Computer Vision Group

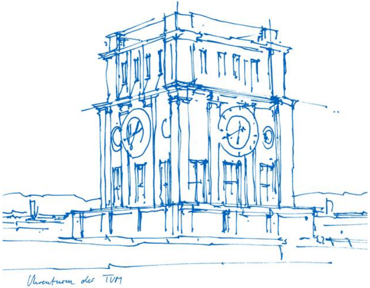
Technische Universität München

Computer Vision II: Multiple View Geometry (IN2228)

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

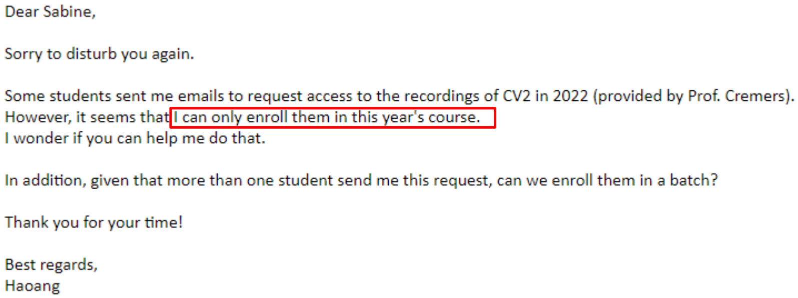
Dr. Haoang Li

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.

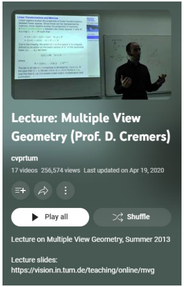
Some students sent me emails to request access to the recordings of CV2 in 2022 (provided by Prof. Cremers).
However, it seems that I can only enroll them in this year's course.
I wonder if you can help me do that.

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
Video in 2013: https://www.youtube.com/playlist?list=PLTBdjV_4f-EJn6udZ34tht9EVIW7lbeo4



Lecture: Multiple View Geometry (Prof. D. Cremers)

cvprtum

17 videos 256,574 views Last updated on Apr 19, 2020

Lecture on Multiple View Geometry, Summer 2013

Lecture slides:
https://vision.in.tum.de/teaching/online/mvg

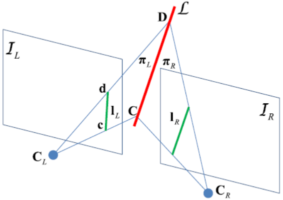
Explanation before Class

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \underbrace{\overset{3*4}{\boxed{K\left[R \mid T\right]}}}_{\text{Projection Matrix (M)}} \cdot \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

✓ Projection plane computed by image line

Projection matrix (3*4)

$$\overset{4*1}{\underline{\boldsymbol{\pi}}_L} = \overset{4*3}{\mathrm{P}^\top} \underbrace{\underline{\mathbf{l}}_L}_{3*1} \in \mathbb{R}^4$$



- Intersection between a 3D line and a 3D plane

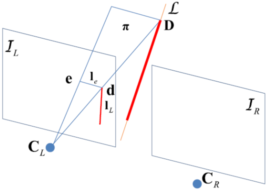
$$\underline{\mathbf{D}} = \overset{4*4}{\mathrm{L}} \underbrace{\underline{\boldsymbol{\pi}}}_{4*1}$$

Homogeneous coordinates

$$\mathrm{L} = \overset{4*4}{\begin{bmatrix} [\mathbf{n}]_\times & \mathbf{v} \\ -\mathbf{v}^\top & 0 \end{bmatrix}} \Leftarrow \overset{6*1}{\mathcal{L} = (\mathbf{n}^\top, \mathbf{v}^\top)^\top}$$

Plucker matrix

Plucker coordinates



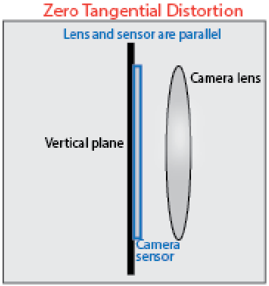
Today’s Outline

- Image Distortion
- Supplementary Knowledge

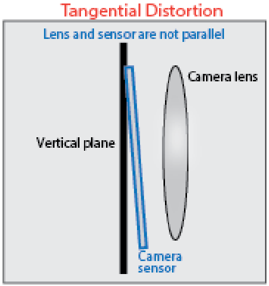
Image Distortion

- Type of Distortion

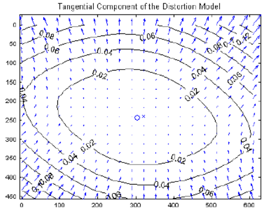
✓ **Tangential Distortion**: if the lens is misaligned (more specifically, not perfectly parallel to the image sensor), a tangential distortion occurs.



film



film

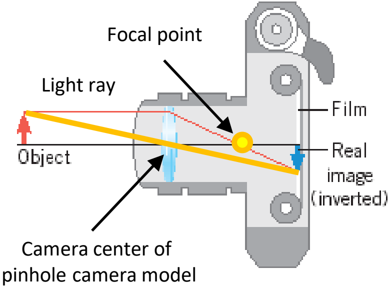


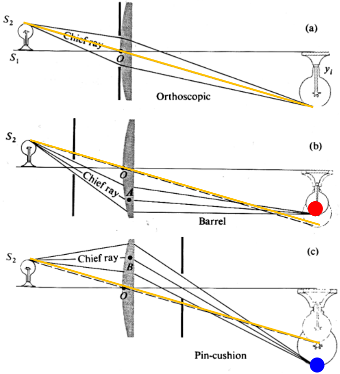
Tangential distortion

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.





Smaller projection

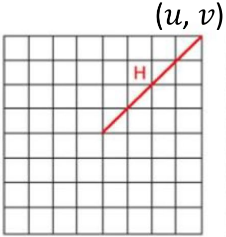
Larger projection

Two types of radial distortion

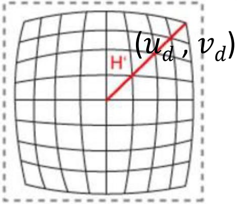
Image Distortion

- Radial Distortion

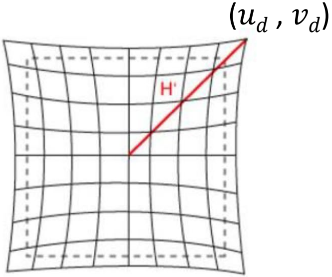
The standard model of radial distortion is a transformation from the ideal (non-distorted) coordinates (u, v) to the real (distorted) coordinates (u_d , v_d).



No distortion



Negative radial distortion
(Barrel distortion)



Positive radial distortion
(Pincushion distortion)

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

$$\begin{bmatrix} u_d \\ v_d \end{bmatrix} = (1 + \underset{\uparrow}{\overset{\text{unknown}}{k_1}} r^2) \begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix} + \overset{\text{Principal point}}{\begin{bmatrix} u_0 \\ v_0 \end{bmatrix}}$$

$$r^2 = (u - u_0)^2 + (v - v_0)^2$$

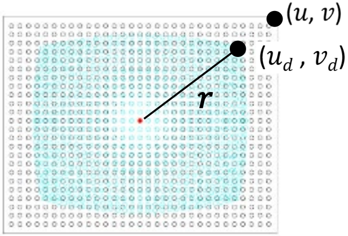


Image Distortion

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

$$\begin{bmatrix} u_d \\ v_d \end{bmatrix} = \overbrace{(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix}}^{\text{Radial distortion}} + \overbrace{\begin{bmatrix} 2k_4(u - u_0)(v - v_0) + k_5(r^2{+}2(u - u_0)^2) \\ k_4(r^2{+}2(v - v_0)^2{+}2k_5(u - u_0)(v - v_0) \end{bmatrix}}^{\text{Tangential distortion}} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix}$$

Original Image (left) vs. Corrected Image (right)

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')

$$\begin{cases} x' = c_x + (x - c_x) \cdot \dfrac{\sqrt{1 + 4 \cdot \overset{\substack{\text{unknown}\\ \downarrow}}{r} \cdot d} - 1}{2 \cdot r \cdot d} \\ y' = c_y + (y - c_y) \cdot \dfrac{\sqrt{1 + 4 \cdot r \cdot d} - 1}{2 \cdot r \cdot d} \end{cases}$$

$$d = (x - c_x)^2 + (y - c_y)^2$$

$$\begin{cases} x = c_x + \dfrac{x' - c_x}{1 - r \cdot d'} \\ y = c_y + \dfrac{y' - c_y}{1 - r \cdot d'} \end{cases}$$

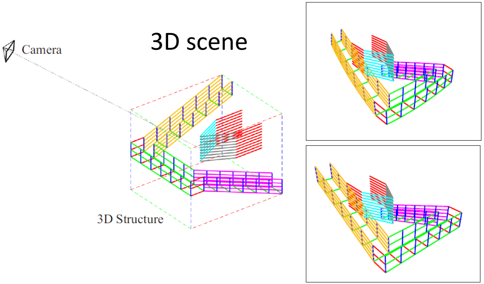
$$d' = (x' - c_x)^2 + (y' - c_y)^2$$

[1] Christian Brauer-Burchardt and Klaus Voss, "A new algorithm to correct fish-eye-and strong wide-angle-lens-distortion from single images," in IEEE International Conference on Image Processing (ICIP), 2001

Image Distortion

- Conversion between Lines and Circles

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



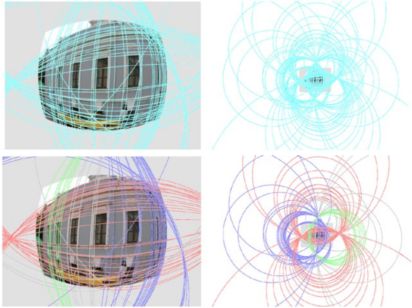
3D scene

Distorted image

$r = 3.00 \times 10^{-6}$

Undistorted image

Synthetic data



Extracted circular curves

Clustered by vanishing points

Real-world data

Supplementary Knowledge

➢ Overview

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

Supplementary Knowledge

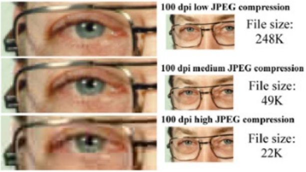
➢ Limitations of Digital Images

- 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)

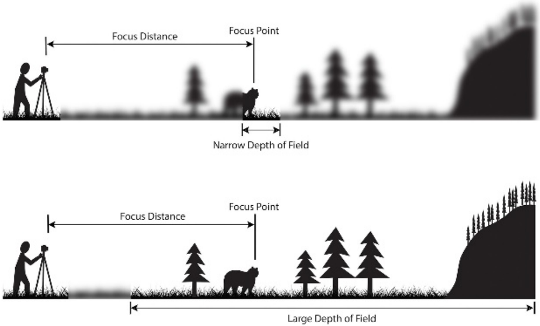
Blurred

Sharp

Supplementary Knowledge

- ➢ Depth of Field

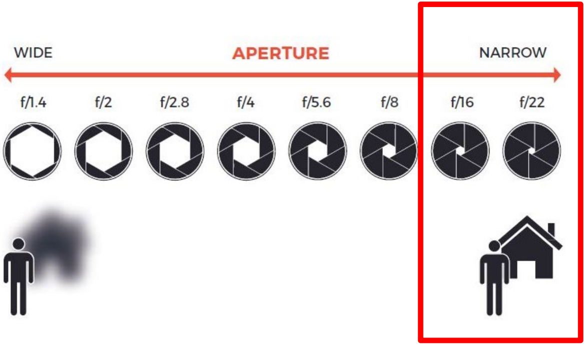
The distance between the nearest and farthest objects in a scene **that appear acceptably sharp** in an image.

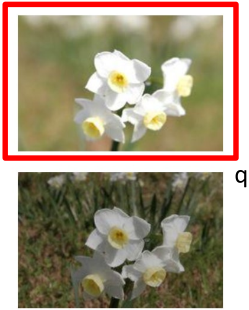


Supplementary Knowledge

- Depth of Field

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





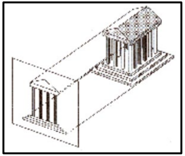
It partly determines the quality of keypoints detection

Keypoint detection needs sharp and bright images

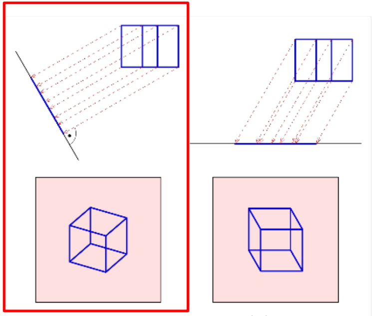
Supplementary Knowledge

- ➢ Orthographic Projection

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



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



orthographic oblique

Two parallel projections of a cube

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.

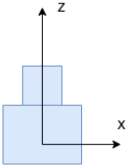
Supplementary Knowledge

➢ 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.



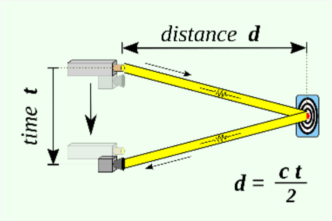
Supplementary Knowledge

➢ Depth Camera

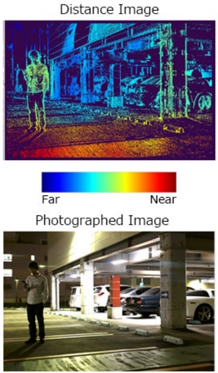
✓ Basic information

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

Microsoft Kinect v2



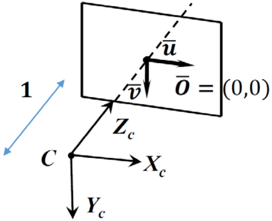
Time-of-flight measurement principle



Supplementary Knowledge

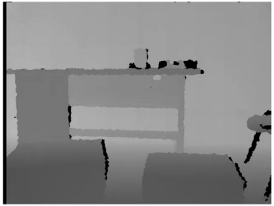
- ➢ Depth Camera

✓ From depth to 3D

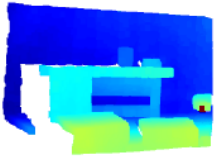


Normalized image plane

$$\begin{cases} z = depth(i, j) \\ x = \dfrac{(j - c_x) \times z}{f_x} \\ y = \dfrac{(i - c_y) \times z}{f_y} \end{cases}$$



A depth image



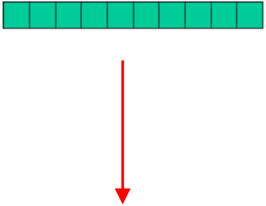
A 3D point cloud

Supplementary Knowledge

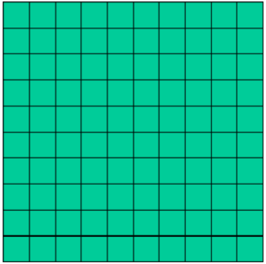
➢ Rolling Shutter vs. Global Shutter Camera

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



(Cell phone)



(Digital single lens reflex)

Supplementary Knowledge

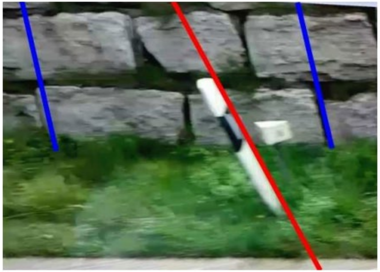
➢ Rolling Shutter vs. Global Shutter Camera

✓ A representative illustration


fan blades are “expanded”

Rolling shutter

Global shutter

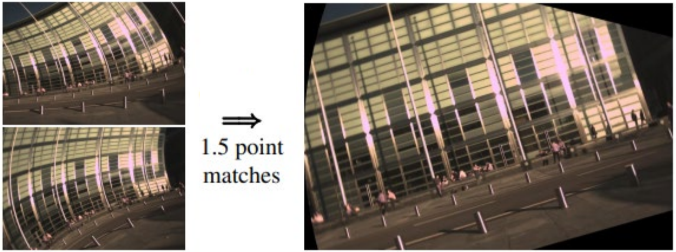


- The pole in the front is vertical but due to fast horizontal camera motion during exposure appears to be slanted.
- The vertical structures in the back are also slanted but much less, as the motion introduces less disparity to distant objects.

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

3D point

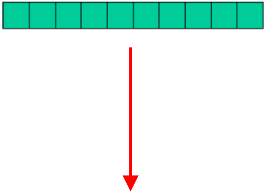
$$\lambda_g \mathbf{u}_{gi} = \mathrm{P}_g \mathrm{X}_i$$
$$\lambda'_g \mathbf{u}'_{gi} = \mathrm{P}'_g \mathrm{X}_i$$

2D point

Projection matrix

$$\mathbf{u}_i = [u_i \ \boxed{v_i} \ 1]^\top$$
$$\mathbf{u}'_i = [u'_i \ \boxed{v'_i} \ 1]^\top$$

v_i: the i-th row



- Adjusted model based on rolling shutter camera

$$\lambda \mathbf{u}_i = \mathrm{P}(\boxed{v_i})\mathrm{X}_i$$
$$\lambda' \mathbf{u}'_i = \mathrm{P}'(\boxed{v'_i})\mathrm{X}_i$$

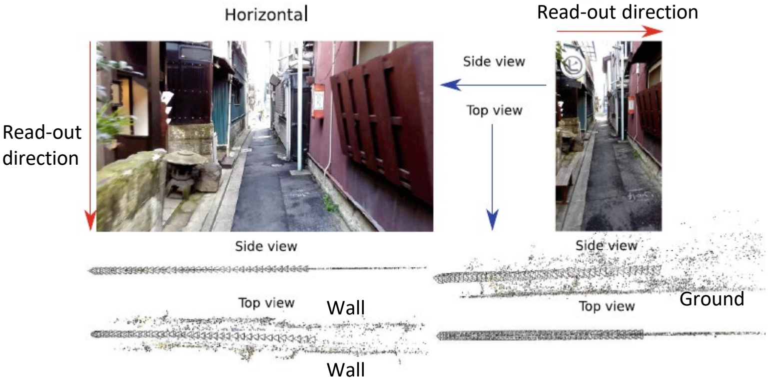
The projection matrices are now functions of the **image row**, because each row is taken at a different time and hence a different camera pose.

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



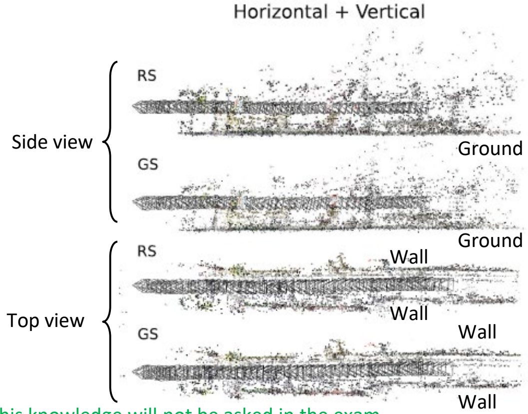
- (Left) A reconstruction from forward camera translation with vertical readout direction.
- (Right) A reconstruction from forward camera translation with horizontal readout direction.
- In both cases, the scene collapses into a plane that is perpendicular to the readout direction.

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



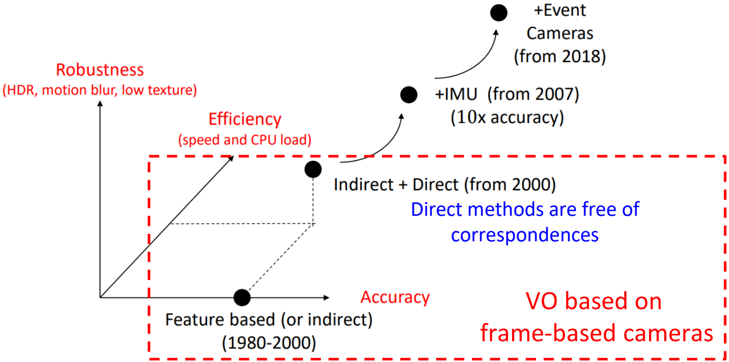
- When both image directions are combined, a correct reconstruction is obtained with rolling shutter (RS) projection model
- Result is close to a reconstruction with global shutter (GS) model.

This knowledge will not be asked in the exam.

Supplementary Knowledge

➢ Event Camera

✓ Progress in visual odometry



+Event Cameras (from 2018)

+IMU (from 2007) (10x accuracy)

Robustness (HDR, motion blur, low texture)

Efficiency (speed and CPU load)

Indirect + Direct (from 2000)

Direct methods are free of correspondences

Accuracy

Feature based (or indirect) (1980-2000)

VO based on frame-based cameras

Motion blur

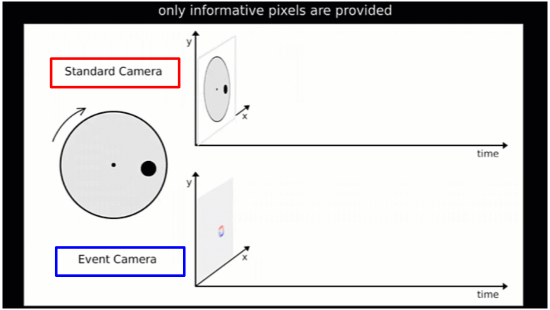
Dynamic Range

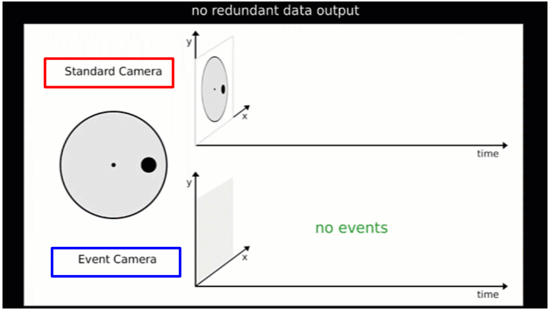
Supplementary Knowledge

➢ 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.

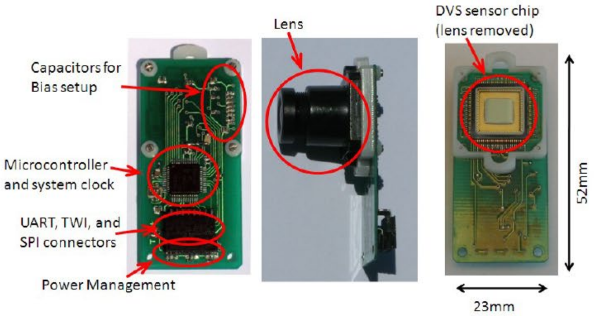


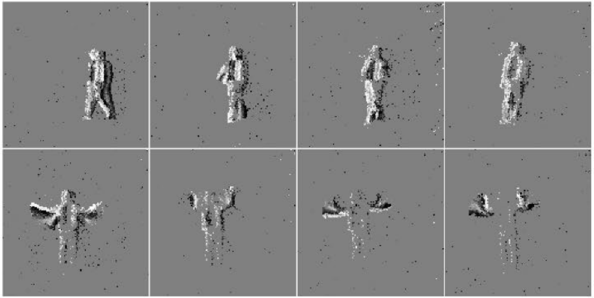


Supplementary Knowledge

- ➢ Event Camera

✓ An example



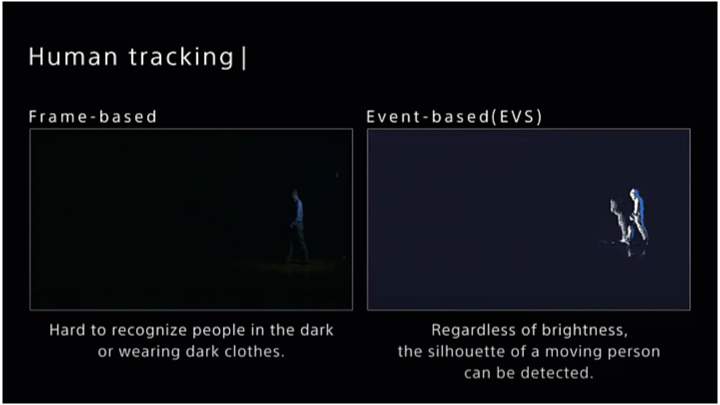


Each image has the resolution of **128x128** pixels. **White pixels** indicate a change of illumination from dark to light; **Black pixels** indicate a change of illumination from light to dark.

Supplementary Knowledge

➢ Event Camera

✓ An example



Human tracking |

Frame-based

Event-based(EVS)

Hard to recognize people in the dark or wearing dark clothes.

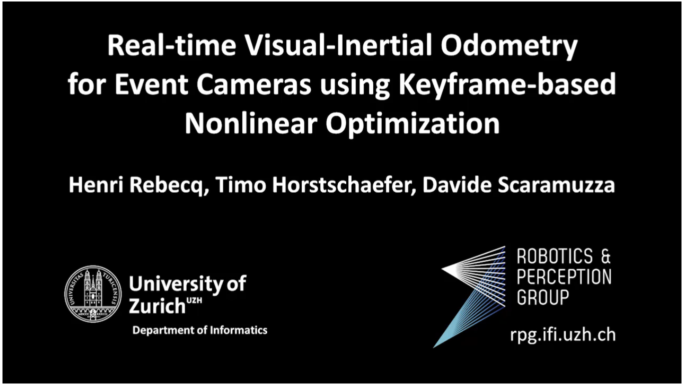
Regardless of brightness, the silhouette of a moving person can be detected.

Human tracking based on event camera

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

University of Zurich UZH
Department of Informatics

ROBOTICS & PERCEPTION GROUP
rpg.ifi.uzh.ch

Demo video

Summary

- Image Distortion
- Supplementary Knowledge

Thank you for your listening!
If you have any questions, please come to me :-)