Robot Vision: Geometric Algorithms – Part 2

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SS 2022
Outline

- Fundamental matrix properties
- The singularity constraint
- The normalized 8-point algorithm
- The Gold Standard method
- Camera matrices from the essential matrix
- The essential matrix for the stereo case
- Triangulation
- Camera pose estimation and the rotation matrix
Learning goals

▪ Understand the properties of the fundamental matrix
▪ Understand the singularity constraint
▪ Be able to compute a fundamental matrix with enforced singularity constraint
▪ Understand the normalized 8-point method and the Gold Standard method
▪ Be able to compute camera poses from an essential matrix
▪ Understand triangulation
▪ Understand the geometry of the stereo normal case
▪ Be able to compute camera matrices with correct rotational part
Fundamental matrix properties

- F is a **unique** 3x3 matrix with **rank 2** (singular, det(F)=0)
- If F is the fundamental matrix for camera matrices (P,P’) then the **transposed** matrix $F^T$ is the fundamental matrix for (P’,P)
- **Epipolar lines** are computed by: $l’=Fx$, $l=F^Tx’$
- **Epipoles** are the null-spaces of F. $Fe=0$, $e’^TF=0$
- F has **7 DOF**, i.e. 3x3 matrix – 1 DOF (homogeneous, scale) – 1 DOF (rank 2 constraint)
The singularity constraint of the fundamental matrix

- Other names: Rank 2 constraint, det(F) = 0 constraint
- A valid fundamental matrix has to be singular (non-invertible), which means the determinant det(F)=0.
- In addition, the rank of a valid fundamental matrix has to be 2
- Explanation: F = K^{-T}EK^{-1} = K^{-T} [t]_x RK^{-1}
- [t]_x has rank 2 and rank(AB) ≤ min(rank(A),rank(B)).

- 8-Point algorithm computes all the 9 elements of the F-matrix independently. It is not guaranteed that the rank(F)=2 or det(F)=0
- These properties need to be enforced!
The singularity constraint of the fundamental matrix

- SVD of a linearly computed F-matrix (rank 3):

\[ F = USV^T = U \begin{bmatrix} s_1 & & \\ & s_2 & \\ & & s_3 \end{bmatrix} V^T \]

- Closest rank-2 approximation by setting the last singular value to 0
- Results in the closest matrix under the Frobenius norm \( \min \|F - F'\|_F \)

\[ F = USV^T = U \begin{bmatrix} s_1 & & \\ & s_2 & \\ & & 0 \end{bmatrix} V^T \]
The singularity constraint of the fundamental matrix

- Example:

\[
A = (8 \times 9)
\]

\[
\begin{array}{cccccccc}
1 & 3 & 5 & 3 & 4 & 3 & 7 & 4 & 1 \\
2 & 9 & 4 & 2 & 8 & 2 & 5 & 7 & 5 \\
7 & 3 & 6 & 6 & 8 & 9 & 9 & 6 & 5 \\
5 & 7 & 6 & 5 & 3 & 6 & 2 & 7 & 8 \\
2 & 2 & 7 & 5 & 6 & 5 & 1 & 9 & 5 \\
4 & 3 & 6 & 6 & 6 & 6 & 1 & 9 & 4 \\
6 & 1 & 9 & 7 & 5 & 5 & 1 & 2 & 7 \\
2 & 6 & 2 & 4 & 8 & 6 & 4 & 2 & 7 \\
\end{array}
\]

\[
F = \begin{pmatrix}
0.0012818033647169 & -0.195296914367969 & -0.404026958783203 \\
0.592627190886001 & -0.0992048118304505 & -0.505391799650038 \\
0.244770293871894 & 0.181983926946307 & 0.298529042380632
\end{pmatrix}
\]

\[
S = \begin{pmatrix}
0.853380835370105 & 0 & 0 \\
0 & 0.521146237658923 & 0 \\
0 & 0 & 0.0121551962950181
\end{pmatrix}
\]

\[
S_\_ = \begin{pmatrix}
0.853380835370105 & 0 & 0 \\
0 & 0.521146237658923 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

\[
F_\_ = U \cdot S_\_ \cdot V^T
\]

\[
\begin{pmatrix}
-0.000493883737627127 & -0.187153153340858 & -0.407762597079129 \\
0.59321760922536 & -0.101912623777308 & -0.504149694914234 \\
0.243327284554864 & 0.188601941472783 & 0.29549328182407
\end{pmatrix}
\]

\[
\text{rank}(F) = 3
\]

\[
\text{rank}(F_\_) = 2
\]

\[
\text{norm}(F - F_\_) = 0.0121
\]
The singularity constraint of the fundamental matrix

- Does it make a difference?

Epipolar lines from corrected F-matrix

Epipolar lines from not corrected F-matrix
Epipolar lines don’t intersect
The normalized 8-point algorithm

- Solving the fundamental matrix equation system using pixel coordinates can give bad results (due to numerical instabilities)
- Solution: Normalization of pixel coordinates

Algorithm:
1. Transform the coordinates such that the image center is at (0,0) and that the maximum distance from the origin is $\sqrt{2}$
2. Compute $F_n$ using the 8-point method from the normalized points
3. Enforce the singularity constraints
4. Transform the fundamental matrix back to original units
The normalized 8-point algorithm

- Example: Transform image coordinates to \([-1,-1] \times [1,1]\)

\[
K = \begin{bmatrix}
\frac{2}{640} & 0 & -1 \\
0 & \frac{2}{480} & -1 \\
0 & 0 & 1
\end{bmatrix}
\]

- Transformation \(K\) is like a calibration matrix
- \(F = K^T F_n K\)
The Gold Standard method

- Accurate solution using non-linear optimization

1. Compute an initial estimate for $\hat{F}$ using the normalized 8-point algorithm (enforcing rank 2 constraint)
2. Extract cameras $P$ and $P'$ from $\hat{F}$
   \[ P = [I|0] \quad P' = [[e']_x\hat{F}|e'] \]
3. Triangulate 3D points from point correspondences
4. Use non-linear optimization e.g. Levenberg-Marquardt to minimize the reprojection error
   \[ \sum_i d(x_i, \hat{x}_i)^2 + d(x'_i, \hat{x}'_i)^2 \]

by optimizing the parameters of $P$ and $P'$ and the 3D points.
Camera matrices from Essential matrix

- Essential matrix represents the relative motion between two cameras
- Camera matrices $P$ and $P'$ can be computed from $E$

\[ E = [t]_x R \quad \text{E} = K^T F K \]

\[ P = [I \ 0] \]

\[ P' = [R \ t] \]

- $R$ and $[t]_x$ can be computed using the SVD of $E$

\[ USV^T = \text{svd}(E) \]

\[ R = U \begin{bmatrix} 0 & \mp 1 & 0 \\ \pm 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} V^T \]

\[ [t]_x = U \begin{bmatrix} 0 & \pm 1 & 0 \\ \mp 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} U^T \]

\[ [t]_x = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \]

- 4 possible combinations of $R$ and $t$
Camera matrices from Essential matrix

- P is set as the canonical coordinate system at the origin, \( ||t|| = 1 \)
  
  \[
P = \begin{bmatrix} I & 0 \end{bmatrix} \quad P' = \begin{bmatrix} R & t \end{bmatrix}
  \]

- Only for one of the 4 configurations the image rays intersect in front of the cameras.

- This is the true configuration and can be found by triangulating points.
The essential matrix for the stereo case

\[ R = I_{3 \times 3} \quad T = \begin{bmatrix} T_x & 0 & 0 \end{bmatrix}^T \]
The essential matrix for the stereo case

\[ R = I_{3 \times 3} \quad T = [T_x \quad 0 \quad 0]^T \]

\[ E = [T]_x R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T_x \\ 0 & T_x & 0 \end{bmatrix} \]

\[ [x' \quad y' \quad 1] \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T_x \\ 0 & T_x & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = 0 \]

\[ [x' \quad y' \quad 1] \begin{bmatrix} 0 \\ -T_x \\ T_x y \end{bmatrix} = 0 \]

\[ -y' T_x + T_x y = 0 \]
Triangulation

- Compute coordinates of world point $X$ given the measurements $x, x'$ and the camera projection matrices $P$ and $P'$
Condition: Measurement vector $x$ needs to have the same direction as projection of $X$ (cross-product equals 0)

- $x \times (PX) = 0$ and $x' \times (P'X) = 0$

- Can be rewritten into equation system $AX = 0$ to solve for $X$
Triangulation

\[ x \times (PX) = 0 \text{ and } x' \times (P'X) = 0 \]
\[ x(P_3^T X) - (P_1^T X) = 0 \]
\[ y(P_3^T X) - (P_2^T X) = 0 \]
\[ x(P_2^T X) - y(P_1^T X) = 0 \]

\[
\begin{bmatrix}
  xP_3^T - P_1^T \\
  yP_3^T - P_2^T \\
  x'P_3'^T - P_1'^T \\
  y'P_3'^T - P_2'^T
\end{bmatrix}
X = 0
\]

\[
P = \begin{bmatrix}
P_1^T \\
P_2^T \\
P_3^T
\end{bmatrix}
\]
Camera pose estimation

- perspective-n-point problem
- Goal is to estimate camera matrix $P$ such that $m_1 = PM_1$
- $m_1, M_1, m_2, M_2, m_3, M_3$ are known
- Algebraic linear solution requires 6 3D-2D point correspondences, minimal nonlinear solution requires only 3
Camera pose estimation

- Derivation similar to Triangulation, but now entries of $P$ are the unknowns instead of $X$
- Condition: Measurement vector $x$ needs to have the same direction as projection of $X$ (cross-product equals 0)
Camera pose estimation

- Derivation similar to Triangulation, but now entries of P are the unknowns instead of X
- Condition: Measurement vector $x$ needs to have the same direction as projection of $X$ (cross-product equals 0)

\[
x \times (PX) = 0 \text{ for all pairs } x \leftrightarrow X
\]
\[
y(P_3^T X) - w(P_2^T X) = 0
\]
\[
x(P_3^T X) - w(P_1^T X) = 0
\]
\[
x(P_2^T X) - y(P_1^T X) = 0
\]

\[
\begin{bmatrix}
0 & -wX^T & yX^T \\
-wX^T & 0 & xX^T \\
-yX^T & xX^T & 0
\end{bmatrix}
\begin{bmatrix}
P_1 \\
P_2 \\
P_3
\end{bmatrix} = 0
\]
Camera pose estimation

- Linear camera pose estimation does **not** enforce inner constraints

\[
P = \begin{bmatrix}
    p_{11} & p_{12} & p_{13} & p_{14} \\
    p_{21} & p_{22} & p_{23} & p_{24} \\
    p_{31} & p_{32} & p_{33} & p_{34}
\end{bmatrix}
\]

- \( R \) is a 3x3 rotation matrix
- Elements of \( R \) are **not independent** of each other
- Rotation matrices belong to the matrix group SO(3)

\[
R^T R = I, \det(R) = +1
\]
Special orthogonal group SO(n)

- The set of all the nxn orthogonal matrices with determinant equal to +1 is a group w.r.t. the matrix multiplication:

\[ SO(n) = \{ A \in O(n) | \det(A) = +1 \}, \times \]  

Special orthogonal group

- \( SO(3) \) … group of orthogonal 3x3 matrices with \( \det=+1 \) …. “rotation matrices”

- \( R_3 = R_1 \times R_2 \) … \( R_3 \) is still an \( SO(3) \) element

- \( R_3 = R_1 + R_2 \) … \( R_3 \) is \textbf{NOT} an \( SO(3) \) element. Not a rotation matrix anymore.
Problems with rotation matrices

- Optimization of rotations (bundle adjustment)
  - Newton’s method \( x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \)

- Filtering and averaging, e.g. \( R' = \frac{R_1 + R_2}{2} \) not allowed
  - E.g. averaging rotation from IMU or camera pose tracker for AR/VR glasses
Enforcing the rotation matrix constraint

- After estimating the camera matrix \( \hat{P} \) it can be replaced with the closest \( P \) that consists of a valid rotational part.
- \( P = [R \mid t] \), where \( R^T R = I, \det(R) = +1 \)
- Such a \( P \) can be found using SVD.

\[
\hat{P} = [M \quad t] \\
USV = \text{svd}(M) \\
R = UV^T \\
P = [R \quad t]
\]
Recap - Learning goals

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