Vision Algorithms for Mobile Robotics

Lecture 09
Multiple View Geometry 3

Davide Scaramuzza
http://rpg.ifi.uzh.ch
Lab Exercise 7 – Today

Implement the P3P algorithm and RANSAC. Additionally, we will outline the mini projects
Outline

• Robust Structure from Motion
• Bundle Adjustment
Robust Estimation

- Matched points are usually contaminated by outliers (i.e., wrong image matches).
Robust Estimation

• Matched points are usually contaminated by outliers (i.e., wrong image matches).
• Causes of outliers are:
  • Repetitive features (i.e., features with the same appearance)
  • Geometric and photometric changes to which the descriptor is not invariant
  • Large image noise
  • Occlusions
  • Moving objects
  • Image or motion blur
• For reliable and accurate visual odometry, outliers must be removed
• This is the task of Robust Estimation
Effect of Outliers on Visual Odometry

Before removing the outliers

After removing the outliers
Expectation Maximization (EM) algorithm

• EM is a simple method for model fitting in the presence of outliers (very noisy points or wrong data)

• It can be applied to all sorts of problems where the goal is to estimate the parameters of a model from the data (e.g., camera calibration, Structure from Motion, DLT, PnP, P3P, Homography, etc.)

• Let’s review EM applied to the line fitting problem

[1] Dellaert, The expectation maximization algorithm, Georgia Institute of Technology, 2002. PDF (explains the original papers below)
EM applied to line fitting
EM applied to line fitting

1. Estimate line parameters that fit all data points (e.g., using least-square: $\min \sum r_i^2$, where $r_i$ is the point-to-line distance)
EM applied to line fitting

1. Estimate line parameters that fit all data points (e.g., using least-square: \( \min \sum r_i^2 \), where \( r_i \) is the point-to-line distance)

2. Calculate residual error \( r_i \) for each data point and assign it a weight (e.g., \( w_i = e^{-r_i^2} \) representing the likelihood that such assignment is correct (estimates the Expectation)
EM applied to line fitting

1. Estimate line parameters that fit all data points (e.g., using least-square: \( \min \sum r_i^2 \), where \( r_i \) is the point-to-line distance)

2. Calculate residual error \( r_i \) for each data point and assign it a weight (e.g., \( w_i = e^{-r_i^2} \) representing the likelihood that such assignment is correct (estimates the Expectation)

3. Re-estimate line parameters (e.g., using weighted least-squares: \( \min \sum w_i r_i^2 \)) (Maximization Step)
EM applied to line fitting

1. Estimate line parameters that fit all data points (e.g., using least-square: $\min \sum r_i^2$, where $r_i$ is the point-to-line distance)

2. Calculate residual error $r_i$ for each data point and assign it a weight (e.g., $w_i = e^{-r_i^2}$ representing the likelihood that such assignment is correct (estimates the Expectation))

3. Re-estimate line parameters (e.g., using weighted least-squares: $\min \sum w_i r_i^2$) (Maximization Step)

4. Iterate 2 and 3 till convergence

5. Select as **inliers** the data points with weight higher than a threshold
Problem of EM algorithm

Very sensitive to initial condition:

• This is because EM selects the initial condition by minimizing the sum of squared residuals $\sum r_i^2$.

• While this is a convex function, the result is strongly influenced by a few large error values (e.g., outliers).

• Thus, EM converges to the wrong solution if initial condition is far from the true one.

• Alternative options:
  • GNC algorithm
  • RANSAC algorithm
Graduated Non-Convexity algorithm (GNC)

**Idea:** optimize a surrogate function \( \sum \rho_{\mu}(r_i) \), where \( \mu \) controls the amount of non-convexity.

- Start by solving the non-robust convex optimization function \( (\mu \to 0, \text{i.e., least squares}) \)
- At each iteration, gradually increase non-convexity \( (\mu \to \infty) \) and recompute weights \( w_i \) till we achieve the desired level of robustness.
- It is shown in [1] to be robust up to 90% of outliers with five times fewer iterations than RANSAC.
- However, RANSAC can cope with even more than 90% outliers.

---


RANSAC (RAndom SAmple Consensus)

- RANSAC is the **standard method for model fitting in the presence of outliers** (very noisy points or wrong data)
- It is **non-deterministic**: you get a different result everytime you run it
- It is **not sensitive to the initial condition**, and **does not get stuck in local maxima**
- It can be applied to all sorts of problems where the goal is to **estimate the parameters of a model from the data** (e.g., camera calibration, Structure from Motion, DLT, PnP, P3P, Homography, etc.)
- Let’s review RANSAC for line fitting and see how we can use it to do Structure from Motion

RANSAC
1. Select a sample of 2 points at random
RANSAC

1. Select a sample of 2 points at random

2. Calculate model parameters that fit the data in the sample
1. Select a sample of 2 points at random

2. Calculate model parameters that fit the data in the sample

3. Calculate the residual error for each data point
RANSAC

1. Select a sample of 2 points at random
2. Calculate model parameters that fit the data in the sample
3. Calculate the residual error for each data point
4. Select data that support current hypothesis
RANSAC

1. Select a sample of 2 points at *random*
2. Calculate model parameters that fit the data in the sample
3. Calculate the residual error for each data point
4. Select data that support current hypothesis
5. Repeat from step 1 for \( k \) times
RANSAC

1. Select a sample of 2 points at random
2. Calculate model parameters that fit the data in the sample
3. Calculate the residual error for each data point
4. Select data that support current hypothesis
5. Repeat from step 1 for $k$ times
1. Select a sample of 2 points at random
2. Calculate model parameters that fit the data in the sample
3. Calculate the residual error for each data point
4. Select data that support current hypothesis
5. Repeat from step 1 for $k$ times
6. Select the set with the maximum number of inliers obtained within $k$ iterations

RANSAC
1. Select a sample of 2 points at random
2. Calculate model parameters that fit the data in the sample
3. Calculate the residual error for each data point
4. Select data that support current hypothesis
5. Repeat from step 1 for $k$ times
6. Select the set with the maximum number of inliers obtained within $k$ iterations
7. Finally, calculate the model parameters using all the inliers

**NB:** RANSAC is **non deterministic:** every time you run it you may get a different result (due to the random hypotheses’ generation process). Conversely, **EM and GNC** are **deterministic**
RANSAC

- How many iterations does RANSAC need?
- Ideally: check all possible combinations of 2 points in a dataset of N points.
- Number of all pairwise combinations: \( \frac{N(N-1)}{2} \)
  - computationally unfeasible if \( N \) is too large. Example, for 1000 points you need to check all \( 1000 \times 999/2 \approx 500'000 \) possibilities!

- Do we really need to check all possibilities or can we stop RANSAC after some iterations?
  - We will see that it is enough to check a subset of all combinations if we have a rough estimate of the percentage of inliers in our dataset
  - This can be done in a probabilistic way
RANSAC

• How many iterations does RANSAC need?
  • \( N := \) total number of data points
  • \( w := \) number of inliers / \( N \rightarrow w: \) fraction of inliers in the dataset \( \rightarrow w = P(\) selecting an inlier-point out of the dataset\()\)
  • Assumption: the 2 points necessary to estimate a line are selected independently
    • \( \rightarrow w^2 = P(\) both selected points are inliers\()\)
    • \( \rightarrow 1 - w^2 = P(\) at least one of these two points is an outlier\()\)
  • Let \( k \) be the number of RANSAC iterations executed so far
    • \( \rightarrow (1 - w^2)^k = P(\) RANSAC never selected two points that are both inliers after \( k \) iterations\()\)
  • Let \( p := \) Probability to have selected at least two points that are both inliers after \( k \) iterations. We call \( p \) Probability of Success
    • \( \rightarrow 1 - p = (1 - w^2)^k \) and therefore:
      \[
k = \frac{\log(1 - p)}{\log(1 - w^2)}
\]
RANSAC

• How many iterations does RANSAC need?

\[ k = \frac{\log(1 - p)}{\log(1 - w^2)} \]

→ knowing the fraction of inliers \( w \), after \( k \) iterations we will have a probability \( p \) of finding a set of points free of outliers

• Example: if we want a probability of success \( p = 99\% \) and we know that \( w = 50\% \) → \( k = 16 \) iterations
  • these are significantly fewer than the number of all possible combinations (500,000)!
  • Notice: the number of data points does not influence the minimum number of iterations \( k \), only \( w \) does!

• In practice we only need a rough estimate of \( w \). More advanced variants of RANSAC estimate the fraction of inliers and adaptively update it at every iteration (how?)
RANSAC applied to Line Fitting

1. Initial: let $A$ be a set of $N$ points

2. repeat

3. Randomly select a sample of 2 points from $A$

4. **Fit a line** through the 2 points

5. Compute the **distances** of all other points from this line

6. Construct the inlier set (i.e. count the number of points whose distance $< d$)

7. Store these inliers

8. **until** maximum number of iterations $k$ reached

9. The set with the maximum number of inliers is chosen as a solution to the problem

$$k = \frac{\log(1 - p)}{\log(1 - w^2)}$$
1. Initial: let $A$ be a set of $N$ points

2. repeat

3. Randomly select a sample of $s$ points from $A$

4. Fit a model from the $s$ points

5. Compute the distances of all other points from this model

6. Construct the inlier set (i.e. count the number of points whose distance $< d$)

7. Store these inliers

8. until maximum number of iterations $k$ reached

9. The set with the maximum number of inliers is chosen as a solution to the problem

$$k = \frac{\log(1 - p)}{\log(1 - w^s)}$$
RANSAC applied to General Model Fitting

1. Initial: let $A$ be a set of $N$ points
2. repeat
3. Randomly select a sample of $s$ points from $A$
4. Fit a model from the $s$ points
5. Compute the distances of all other points from this model
6. Construct the inlier set (i.e. count the number of points whose distance < $d$)
7. Store these inliers
8. until maximum number of iterations $k$ reached
9. The set with the maximum number of inliers is chosen as a solution to the problem

$$k = \frac{\log(1 - p)}{\log(1 - (1 - \varepsilon)^s)}$$

NB: The formula is more commonly written as a function of the fraction of outliers $\varepsilon$
The Three Key Ingredients of RANSAC

In order to implement RANSAC for Structure From Motion (SFM), we need three key ingredients:

1. What’s the model in SFM?
2. What’s the minimum number of points to estimate the model?
3. How do we compute the distance of a point from the model? In other words, can we define a distance metric that measures how well a point fits the model?
1. What’s the model in SFM?
   - The **Essential Matrix** (for calibrated cameras) or the **Fundamental Matrix** (for uncalibrated cameras)
   - Alternatively, $\mathbf{R}$ and $\mathbf{T}$

2. What’s the **minimum number of points** to estimate the model?
   1. We know that 5 points is the theoretical minimum number of points for calibrated cameras
   2. However, if we use the **8-point algorithm**, then 8 is the minimum (for both calibrated or uncalibrated cameras)

3. How do we compute the **distance** of a point from the model?
   1. Algebraic error
   2. Directional error
   3. Epipolar line distance
   4. Reprojection error
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows

![Image 1](image1.png) ![Image 2](image2.png)
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows

• For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows

• For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features

1. Randomly select 8 point correspondences and compute the model

Image 1
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows
• For convenience, we overlay the features of the second image on the first image and use arrows to denote the *motion vectors* of the features

1. Randomly select 8 point correspondences and compute the model
2. Compute distance of all other points from this model and count the inliers
Example: 8-point RANSAC applied to SFM

- Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows.
- For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features.

1. Randomly select 8 point correspondences and compute the model.
2. Compute distance of all other points from this model and count the inliers.
3. Repeat from 1.
Example: 8-point RANSAC applied to SFM

- Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows.
- For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features.
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows

• For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features

1. Randomly select 8 point correspondences and compute the model

Image 1
Example: 8-point RANSAC applied to SFM

• Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows
• For convenience, we overlay the features of the second image on the first image and use arrows to denote the *motion vectors* of the features

1. Randomly select 8 point correspondences and compute the model
2. Compute distance of all other points from this model and count the inliers
Example: 8-point RANSAC applied to SFM

- Let’s consider the following image pair and its image correspondences (e.g., Harris, SIFT, etc.), denoted by arrows
- For convenience, we overlay the features of the second image on the first image and use arrows to denote the motion vectors of the features

1. Randomly select 8 point correspondences and compute the model
2. Compute distance of all other points from this model and count the inliers
3. Repeat from 1 for $k$ times

\[ k = \frac{\log(1 - p)}{\log(1 - (1 - \varepsilon)^8)} \]
RANSAC iterations $k$ vs. $s$

$k$ increases exponentially with the number of points $s$ estimate the model.

Let’s assume $p = 99\%$ and $\varepsilon = 50\%$ (fraction of outliers):

- **8-point RANSAC**
  - $s = 8$ points (8-point algorithm)

  $k = \frac{\log(1 - p)}{\log(1 - (1 - \varepsilon)^8)} = 1177 \text{ iterations}$

- **5-point RANSAC**
  - $s = 5$ points (5-point algorithm)

  $k = \frac{\log(1 - p)}{\log(1 - (1 - \varepsilon)^5)} = 145 \text{ iterations}$

- **2-point RANSAC (e.g., line fitting)**
  - $s = 2$ points

  $k = \frac{\log(1 - p)}{\log(1 - (1 - \varepsilon)^2)} = 16 \text{ iterations}$
**RANSAC iterations $k$ vs. $\varepsilon$**

$k$ is increases exponentially with the fraction of outliers $\varepsilon$:

These plots were computed assuming $p = 99\%$
RANSAC iterations

• As observed, $k$ is exponential with the number of points $s$ necessary to estimate the model

• The 8-point algorithm is extremely simple and was very successful; however, it requires more than 1177 iterations

• Because of this, there has been a large interest by the research community in using smaller motion parameterizations (i.e., smaller $s$)

• The first efficient solution to the minimal-case solution (5-point algorithm) took almost a century (Kruppa 1913 → Nister 2004)

• The 5-point RANSAC (Nister 2004) only requires 145 iterations; however:
  • The 5-point algorithm can return up to 10 solutions of $E$ (worst case scenario)
  • The 8-point algorithm only returns a unique solution of $E$

Can we use less than 5 points?
Yes, if you use motion constraints!
Planar Motion

Planar motion is described by three parameters: $\theta$, $\phi$, $\rho$

$$
R = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

$$
T = \begin{bmatrix}
\rho \cos \phi \\
\rho \sin \phi \\
0
\end{bmatrix}
$$

Let’s compute the Epipolar Geometry

$$
E = [T_x]R \quad \text{Essential matrix}
$$

$$
\overline{p}_2^T E \overline{p}_1 = 0 \quad \text{Epipolar constraint}
$$
Planar Motion

Planar motion is described by three parameters: $\theta$, $\varphi$, $\rho$

$$R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \varphi \\ \rho \sin \varphi \\ 0 \end{bmatrix}$$

Let’s compute the Epipolar Geometry

$$[T_x] = \begin{bmatrix} 0 & 0 & \rho \sin \varphi \\ 0 & 0 & -\rho \cos \varphi \\ -\rho \sin \varphi & \rho \cos \varphi & 0 \end{bmatrix}$$
Planar motion is described by three parameters: \( \theta \), \( \varphi \), \( \rho \)

\[
R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \varphi \\ \rho \sin \varphi \\ 0 \end{bmatrix}
\]

Let’s compute the Epipolar Geometry

\[
E = [T_x] R = \begin{bmatrix} 0 & 0 & \rho \sin \varphi \\ 0 & 0 & -\rho \cos \varphi \\ -\rho \sin \varphi & \rho \cos \varphi & 0 \end{bmatrix} \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]
Planar Motion

Planar motion is described by three parameters: $\theta$, $\varphi$, $\rho$

$$R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \varphi \\ \rho \sin \varphi \\ 0 \end{bmatrix}$$

Let’s compute the Epipolar Geometry

$$E = [T_x]R = \begin{bmatrix} 0 & 0 & \rho \sin (\varphi) \\ 0 & 0 & -\rho \cos (\varphi) \\ -\rho \sin (\varphi - \theta) & \rho \cos (\varphi - \theta) & 0 \end{bmatrix}$$

“2-Point RANSAC”, Ortin & Montiel, Indoor robot motion based on monocular images, Robotica, 2001. [PDF].
Planar Motion

Planar motion is described by three parameters: $\theta$, $\phi$, $\rho$

$$R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \phi \\ \rho \sin \phi \\ 0 \end{bmatrix}$$

Let’s compute the Epipolar Constraint: $\overline{p}_2^T E \overline{p}_1 = 0$

$$-u_1 \sin(\phi - \theta) + v_1 \cos(\phi - \theta) + u_2 \sin(\phi) - v_2 \cos(\phi) = 0$$

“2-Point RANSAC”, Ortin & Montiel, Indoor robot motion based on monocular images, Robotica, 2001. PDF.
Planar Motion

Planar motion is described by three parameters: \( \theta, \varphi, \rho \)

\[
R = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
T = \begin{bmatrix}
\rho \cos \varphi \\
\rho \sin \varphi \\
0
\end{bmatrix}
\]

Observe that \( \rho \) was cancelled out. Since only \( \theta, \varphi \) can be determined and every point correspondence provides one scalar equation, then 2 point correspondences are sufficient to estimate \( \theta \) and \( \varphi \)

\[-u_1 \sin(\phi - \theta) + v_1 \cos(\phi - \theta) + u_2 \sin(\phi) - v_2 \cos(\phi) = 0\]

“2-Point RANSAC”, Ortin & Montiel, Indoor robot motion based on monocular images, Robotica, 2001. [PDF]
Less than 2 points?

• Can we use less than 2 point correspondences?
  • Yes, if we exploit wheeled vehicles with non-holonomic constraints
Planar & Circular Motion (e.g., cars)

Wheeled vehicles, like cars, follow locally-planar circular motion about the Instantaneous Center of Rotation (ICR)

Example of Ackerman steering principle

Locally-planar circular motion
Planar & Circular Motion (e.g., cars)

Wheeled vehicles, like cars, follow locally-planar circular motion about the Instantaneous Center of Rotation (ICR)

\[ \varphi = \theta / 2 \Rightarrow \text{only 1 DoF (}\theta\text{)}; \text{thus, only 1 point correspondence is sufficient [Scaramuzza, 2011]} \]

This is the smallest parameterization possible and results in the most efficient algorithm for removing outliers

Planar & Circular Motion (e.g., cars)

Let’s compute the Epipolar Geometry

\[ E = [T_x]R \quad \text{Essential matrix} \]

\[ R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \frac{\theta}{2} \\ \rho \sin \frac{\theta}{2} \\ 0 \end{bmatrix} \]

\[ \bar{p}_2^T E \bar{p}_1 = 0 \quad \text{Epipolar constraint} \]

Locally-planar circular motion

Planar & Circular Motion (e.g., cars)

Let’s compute the Epipolar Geometry

$$E = [T_x]R$$  

**Essential matrix**

$$R = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad T = \begin{bmatrix} \rho \cos \frac{\theta}{2} \\ \rho \sin \frac{\theta}{2} \\ 0 \end{bmatrix}$$

$$\overline{p}_2^T E \overline{p}_1 = 0$$  

**Epipolar constraint**

$$E = [T_x]R = \begin{bmatrix} 0 & 0 & \rho \sin \frac{\theta}{2} \\ 0 & 0 & -\rho \cos \frac{\theta}{2} \\ -\rho \sin \frac{\theta}{2} & \rho \cos \frac{\theta}{2} & 0 \end{bmatrix} \cdot \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \rho \sin \frac{\theta}{2} \\ 0 & 0 & -\rho \cos \frac{\theta}{2} \\ \rho \sin \frac{\theta}{2} & -\rho \cos \frac{\theta}{2} & 0 \end{bmatrix}$$

$$\overline{p}_2^T E \overline{p}_1 = 0 \Rightarrow \sin \left(\frac{\theta}{2}\right) \cdot (u_2 + u_1) + \cos \left(\frac{\theta}{2}\right) \cdot (v_2 - v_1) = 0$$

Notice that $\rho$ can be cancelled out

$$\theta = -2 \tan^{-1}\left(\frac{v_2 - v_1}{u_2 + u_1}\right)$$

1-Point RANSAC Algorithm

Compute $\theta$ for every point correspondence

$$\theta = -2 \tan^{-1} \left( \frac{v_2 - v_1}{u_2 + u_1} \right)$$

Only 1 iteration!
The most efficient algorithm for removing outliers (<1ms)

1-Point RANSAC is ONLY used to find the inliers.
Motion is then estimated from them in 6DOF
1-Point RANSAC Algorithm

Compute $\theta$ for every point correspondence:

$$\theta = -2 \tan^{-1} \left( \frac{v_2 - v_1}{u_2 + u_1} \right)$$

Only 1 iteration!
The most efficient algorithm for removing outliers (<1ms)

1-Point RANSAC is ONLY used to find the inliers.
Motion is then estimated from them in 6DOF
Comparison of RANSAC algorithms

\[ N = \frac{\log(1 - p)}{\log(1 - (1 - \epsilon)^s)} \]

where we typically use \( p = 99\% \)

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Numb. of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Point RANSAC [Longuet-Higgins’81]</td>
<td>&gt; 1177</td>
</tr>
<tr>
<td>5-Point RANSAC [Nister’04]</td>
<td>&gt;145</td>
</tr>
<tr>
<td>2-Point RANSAC [Ortin’01]</td>
<td>&gt;16</td>
</tr>
<tr>
<td>1-Point RANSAC [Scaramuzza’11]</td>
<td>=1</td>
</tr>
</tbody>
</table>
Visual Odometry with 1-Point RANSAC

Latest and Greatest 😊
Differentiable RANSAC

- RANSAC is not differentiable since it relies on selecting a hypothesis based on maximizing the number of inliers (i.e., argmax).
- DSAC shows how sample consensus can be used in a differentiable way.
- This enables the use of sample consensus in a variety of learning tasks.

E. Brachmann et al., DSAC - Differentiable RANSAC for Camera Localization, International Conference on Computer Vision and Pattern Recognition (CVPR), 2017. [PDF](#). [Video](#).
Deep Fundamental Matrix Estimation

- **Input**: two sets of noisy local features (coordinates + descriptors) contaminated by outliers
- **Output**: fundamental matrix
- **Idea**: solve a weighted homogeneous least-squares problem, where robust weights are estimated using deep networks
- **Robust**: handles extreme wide-baseline image pairs

SuperGlue: Learning Feature Matching with Graph Neural Networks

- **Input**: two sets of noisy local features (coordinates + descriptors) contaminated by outliers
- **Output**: strong & outlier-free matches
- **Combines deep learning with classical optimization** (Graph Neural Networks, Attention, Optimal Transport)
- **Robust**: handles extreme wide-baseline image pairs

Sarlin, DeTone, Malisiewicz, Rabinovich, *SuperGlue: Learning Feature Matching with Graph Neural Networks*, International Conference on Computer Vision and Pattern Recognition (CVPR), 2020. [PDF](#), [Code](#).
Outline

• Robust Structure from Motion
• Bundle Adjustment
2-View Bundle Adjustment (BA)

• Non-linear, joint optimization of structure, \( P^i \), and motion \( R, T \)
• Commonly used after least square estimation of \( R \) and \( T \) (e.g., after 8- or 5-point algorithm)
• Optimizes \( P^i, R, T \) by minimizing the **Sum of Squared Reprojection Errors**:

\[
P^i, R, T = \arg\min_{P^i, R, T} \sum_{i=1}^{N} \| p_1^i - \pi(P^i, K_1, I, 0) \|^2 + \| p_2^i - \pi(P^i, K_2, R, T) \|^2
\]

2-View Bundle Adjustment (BA)

- Non-linear, joint optimization of structure, \( P^i \), and motion \( R, T \)
- Commonly used after least square estimation of \( R \) and \( T \) (e.g., after 8- or 5-point algorithm)
- Optimizes \( P^i, R, T \) by minimizing the **Sum of Squared Reprojection Errors**:

\[
P^i, R, T = \arg\min_{P^i, R, T} \sum_{i=1}^{N} \left\| p_i^1 - \pi(P^i, K_1, I, 0) \right\|^2 + \left\| p_i^2 - \pi(P^i, K_2, R, T) \right\|^2
\]

Good to know:
- Like in the formula, we typically assume the first camera as the world frame, but it’s arbitrary
- Occasionally, the residual terms are weighted
- In order to not get stuck in local minima, the **initial values of \( P^i, R, T \) should be close to the optimum**
- Can be minimized using **Levenberg–Marquardt** (more robust than Gauss-Newton to local minima)
- **Can be modified to also optimize the intrinsic parameters**
- Implementation details in **Exercise 9**

What is the key difference with the reprojection error minimization seen in previous lectures (Lecture 3, slide 21, and Lecture 7, slide 26)?
\( n \)-View Bundle Adjustment (BA)

- Non-linear, joint optimization of structure, \( P^i \), and camera poses \( C_1 = [I, 0], \ldots, C_k = [R_k, T_k] \)
- Minimizes the Sum of Squared Reprojection Errors \textbf{across all views}

\[
p^i, C_2, \ldots, C_n = \arg\min_{P^i, C_2, \ldots, C_n} \sum_{k=1}^{n} \sum_{i=1}^{N} \|p^i_k - \pi(P^i, K_k, C_k)\|^2
\]

- NB: we assume the first camera as the world frame, that’s why \( C_1 = [I, 0] \)

Huber and Tukey Norms

- To prevent that large reprojection errors can negatively impact the optimization, a more robust norm $\rho(\cdot)$ is used instead of the $L_2$:

$$P^i, C_2, \ldots, C_n = \arg\min_{P^i, C_2, \ldots, C_n} \sum_{k=1}^{n} \sum_{i=1}^{N} \rho(p^i_k - \pi(P^i, K_k, C_k))$$

- $\rho(\cdot)$ is a robust cost function (Huber or Tukey) to alleviate the contribution of wrong matches:

  - **Huber norm:** $\rho(x) = \begin{cases} x^2 & \text{if } |x| \leq k \\ k(2|x| - k) & \text{if } |x| \geq k \end{cases}$

  - **Tukey norm:** $\rho(x) = \begin{cases} \alpha^2 & \text{if } |x| \geq \alpha \\ \alpha^2 \left(1 - \left(1 - \left(\frac{x}{\alpha}\right)^2\right)^3\right) & \text{if } |x| \leq \alpha \end{cases}$

These formulas are not asked at the exam but their plots and meaning is asked ☺
Things to remember

• EM algorithm
• RANSAC algorithm and its application to SFM
• 8 vs 5 vs 1 point RANSAC, pros and cons
• Bundle Adjustment
Reading

- CH. 8.1.4, 8.3.1, 11.3 of Szeliski book, 2nd edition
- Ch. 14.2 of Corke book
Understanding Check

Are you able to answer the following questions?

• What are the causes of outliers?
• What effects may outliers have on VO?
• How does EM work? What are the issues?
• Why do we need RANSAC?
• What is the theoretical maximum number of combinations to explore?
• After how many iterations can RANSAC be stopped to guarantee a given success probability?
• What is the trend of RANSAC vs. iterations, vs. the fraction of outliers, vs. the number of points to estimate the model?
• How do we apply RANSAC to the 8-point algorithm, DLT, P3P?
• How can we reduce the number of RANSAC iterations for the SFM problem? (1- and 2-point RANSAC)
• Bundle Adjustment. Mathematical expression and illustration. Tukey and Huber norms.