manually-selected ground truth point correspondences through both F and F^{TIP}.
  - Calculate the re-projected distance (d) from the point ($\mathbf{x}_i$) to it's corresponding epipolar line:

$$\varepsilon^2 = \frac{1}{N}\sum_i d\left(\mathbf{x}'_i, \mathrm{F}\mathbf{x}_i\right)^2 + d\left(\mathbf{x}_i, \mathrm{F}^{\mathrm{T}}\mathbf{x}'_i\right)^2$$

- Catastrophic failure
  - FM estimates resulting in $\varepsilon > 25$

Results

- TIP estimates result in fewer catastrophic cases.

Results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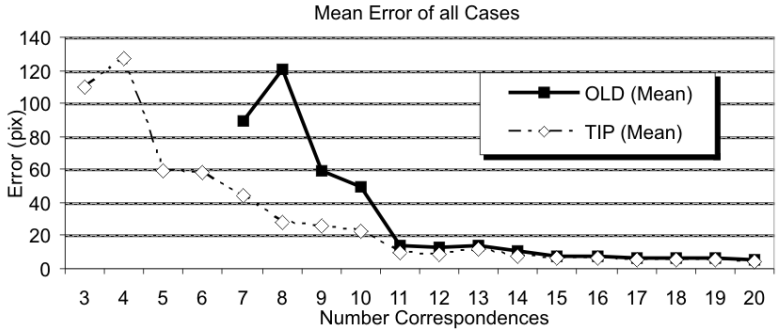
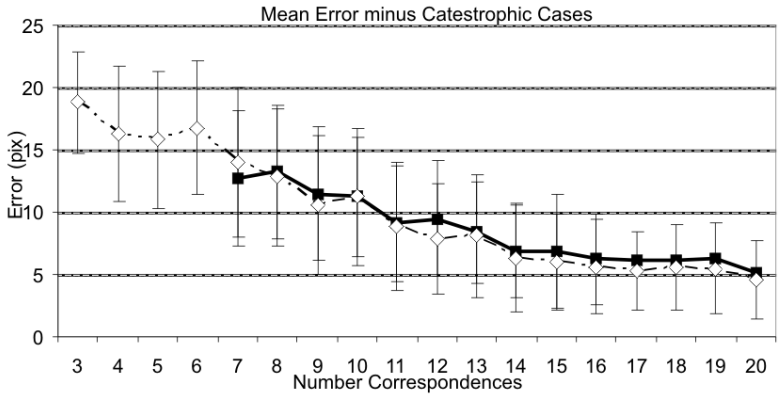
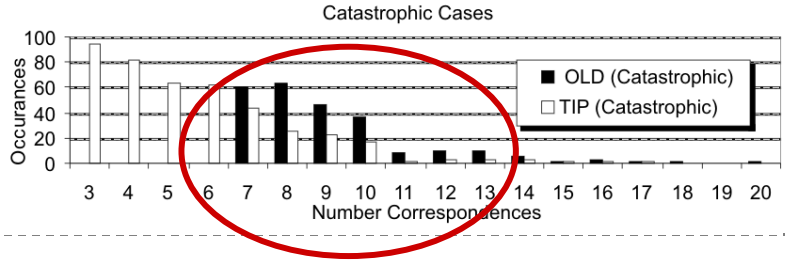

Mean Error of all Cases
Error (pix)
Number Correspondences
OLD (Mean)
TIP (Mean)


Mean Error minus Catestrophic Cases
Error (pix)
Number Correspondences


Catastrophic Cases
Occurances
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OLD (Catastrophic)
TIP (Catastrophic)

Results

- TIP estimates result in fewer catastrophic cases.
- TIP estimates result in lower re-projection error.

Results


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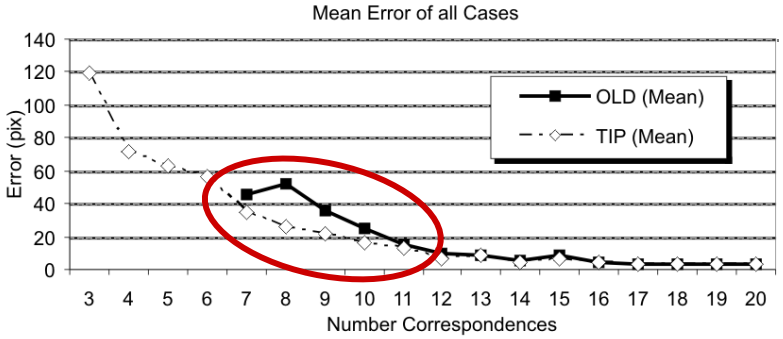
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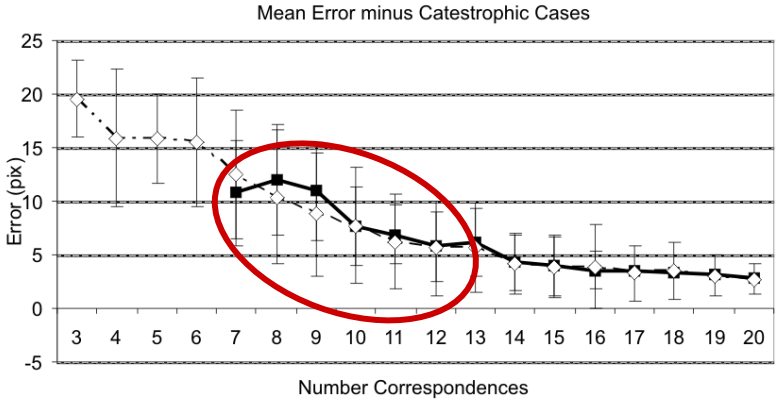
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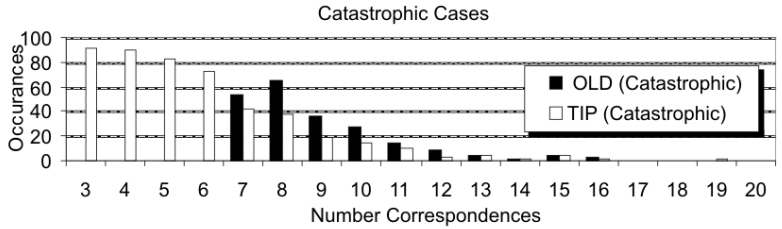
Catastrophic Cases
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OLD (Catastrophic)
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Results

- TIP estimates result in fewer catastrophic cases.
- TIP estimates result in lower re-projection error.
- TIP allows for FM estimates with less than 7 invariant feature correspondences using standard point-based techniques.

Results


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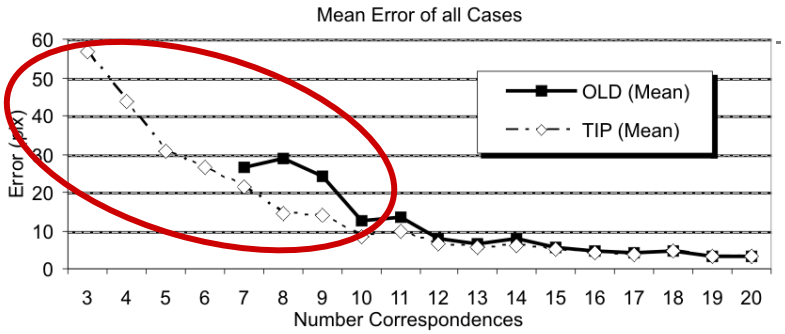
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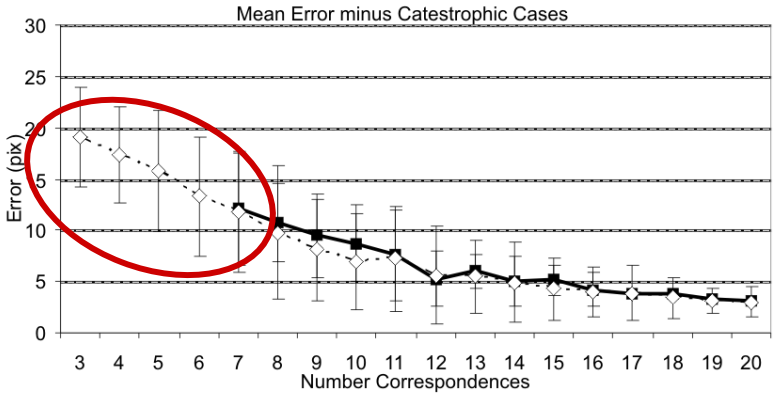
Mean Error minus Catestrophic Cases
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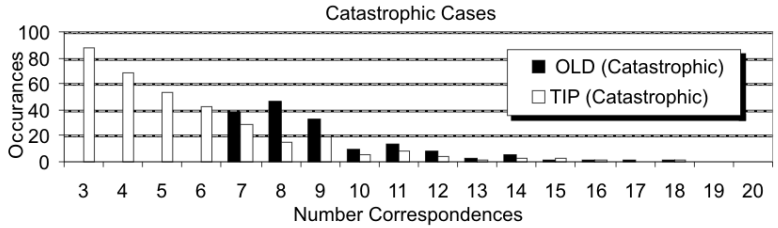
Catastrophic Cases
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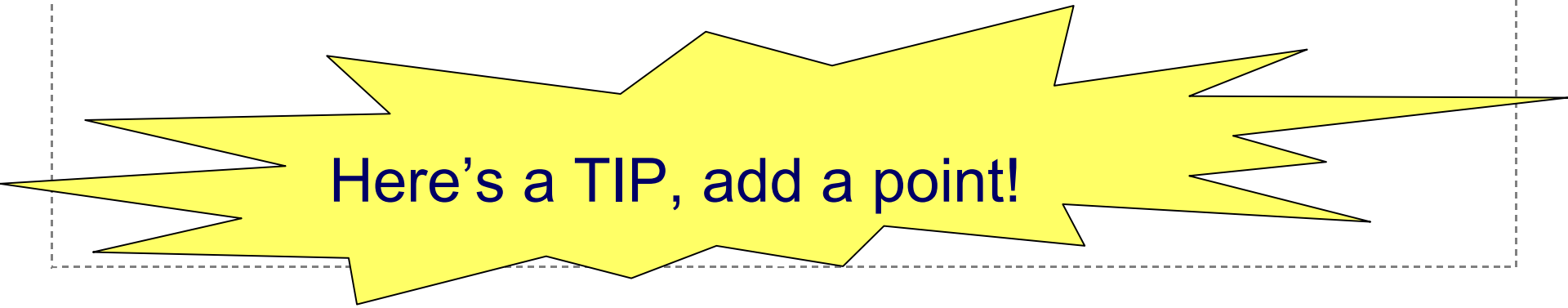
OLD (Catastrophic)
TIP (Catastrophic)

Discussion

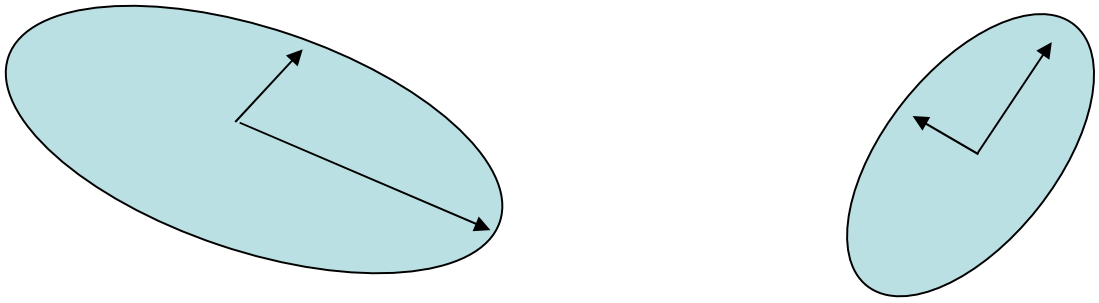
- The TIP method
  - Effective for correspondences arising from planar surfaces.
  - Less effective for complex 3D surfaces, difficult to represent accurately via invariant regions.
- Invariant feature geometrical information
  - Sufficient for matching but less effective for precise geometrical modeling.
  - Additional alignment of invariant regions after correspondence would improve the precision of additional TIP points.
  - Perspective alignment would allow estimation from as few as 2 invariant correspondences.

Summary

- The TIP method
  - Converts invariant correspondence parameters into point-to-point correspondences.
  - Incorporates local geometrical information into common point-based FM estimation routines.
  - Results in more robust FM estimation from fewer correspondences.

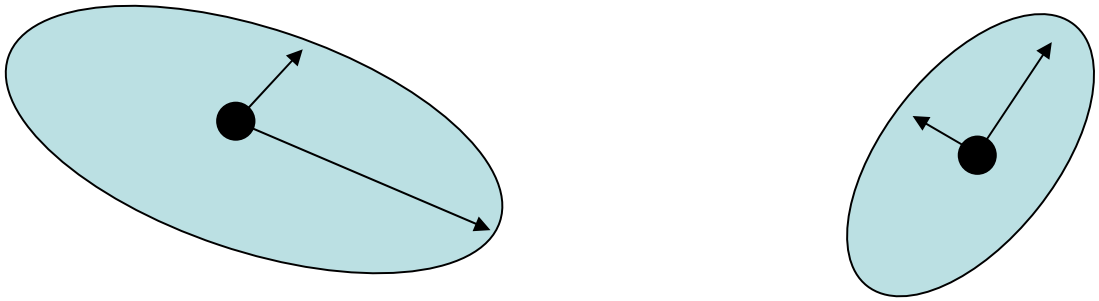


TIP Methodology



TIP Methodology

- Each invariant feature region is centered on an (x, y) point which we refer to as the *parent* point.



TIP Methodology

- Each invariant feature region is centered on an (x, y) point which we refer to as the *parent* point.
- Additional *child* points are canonically placed along the border of the invariant region of given scale, and rotation.