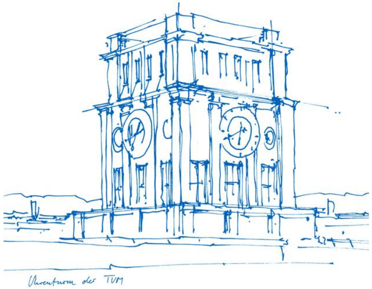
Computer Vision II: Multiple View Geometry (IN2228)

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

Dr. Haoang Li

04 May 2023 11:00-11:45



Announcement

Access to the recording of course in 2022

Dear Sabine,

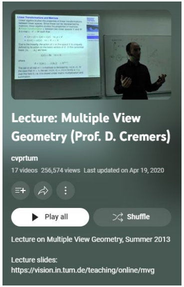
Sorry to disturb you again.

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

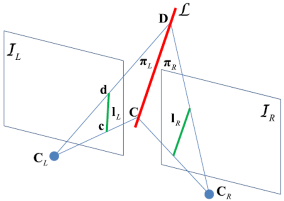
Explanation

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

✓ Projection plane computed by image line

Projection matrix (3*4)

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



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

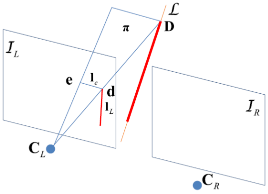
$$\underline{\mathbf{D}} = \overset{4*4}{\mathrm{L}}\underset{4*1}{\underline{\boldsymbol{\pi}}}$$

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



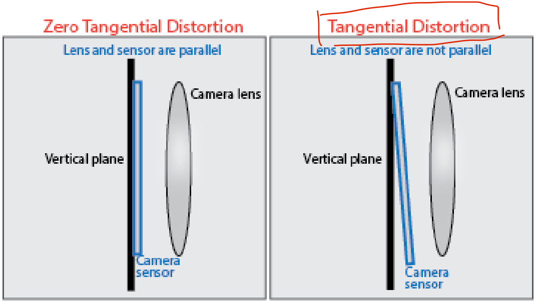
Outline

- Image Distortion
- Supplementary Knowledge

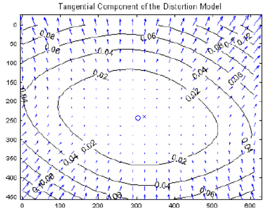
Image Distortion

➢ 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



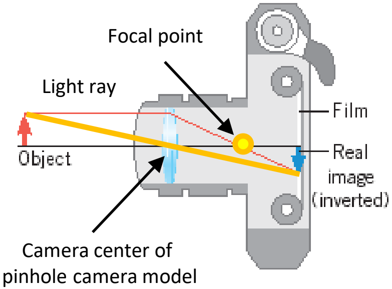
Tangential distortion

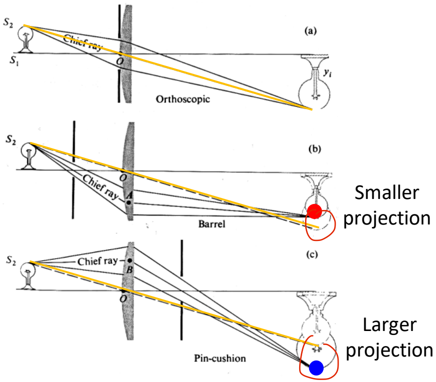
Image Distortion

➢ Type of Distortion

当光线在镜头边缘的弯曲程度比在光学中心的弯曲程度大时，就会发生径向畸变。

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





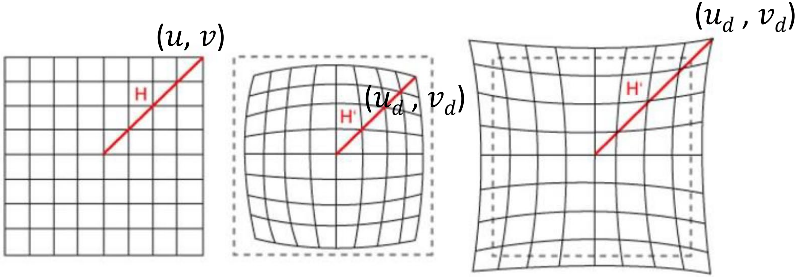
Two types of radial distortion

Image Distortion

➤ Radial Distortion

径向畸变的标准模型是从理想（非畸变）坐标（*uu* , *vv*）到真实（畸变）坐标（*udd* , *vdd*）的转变。

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

对于一个给定的非扭曲图像点（uu , vv），扭曲量是其与主点距离rr的非线性函数。

- Radial Distortion

对于大多数镜头来说，这个简单的径向畸变的二次模型就足够了

✓ 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

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

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

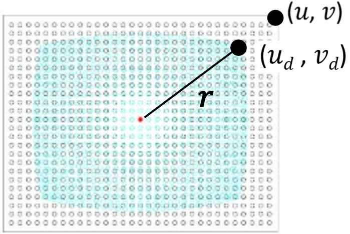


Image Distortion

- 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

Demo videos

Image Distortion

我们还可以使用关于单一径向失真参数r的显式模型[1]，而不是多项式模型。

➢ An Explicit Model

原始点和失真点之间的转换

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')

unknown

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

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

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

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

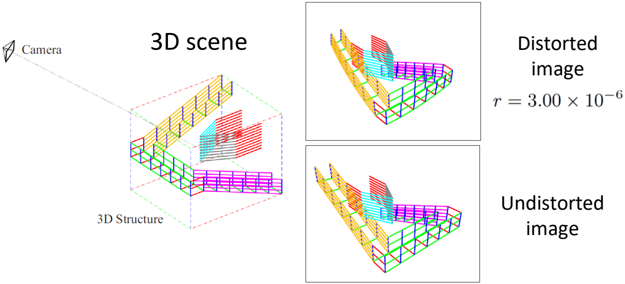
[1] Christian Brauer-Burchardt and Klaus Voss, “A new algorithm to correct fish-eye-and strong wide-angle-lens-distortion from single images," in IEEE International Conference on Image Processing (ICIP), 2001

Image Distortion

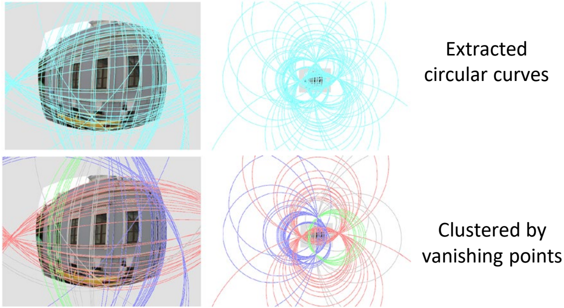
- Conversion between Lines and Circles

推而广之，一条直线和一个圆弧可以相互转换。

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



Synthetic data



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

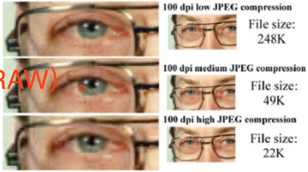
Supplementary Knowledge

➢ Limitations of Digital Images

- Noise

Low light is where you notice noise

- 噪声 低光是你注意到噪声的地方



- Compression

- 压缩会产生伪影，除非是未压缩的格式（TIFF，RAW）。

Creates artifacts except in uncompressed formats (tiff, raw)

- 稳定 补偿相机抖动（机械与电子）。

Blurred

Sharp

- Stabilization

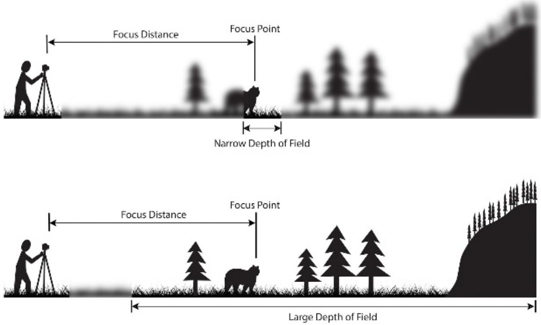
Compensate for camera shake (mechanical vs. electronic)

Supplementary Knowledge

- Depth of Field

场景中最近和最远的物体之间的距离，在图像中出现可接受的清晰度。

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

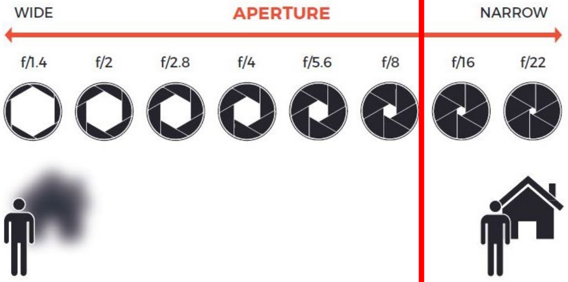


Supplementary Knowledge

➢ Depth of Field

较窄的光圈会增加景深，但会减少进入相机的光量。

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



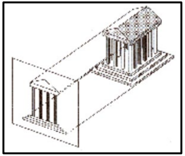
It partly determines the quality of keypoints detection

Keypoint detection needs sharp and bright images

Supplementary Knowledge

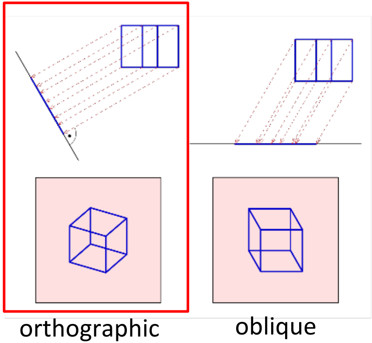
➤ Orthographic Projection

Length of a pillar in 2D is identical to that in 3D



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

正投影是一种 "特殊 "的平行投影，投影射线垂直于投影平面。



Two parallel projections of a cube

Left: orthographic projection. The projection lines are **perpendicular** to the image plane.

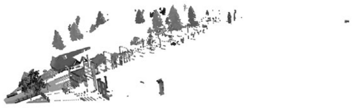
Right: oblique projection. The projection lines are at a **skew angle** to the image plane.

左图：正投影。投影线垂直于图像平面。

右图：斜向投影。投影线与图像平面有一个倾斜的角度。

Supplementary Knowledge

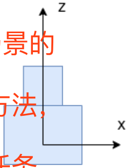
➢ Orthographic Projection



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.



应用 有了三维的点，我们可以把它们投射到场景的俯视图上。
- 对于移动机器人来说，这是一个有用的表示方法，因为障碍物之间的距离被保留了下来。
- 它很容易解释和利用来执行路径规划和导航任务。

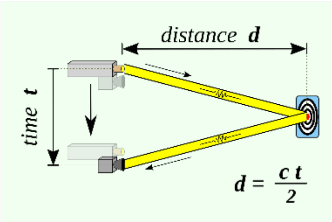
Supplementary Knowledge

➤ Depth Camera

✓ Basic information 一种能够确定物体深度信息的特殊相机，可用于三维重建。

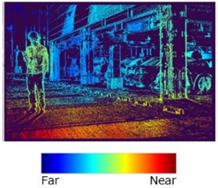
A special camera capable of determining the depth information of objects which can be used for 3D reconstruction

Microsoft Kinect v2



Time-of-flight measurement principle

Distance Image

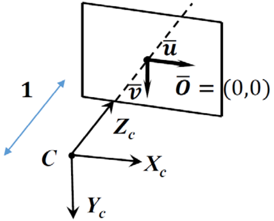


Photographed Image

Supplementary Knowledge

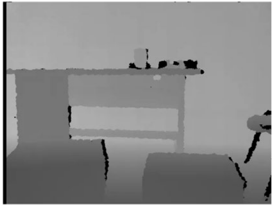
- ➢ Depth Camera

✓ From depth to 3D

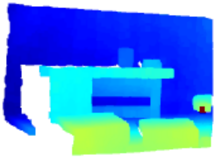


Normalized image plane

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



A depth image



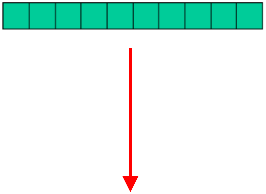
A 3D point cloud

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



卷帘门

- 一排排的像素在不同的时间被曝光和读取，一个接一个。

- 可能会扭曲（倾斜）移动的物体

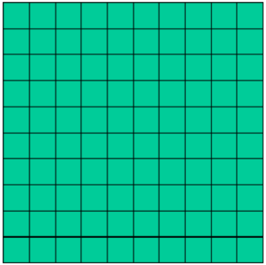
Global Shutter

- All pixels are exposed simultaneously
- No distortion of moving objects

全球快门

- 所有像素同时曝光

- 移动物体不失真



Supplementary Knowledge

- 前面的杆子是垂直的，但由于曝光时相机快速水平运动，看起来是倾斜的。

- 后面的垂直结构也是倾斜的，但要小得多，因为运动给远处物体带来的差异较小。

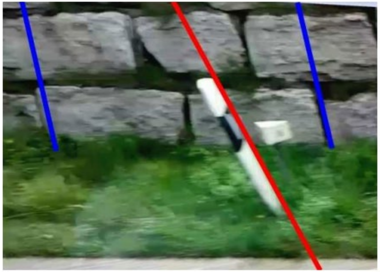
➢ Rolling Shutter vs. Global Shutter Camera

✓ 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

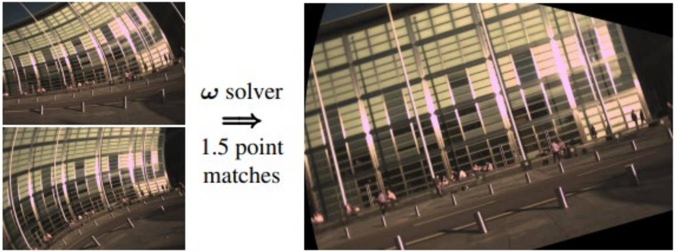
从两个卷帘门到一个全球卷帘门

- 当两个图像以不同的滚动快门方向（读出方向）记录时，其运动引起的失真是不同的。

- 几个点的对应关系就足以恢复运动以及不失真的图像。

➢ 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

从两个卷帘门到一个全球卷帘门

✓ From two rolling shutters to one global shutter

- 基于全局快门相机的透视投影

- Perspective projection based on global shutter camera

v_i: the i-th row

3D point

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

2D point

Projection matrix

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

- Adjusted model based on rolling shutter camera

基于滚动快门相机的调整后的模型

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

投影矩阵现在是图像行的函数，因为每一行都是在不同的时间拍摄的，因此是不同的相机姿态。

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

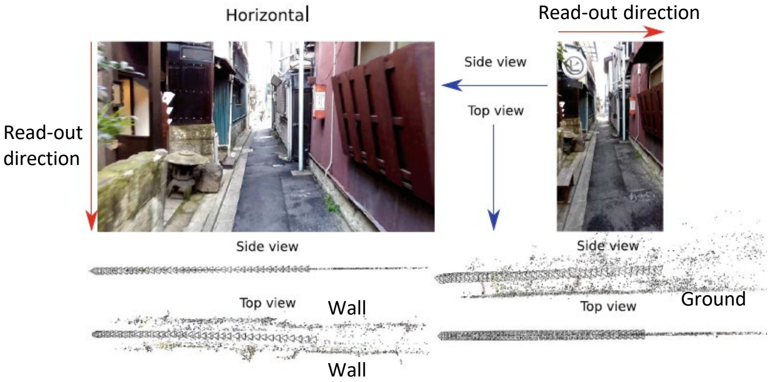
- (左图)来自前向相机平移的重建，垂直读出方向。

- (右图)水平读出方向的相机前向平移的重建。

- 在这两种情况下，场景都会坍缩到一个与读出方向垂直的平面。

➢ Rolling Shutter vs. Global Shutter Camera

✓ Structure from Motion based on rolling shutter camera

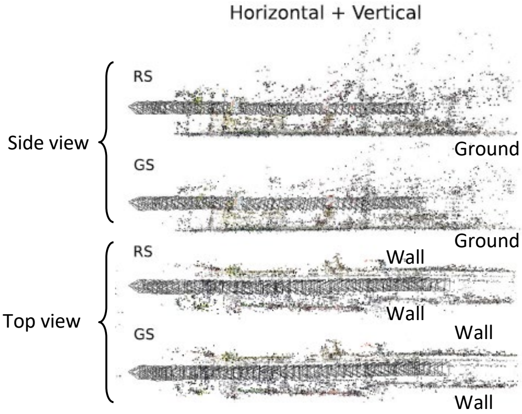


- (Left) A reconstruction from forward camera translation with vertical readout direction.
- (Right) A reconstruction from forward camera translation with horizontal readout direction.
- In both cases, the scene collapses into a plane that is perpendicular to the readout direction.

Supplementary Knowledge

➢ Rolling Shutter vs. Global Shutter Camera

Structure from Motion based on rolling shutter camera



- 当两个图像方向结合起来时，用滚动快门（RS）投影模型可以得到一个正确的重建。

- When both image directions are combined, a correct reconstruction is obtained with rolling shutter (RS) projection model

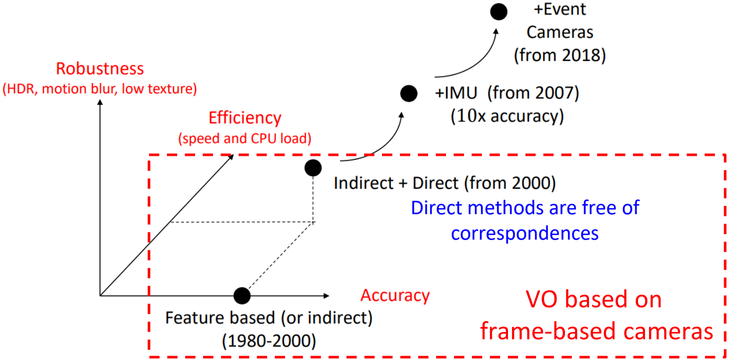
- Result is close to a reconstruction with global shutter (GS) model.

结果接近于用全局快门（GS）模型重建。

Supplementary Knowledge

➢ Event Camera

✓ Progress in visual odometry



Motion blur

Dynamic Range

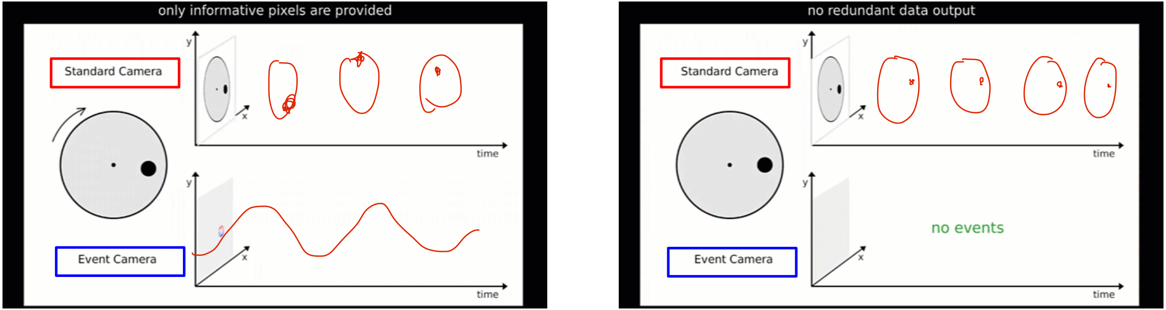
Supplementary Knowledge

➤ Event Camera

原理 对于事件相机来说，事件相机内的每个像素都独立地、异步地运行，在亮度发生变化时报告，否则保持沉默。

✓ Principle

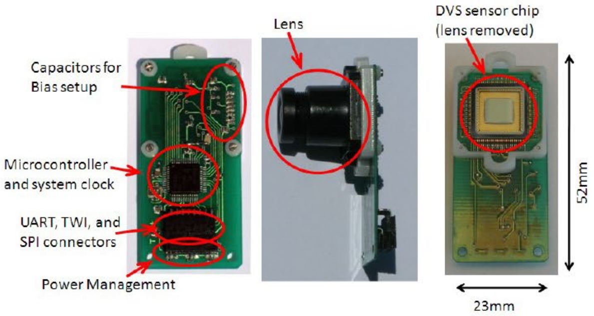
For event camera, each pixel inside an event camera operates independently and asynchronously, reporting changes in brightness as they occur, and staying silent otherwise.

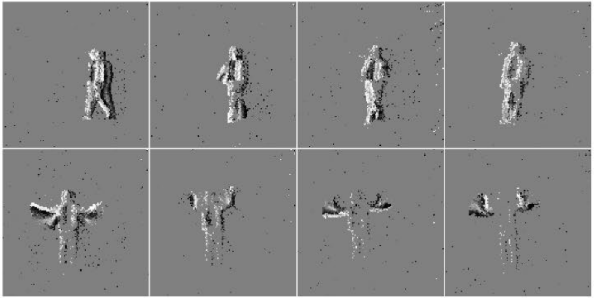


Supplementary Knowledge

➢ Event Camera

✓ An example



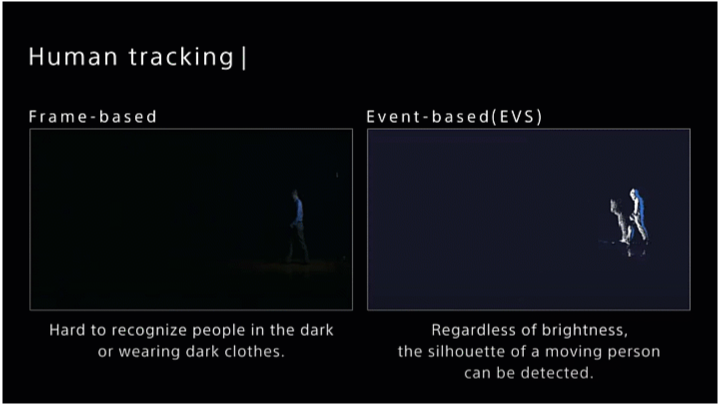


Each image has the resolution of **128x128** pixels. **White pixels** indicate a change of illumination from dark to light; **Black pixels** indicate a change of illumination from light to dark.

Supplementary Knowledge

➤ Event Camera

✓ An example

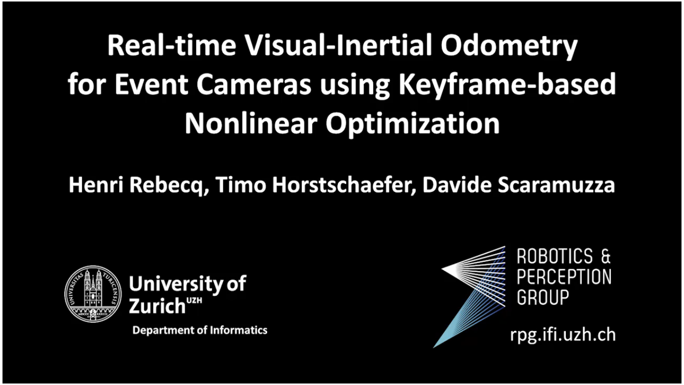


Human tracking based on event camera

Supplementary Knowledge

➢ Event Camera

✓ Application to visual SLAM/visual odometry



Demo video

Summary

- Image Distortion
- Supplementary Knowledge

Thank you for your listening!

If you have any questions, please come to me :-)