Computer Vision II: Multiple View Geometry (IN2228)

Chapter 03 Image Formation
(Part 2 Distortion and Supplementary Knowledge)

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04 May 2023 11:00-11:45
Announcement before Class

Access to the recording of course in 2022

Dear Sabine,

Sorry to disturb you again.

Some students sent me emails to request access to the recordings of CV2 in 2022 (provided by Prof. Cremers). However, it seems that I can only enroll them in this year’s course. I wonder if you can help me do that.

In addition, given that more than one student send me this request, can we enroll them in a batch?

Thank you for your time!

Best regards,
Haoang

Materials in 2022: [https://cvg.cit.tum.de/teaching/ss2022/mvg2022](https://cvg.cit.tum.de/teaching/ss2022/mvg2022)
Video in 2013: [https://www.youtube.com/playlist?list=PLTBdjV_4f-EJn6udZ34tht9EVIW7lbeo4](https://www.youtube.com/playlist?list=PLTBdjV_4f-EJn6udZ34tht9EVIW7lbeo4)
Explanation before Class

✓ Projection plane computed by image line

Projection matrix (3*4)

\[
\Pi_L = P^\top L \in \mathbb{R}^4
\]

Intersection between a 3D line and a 3D plane

\[
D = L\pi
\]

Homogeneous coordinates

\[
L = \begin{bmatrix}
[n] \times & v \\
-v^\top & 0
\end{bmatrix}
\]

Plücker matrix

\[
\mathcal{L} = (n^\top, v^\top)^\top
\]

Plücker coordinates

\[
\lambda \begin{bmatrix}
u \\
v \\
1
\end{bmatrix} = K[R \mid T]
\]

Projection Matrix (M)
Today’s Outline

- Image Distortion
- Supplementary Knowledge
Image Distortion

- Type of Distortion

- **Tangential Distortion**: if the lens is misaligned (more specifically, not perfectly parallel to the image sensor), a tangential distortion occurs.
Image Distortion

- Type of Distortion

- **Radial Distortion** occurs when light rays **bend more** near the edges of a lens than they do at its optical center.
Image Distortion

- Radial Distortion

The standard model of radial distortion is a transformation from the ideal (non-distorted) coordinates \((u, v)\) to the real (distorted) coordinates \((u_d, v_d)\).
Image Distortion

- Radial Distortion

✓ For a given non-distorted image point \((u, v)\), the amount of distortion is a **nonlinear function of its distance** \(r\) from the principal point.

✓ For most lenses, this simple **quadratic** model of radial distortion is sufficient

\[
\begin{bmatrix} u_d \\ v_d \end{bmatrix} = (1 + k_1 r^2) \begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix}
\]

\[ r^2 = (u - u_0)^2 + (v - v_0)^2 \]
Image Distortion

- High-order Distortion Model (for Wide-angle Lens)

\[
\begin{bmatrix}
u_d \\
v_d
\end{bmatrix} = (1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \begin{bmatrix}
u - u_0 \\
v - v_0
\end{bmatrix} + \begin{bmatrix}2k_4(u - u_0)(v - v_0) + k_5(r^2 + 2(u - u_0)^2) \\
\frac{1}{k_4}(r^2 + 2(v - v_0)^2 + 2k_5(u - u_0)(v - v_0))\end{bmatrix} + \begin{bmatrix}u_0 \\
v_0
\end{bmatrix}
\]

Image undistortion (parameter estimation) will be introduced in our future classes.
Image Distortion

- Effects to Visual SLAM

Higher accuracy of calibration leads to higher accuracy of SLAM

Supplementary Video:
Degeneracy in Self-Calibration Revisited and a Deep Learning Solution for Uncalibrated SLAM

IROS 2019

Bingbing Zhuang, Quoc-Huy Tran, Gim Hee Lee
Loong Fah Cheong, Manmohan Chandraker

Demo videos
Image Distortion

- An Explicit Model

We can also use the explicit model [1] with respect to a single radial distortion parameter $r$, instead of the polynomial model.

Conversion between the original point $(x, y)$ and distorted point $(x', y')$

\[
\begin{align*}
    x' &= c_x + (x - c_x) \cdot \frac{\sqrt{1 + 4 \cdot r \cdot d} - 1}{2 \cdot r \cdot d} \\
    y' &= c_y + (y - c_y) \cdot \frac{\sqrt{1 + 4 \cdot r \cdot d} - 1}{2 \cdot r \cdot d} \\
    d &= (x - c_x)^2 + (y - c_y)^2
\end{align*}
\]

\[
\begin{align*}
    x &= c_x + \frac{x' - c_x}{1 - r \cdot d'} \\
    y &= c_y + \frac{y' - c_y}{1 - r \cdot d'} \\
    d' &= (x' - c_x)^2 + (y' - c_y)^2
\end{align*}
\]

Image Distortion

Conversion between Lines and Circles

By extension, a straight line and a circular arc can be mutually converted.
Supplementary Knowledge

Overview

- Limitations of digital images
- Depth of field
- Orthographic projection
- Depth camera
- Rolling shutter and global shutter camera
- Event camera
Supplementary Knowledge

- Limitations of Digital Images

  - Noise
  Low light is where you notice noise

  - Compression
  Creates artifacts except in uncompressed formats (tiff, raw)

  - Stabilization
  Compensate for camera shake (mechanical vs. electronic)
Supplementary Knowledge

- Depth of Field

The distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image.

Diagram showing focus distance and focus point with different depth of fields.
Supplementary Knowledge

Depth of Field

A narrower aperture increases the depth of field but reduces the amount of light into the camera.

It partly determines the quality of keypoints detection.

Keypoint detection needs sharp and bright images.
Supplementary Knowledge

Orthographic Projection

Orthographic projection is a “special” type of parallel projection where the projection rays are perpendicular to the projection plane.

- **Left**: orthographic projection. The projection lines are perpendicular to the image plane.
- **Right**: oblique projection. The projection lines are at a skew angle to the image plane.

**Light rays are not converged; Scale remains unchanged; Parallelism is maintained**
Supplementary Knowledge

➢ Orthographic Projection

Application
With the **points in 3D**, we can project them to a top-down view of the scene.

• A useful representation for mobile robots as the distances between **obstacles** are preserved.
• It is easy to interpret and utilize to perform **path planning** and **navigation** task.
Supplementary Knowledge

Depth Camera

Basic information
A special camera capable of determining the depth information of objects which can be used for 3D reconstruction

Time-of-flight measurement principle

\[ d = \frac{ct}{2} \]

Distance Image
Far
Near
Photographed Image

Microsoft Kinect v2

Time-of-flight measurement principle
Supplementary Knowledge

- Depth Camera

✓ From depth to 3D

\[
\begin{align*}
  z & = \text{depth}(i, j) \\
  x & = \frac{(j - c_x) \times z}{f_x} \\
  y & = \frac{(i - c_y) \times z}{f_y}
\end{align*}
\]

A depth image

A 3D point cloud
Supplementary Knowledge

Rolling Shutter vs. Global Shutter Camera

**Rolling Shutter**
- Rows of pixels are exposed and read at different times, one after the other
- May distort (skew) moving objects

**Global Shutter**
- All pixels are exposed simultaneously
- No distortion of moving objects
Supplementary Knowledge

Rolling Shutter vs. Global Shutter Camera

A representative illustration

- The pole in the front is vertical but due to fast horizontal camera motion during exposure appears to be slanted.
- The vertical structures in the back are also slanted but much less, as the motion introduces less disparity to distant objects.

fan blades are “expanded”
Supplementary Knowledge

 Rolling Shutter vs. Global Shutter Camera

✓ From two rolling shutters to one global shutter

• When two images are recorded with different rolling shutter directions (read-out directions), their motion-induced distortion is different.
• A few point correspondences are enough to recover the motion as well as an undistorted image.
Supplementary Knowledge

Rolling Shutter vs. Global Shutter Camera

- From two rolling shutters to one global shutter
  - Perspective projection based on global shutter camera
  - Adjusted model based on rolling shutter camera

\[
\lambda_g u_{gi} = P_g X_i \\
\lambda'_{gi} = P'_g X_i
\]

\[
\lambda u_i = P \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} \\
\lambda' u'_i = P' \begin{bmatrix} u'_i \\ v'_i \\ 1 \end{bmatrix}
\]

vi: the i-th row

This knowledge will not be asked in the exam.

The projection matrices are now functions of the image row, because each row is taken at a different time and hence a different camera pose.
Supplementary Knowledge

Rolling Shutter vs. Global Shutter Camera

- Structure from Motion based on rolling shutter camera

  (Left) A reconstruction from forward camera translation with vertical readout direction.

  (Right) A reconstruction from forward camera translation with horizontal readout direction.

- In both cases, the scene collapses into a plane that is perpendicular to the readout direction.

This knowledge will not be asked in the exam.
Supplementary Knowledge

- Rolling Shutter vs. Global Shutter Camera

Structure from Motion based on rolling shutter camera

- When both image directions are combined, a correct reconstruction is obtained with rolling shutter (RS) projection model.
- Result is close to a reconstruction with global shutter (GS) model.

This knowledge will not be asked in the exam.
Supplementary Knowledge

- **Event Camera**

  - Progress in visual odometry

  ![Graph](image)

  - Direct methods are free of correspondences
  - VO based on frame-based cameras
  - Robustness (HDR, motion blur, low texture)
  - Efficiency (speed and CPU load)
  - Accuracy
  - Feature based (or indirect) (1980-2000)
  - Indirect + Direct (from 2000)
  - +Event Cameras (from 2018)
  - +IMU (from 2007) (10x accuracy)

- Motion blur
- Dynamic Range
Supplementary Knowledge

- Event Camera

✓ Principle
For event camera, each pixel inside an event camera operates independently and asynchronously, reporting changes in brightness as they occur, and staying silent otherwise.
Supplementary Knowledge

Event Camera

An example

Each image has the resolution of 128x128 pixels. White pixels indicate a change of illumination from dark to light; Black pixels indicate a change of illumination from light to dark.
Supplementary Knowledge

- Event Camera

✓ An example

Human tracking based on event camera

Frame-based vs. Event-based (EVS)

- Frame-based: Hard to recognize people in the dark or wearing dark clothes.
- Event-based (EVS): Regardless of brightness, the silhouette of a moving person can be detected.
Supplementary Knowledge

- Event Camera

- Application to visual SLAM/visual odometry

Real-time Visual-Inertial Odometry for Event Cameras using Keyframe-based Nonlinear Optimization

Henri Rebecq, Timo Horstschaefer, Davide Scaramuzza

Demo video
Summary

- Image Distortion
- Supplementary Knowledge
Thank you for your listening!
If you have any questions, please come to me :-}