Robot Vision:
Robust Estimation

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SS 2023
Outline

- Ransac concept
- Ransac for fundamental matrix estimation
- Robust optimization (robust cost functions)
Learning goals

- Understand the Ransac concept
- Be able to apply the equation for Ransac iterations
- Understand the use of Ransac for fundamental matrix estimation
- Understand the problem of least squares estimation with outliers
- Understand how robust cost functions work
In computer vision the analogy to the line would be the fundamental matrix.
Robust estimation in computer vision

- Outliers in general estimation

- Rare unexpected measurements that don’t fit the model
Robust estimation in computer vision

- Outliers in computer vision

- Frequent expected measurements that don‘t give useful information
Robust estimation in computer vision

- Multiple areas in computer vision require robust estimation techniques
  - Fundamental matrix estimation
  - Essential matrix estimation
  - Camera pose estimation
  - Camera calibration
  - Triangulation
  - Bundle adjustment
  - 2D Registration
  - 3D Registration
  - 3D Model fitting
  - Line detection

- Techniques:
  - Ransac
  - Robust loss functions for optimization
Camera motion estimation

\[ x'^T E x = 0 \]
Camera motion estimation

\[ x'^T E x = 0 \]

\[ x \quad \text{image matches with mis-matches} \quad x' \]
Camera motion estimation

\[ x' E x = 0 \]

\( x \) image matches with mis-matches \( x' \)
Camera motion estimation

\[ x'^T E x = 0 \]

\( x \) image matches with mis-matches \( x' \)
RANSAC Example: Line extraction
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- Random sampling of 2 points
RANSAC Example: Line extraction

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- Calculate line model from this 2 data points
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- Calculate residual error for each data point (normal distance to line)
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- Calculate residual error for each data point (normal distance to line)
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- Repeat sampling
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RANSAC Example: Line extraction

- Random sampling of 2 points
- Calculate line model from this 2 data points
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- Select data points that support current hypothesis
- Repeat sampling
- Until a hypothesis with a maximum number of inliers has been found
RANSAC Algorithm

1. Initial: Let $A$ be a set of $N$ data points
2. Repeat
   1. Randomly select a sample of $s$ data points from $A$
   2. Fit a model to these points
   3. Compute the distance of all other points to this model
   4. Construct the inlier set (i.e. count the number of data points whose distance from the model < threshold $d$
   5. Store these inliers
3. Until maximum number of iterations reached
4. The model with the maximum number of inliers is chosen as the solution to the problem
5. Re-estimate the model using all the inliers
How many iterations of RANSAC?

- The number of iterations $N$ which is necessary to guarantee that at least a single correct solution is found can be computed by

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

- $s$ is the number of data points from which a model can be minimally computed
- $\varepsilon$ is the percentage of outliers in the data (can only be guessed)
- $p$ is the requested probability of success

- Example: $p = 0.99$, $s = 5$, $\varepsilon = 0.5$ -> $N = 145$
How many iterations of RANSAC?

- RANSAC is an iterative method and it is non-deterministic. It returns different solutions on different runs.

- For reasons of reliability, in many practical implementations $N$ is usually multiplied by a factor of 10.

- More advanced implementations of RANSAC estimate the fraction of inliers adaptively, for every iteration, and use it to update $N$. 
RANSAC iterations

- N is exponential in the number of data points s necessary to estimate the model
- Therefore, it is very important to use a minimal parameterization of the model

<table>
<thead>
<tr>
<th>Number of points (s)</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>p=0.99, e=0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Number of iterations (N)</td>
<td>1177</td>
<td>587</td>
<td>292</td>
<td>145</td>
<td>71</td>
<td>16</td>
<td>7</td>
</tr>
</tbody>
</table>
Ransac for fundamental matrix estimation

- Inlier set for fundamental matrix estimation is set of correct image matches
- Cost function for Ransac: Epipolar distance

\[ r_i = d(x'_i, Fx_i)^2 + d(x_i, F^T x'_i)^2 \]

\[ = (x'_i^T F x_i)^2 \left( \frac{1}{(Fx_i)^2} + \frac{1}{(F^T x'_i)^2} \right) \]
Why is least-squares not robust to outliers?

- Least squares means quadratic loss function
- Robust estimation can be achieved by different loss functions than quadratic
Robust optimization

- Iteratively reweighted least squares (IRLS)
  - Estimates weights in every iteration to down-weigh outliers

\[
\min_x \left\| w(Ax - b) \right\|
\]

- Non-linear optimization with robust loss function
  - A robust loss function is used that down-weighs the influence of outliers

\[
\min_x \sum_i \rho_i(\|f_i(x_i)\|^2)
\]

\[
\min_x \|A(x) - b\|
\]
Example: Gold standard method for fundamental matrix

\[
\min_{P, P', X_i} \sum_i d(x_i, PX_i)^2 + d(x'_i, P'X_i)^2
\]

- \(x_i\) … image measurement
- \(P, P'\) … camera matrices (will be optimized)
- \(X_i\) … 3D points (will be optimized)
Non-linear estimation with robust loss function

\[ \min_x \sum_i \rho_i(\|f_i(x_i)\|^2) \]

- Non-linear optimization (e.g. Levenberg-Marquard)
- Squared error will be modified by robust loss function \( \rho(x) \)
- Loss function should be differentiable
- Jacobian needs to be calculated
More robust loss functions

<table>
<thead>
<tr>
<th>loss function</th>
<th>p(x)</th>
</tr>
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<tbody>
<tr>
<td>$L_1$</td>
<td>$</td>
</tr>
<tr>
<td>Huber $\begin{cases} \frac{x^2}{2} \ k(</td>
<td>x</td>
</tr>
<tr>
<td>Tukey $\begin{cases} \frac{k^2}{6} \ k^2/6 \end{cases}$</td>
<td>$\begin{cases} \frac{k^2}{6} \ k^2/6 \end{cases}$</td>
</tr>
<tr>
<td>Cauchy</td>
<td>$\frac{k^2}{2} \log(1 + (x/k)^2)$</td>
</tr>
</tbody>
</table>
Effects of different loss functions

- $L_2$ (quadratic) loss works fine for outlier-free data

\[
\min_x \sum_i r_i^2(x)
\]
Effects of different loss functions

- Outliers lead to wrong estimate

\[ \min_x \sum_i r_i^2(x) \]
Effects of different loss functions

- $L_1$ loss leads to correct solution (estimation robust to outliers)
Effects of different loss functions

- Does work for larger number of outliers as well

\[ \min_x \sum_i |r_i(x)| \]
Effects of different loss functions

- Breaks down eventually (> 50% outliers)

\[ \min_x \sum_i |r_i(x)| \]
Effects of different loss functions

- However, can be solved with different cost function (e.g. Truncated L$_2$)
- However, not easy to predict this behaviour

\[
\min_x \sum_i \min(r_i^2(x), t^2)
\]
Learning goals - Recap

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