Technische Universität Berlin

EINSTEIN CENTER Digital Future

Event-based Robot Vision

Prof. Dr. Guillermo Gallego
Chair: Robotic Interactive Perception

guillermo.gallego@tu-berlin.de

http://www.guillermogallego.es

Use TU Berlin's Zoom

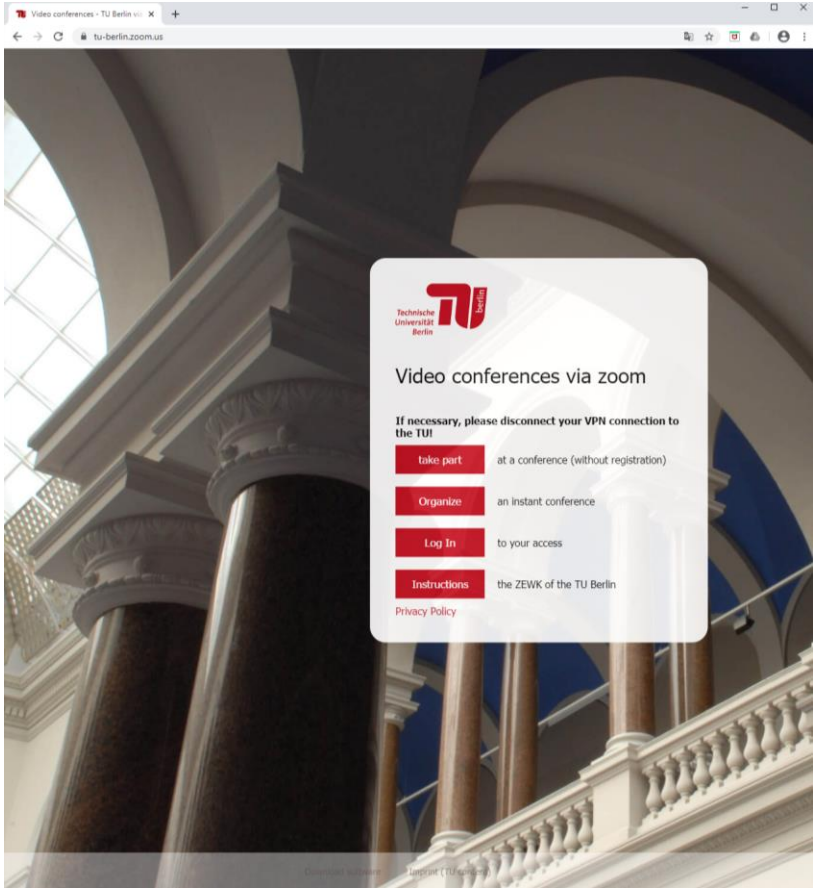
- Register / Login here: https://tu-berlin.zoom.us/

- Please download the Zoom client and **familiarize** yourself with this tool.

- **Join the lectures** either using URL or meeting ID and password.

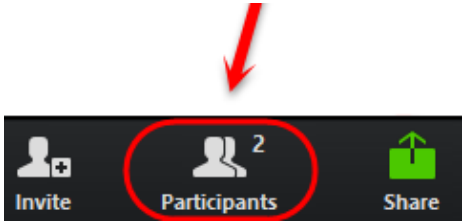
  - **Tuesdays, 10 – 14 h** (Vorlesung):
    Join with this link
    Meeting ID: 956-1107-4544
    Password: 93310701

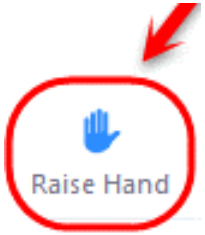
  - **Thursday, 14 - 16 h** (Übung)
    Join with this link
    Meeting ID: 988-0732-8139
    Password: 50820495



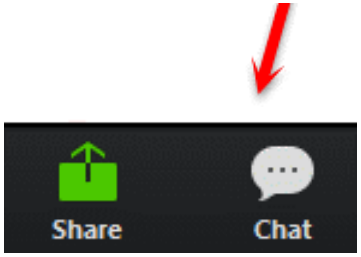
Questions during the presentation?

- "**Raise your hand**" on Zoom or
  - Participants → Blue icon "Raise Hand"





- Write the question in the **Zoom chat**



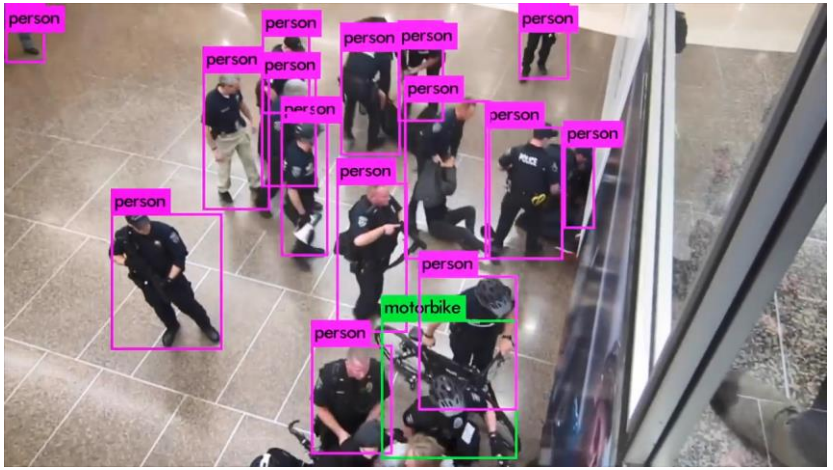
Robotics & Computer Vision have endless applications

AR/VR. Augmented life, work, entertainment.

Drones. Entertainment. Autonomous vehicles

Agricultural Robotics

YOLOv3: Real-Time Object Detection. Surveillance,…



Is everything solved?

- What are the limitations of these systems?
- What are the challenging scenarios?

Latency

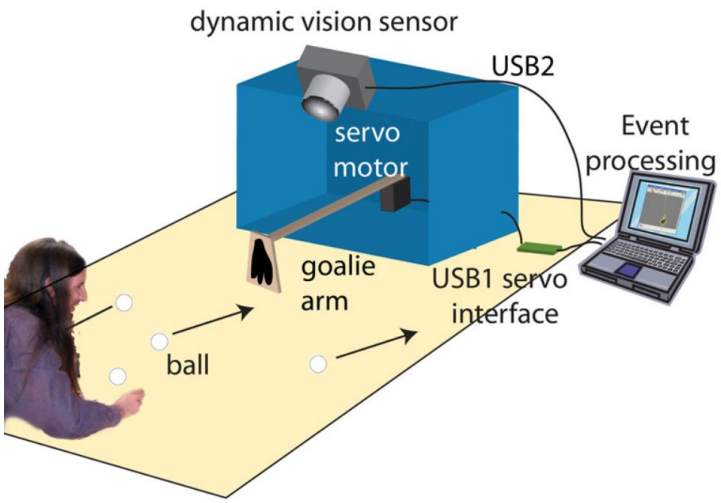
Motion blur

Dynamic Range

Event-based cameras do not suffer from these problems!

“RoboGoalie”. Low Latency

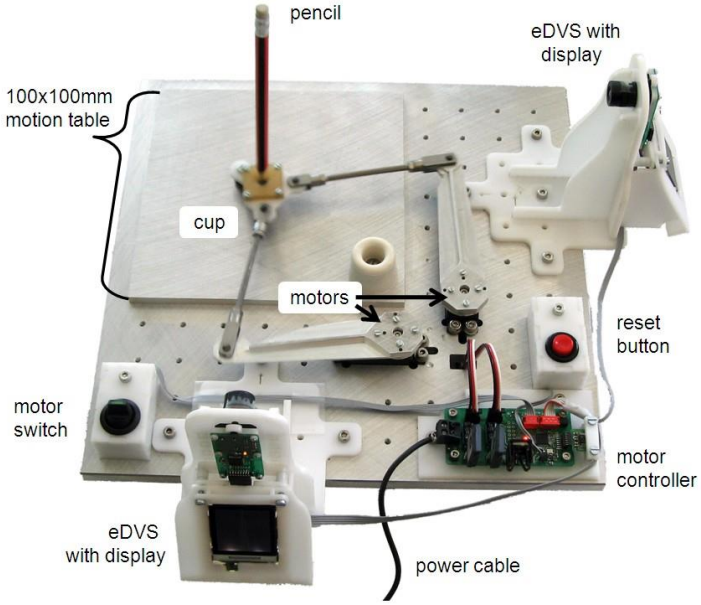
- High-speed perception (with a DVS) and control

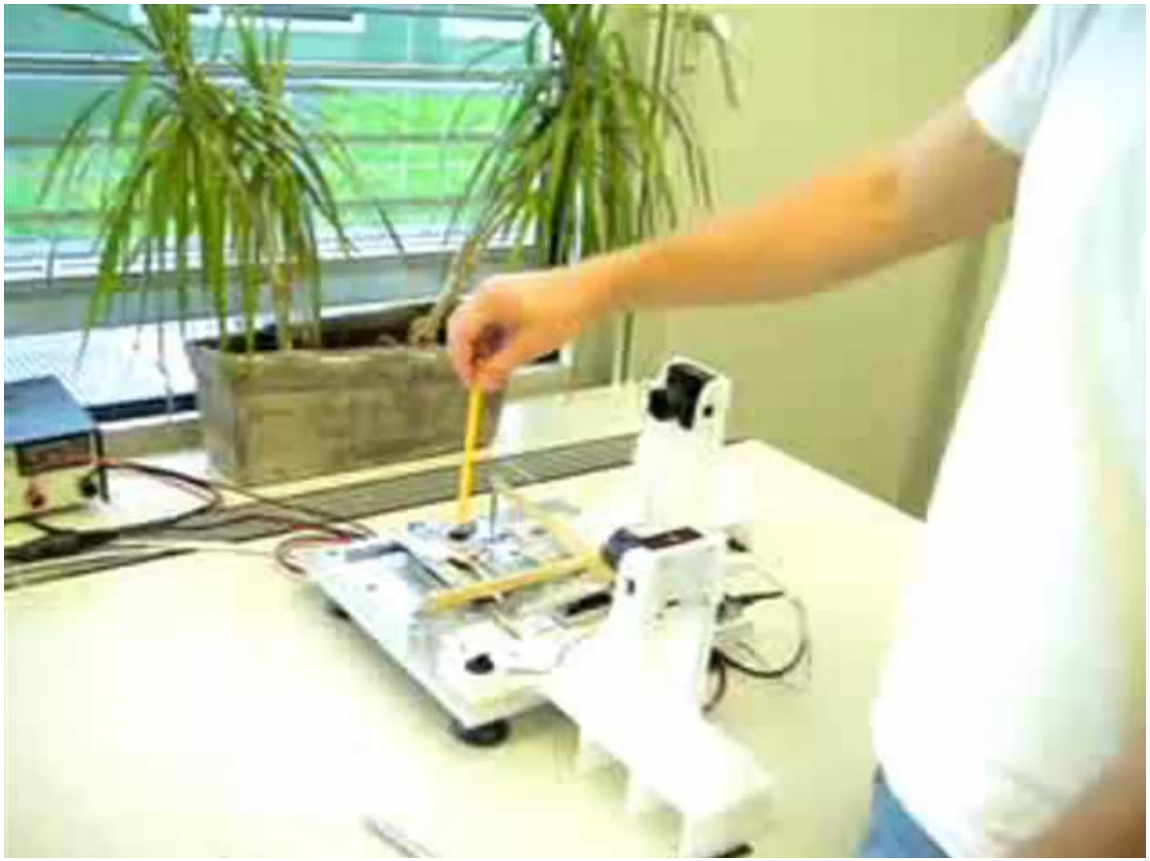


Delbruck et al., *Robotic Goalie with **3ms Reaction Time** at **4% CPU Load** Using Event-Based Dynamic Vision Sensor*, Front. Neurosci. (2013).
Video: https://youtu.be/6eOM15U_t1M

Pencil Balancer. Low Latency

- High-speed perception (with two DVSs) and control





Conradt et al., *A Pencil Balancing Robot Using a Pair of AER Dynamic Vision Sensors*, ISCAS 2009. Video: https://youtu.be/f9UngTdngY4

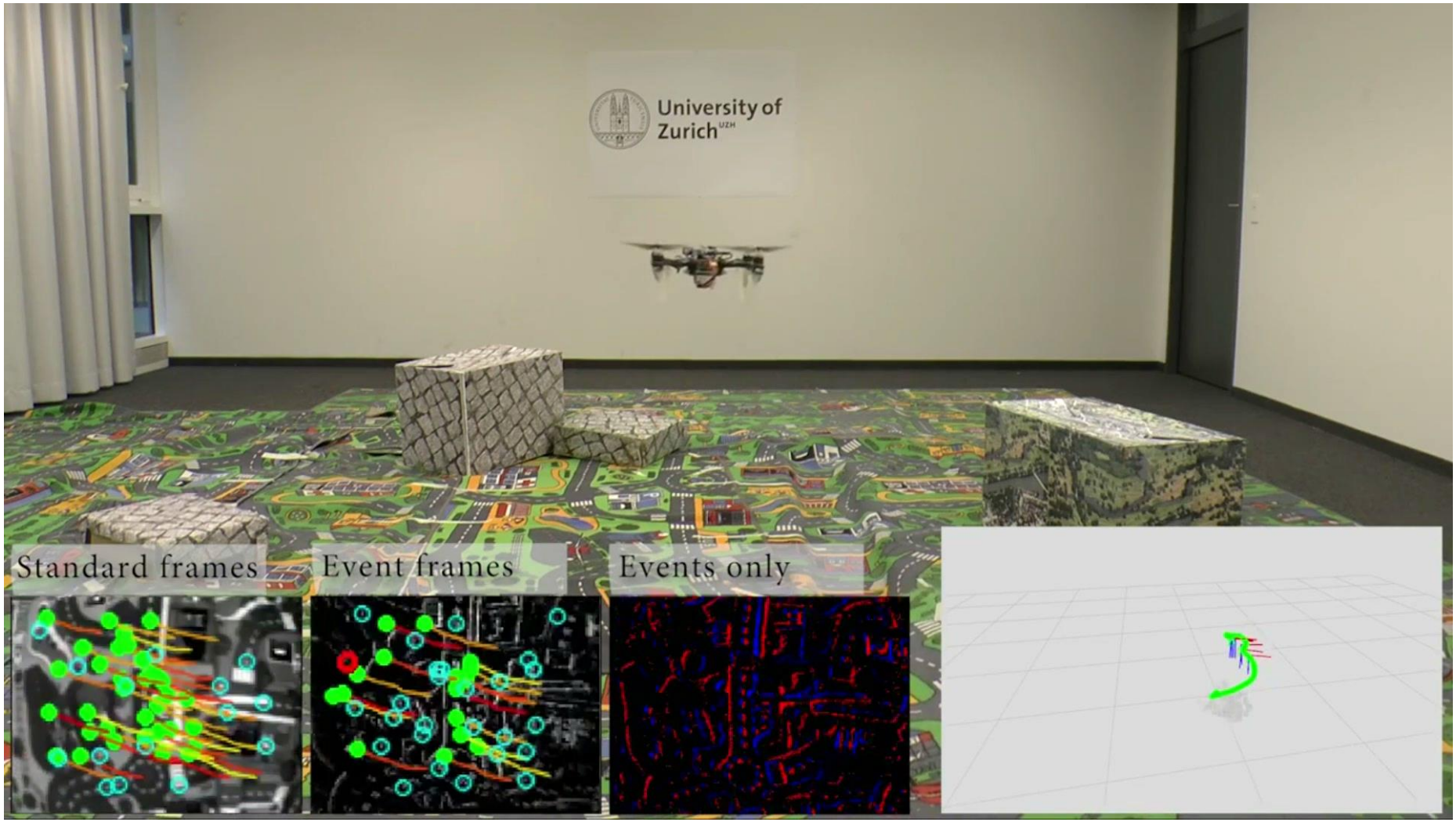
High speed 3D scanner

- Using an event-based camera and a laser projector

Matsuda et al., *MC3D: Motion Contrast 3D Scanning*, ICCP 2015. https://youtu.be/m7qOEsTyVwU

Robot in Difficult Illumination Conditions

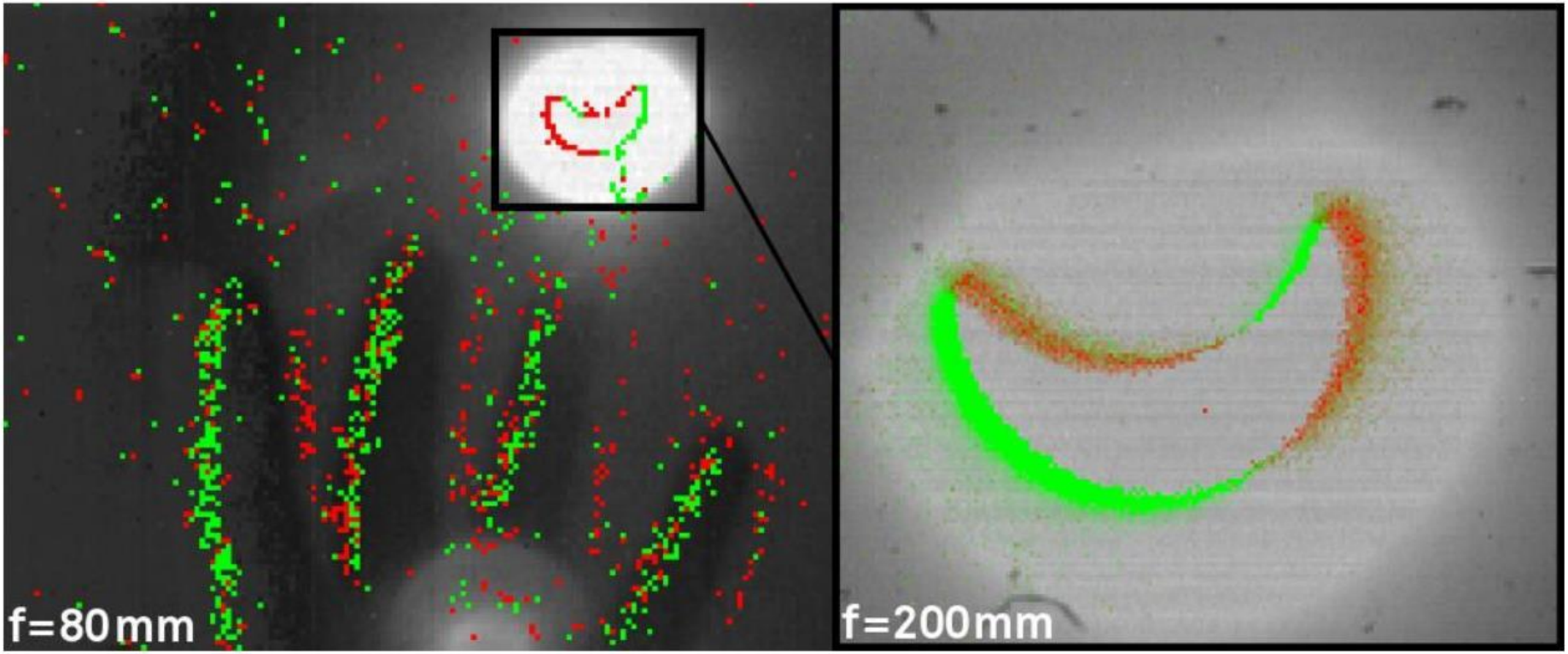
- Tightly coupled sensor fusion, fully onboard processing



Rosinol et al., *Ultimate SLAM? Combining Events, Images, and IMU for Robust Visual SLAM*…, RAL 2018. https://youtu.be/jIvJuWdmemE

High Dynamic Range Scene

- Ability to see very bright and very dark scenes, simultaneously
- Image of the solar eclipse (March 2015) captured by a DAVIS



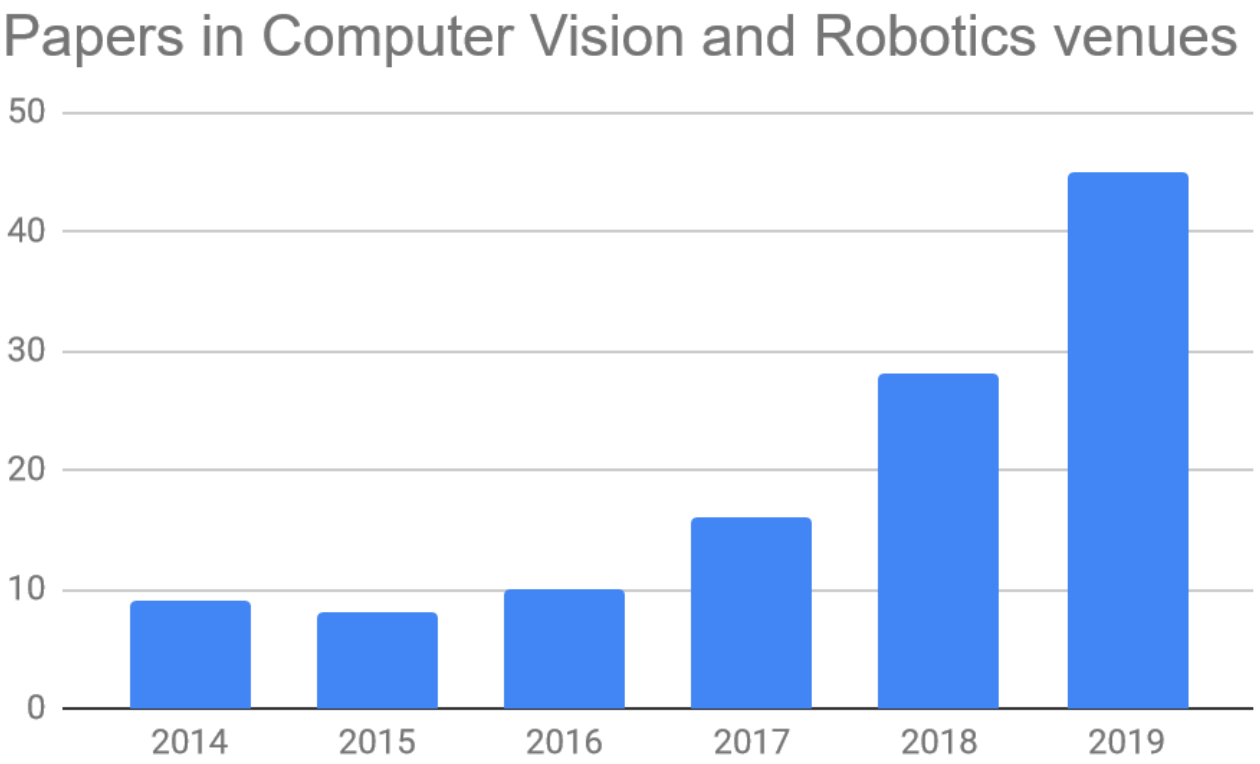
Video credit: M. Osswald, T. Delbruck and S. Bamford. https://youtu.be/hQI7e1TpXmA

Couse Objectives

- To understand a new, efficient way of acquiring and processing visual information that is inspired in the human visual system.
- Know the state of the art in Event-based Vision
- Gain practical experience in processing event data

Event-based vision is growing

- Papers published during the last six years at Computer Vision and Robotics venues*



* PAMI, IJCV, CVPR+W, ECCV+W, ICCV +W, BMVC, WACV, 3DV, ICIP, IROS +W, ICRA +W, RSS, ICCP, ICASSP, CoRL, IJRR, TRO, RAL

https://sites.google.com/view/guillermogallego/research/event-based-vision

Course Content in Questions

The topics covered include answering the following questions:

1. **What is** an event-based camera?
   - **How does it work?**
   - How does it capture a scene?
   - Why does it work like that?
   - What are the **pros and cons with respect to standard cameras**?
   - How have event-based cameras evolved over the years?
2. What can it be **used for**?
   - **How can we extract information** from the camera's output to solve our problem?
   - What are the **pros and cons of the resulting vision system**?
   - How can we use it to estimate motion?
   - How can you use it for 3D reconstruction?
   - Is it possible to recover absolute intensity from the events? How?
   - How can we use it to recognize objects or gestures?
   - How can these novel sensors **be combined** with others to produce more robust systems?
3. Where can I get one? (**Practice**)
   - How can I play with the data that it produces?

Course Content

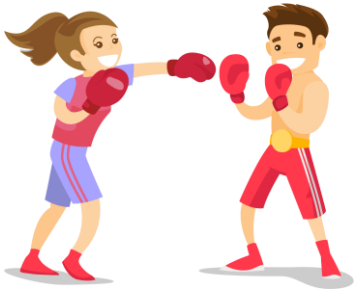
Mahowald & Mead
Scientific American 1991

The topics covered include the following:

1. **Principle of operation** of event-based cameras
   - Bio-inspired motivation.
   - Advantages, disadvantages and challenges / opportunities.
2. **Algorithms / Applications**:
   - Feature detection and tracking
   - Motion estimation: optical flow estimation, ego-motion estimation, simultaneous localization and mapping (SLAM)
   - Depth estimation (3D reconstruction) monocular or stereo
   - Image intensity reconstruction from events
   - Event-based filtering and signal processing
   - Event-based pattern recognition and machine learning
   - Event-based sensor fusion
   - …
3. **Physical devices**: actual event-based cameras & companies

Difference with Bio-inspired Computer Vision

- This course:
  - Lectures + per-session exercises
  - Cover a **broad range of topics in event-based vision**
  - Engineering viewpoint:
    - Being bio-inspired is nice, but it is not enforced.



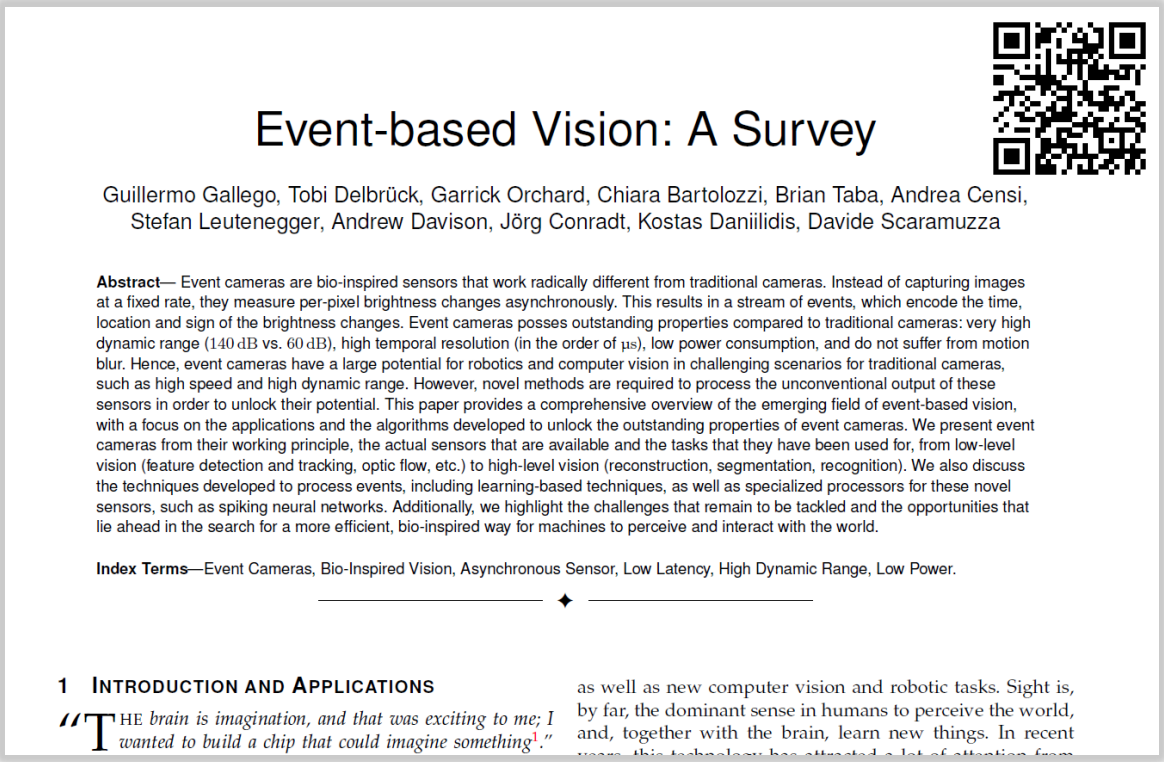
- Bio-inspired Computer Vision:
  - **Brings together two subjects**:
    - Human visual perception – Biology, Psychology (Prof. Maertens)
    - Technological advances in handling visual information – Engineering
  - 4 introductory lectures, then students work in teams on **projects**

Materials

- ISIS Webpage of the course:
  https://isis.tu-berlin.de/course/view.php?id=19385

ISIS INFORMATION SYSTEM FOR INSTRUCTORS AND STUDENTS

- Overview paper:
  Gallego et al., Event-based Vision: A Survey, arXiv 2019.



Event-based Vision: A Survey

Guillermo Gallego, Tobi Delbrück, Garrick Orchard, Chiara Bartolozzi, Brian Taba, Andrea Censi, Stefan Leutenegger, Andrew Davison, Jörg Conradt, Kostas Daniilidis, Davide Scaramuzza

Abstract— Event cameras are bio-inspired sensors that work radically different from traditional cameras. Instead of capturing images at a fixed rate, they measure per-pixel brightness changes asynchronously. This results in a stream of events, which encode the time, location and sign of the brightness changes. Event cameras posses outstanding properties compared to traditional cameras: very high dynamic range (140 dB vs. 60 dB), high temporal resolution (in the order of µs), low power consumption, and do not suffer from motion blur. Hence, event cameras have a large potential for robotics and computer vision in challenging scenarios for traditional cameras, such as high speed and high dynamic range. However, novel methods are required to process the unconventional output of these sensors in order to unlock their potential. This paper provides a comprehensive overview of the emerging field of event-based vision, with a focus on the applications and the algorithms developed to unlock the outstanding properties of event cameras. We present event cameras from their working principle, the actual sensors that are available and the tasks that they have been used for, from low-level vision (feature detection and tracking, optic flow, etc.) to high-level vision (reconstruction, segmentation, recognition). We also discuss the techniques developed to process events, including learning-based techniques, as well as specialized processors for these novel sensors, such as spiking neural networks. Additionally, we highlight the challenges that remain to be tackled and the opportunities that lie ahead in the search for a more efficient, bio-inspired way for machines to perceive and interact with the world.

Index Terms—Event Cameras, Bio-Inspired Vision, Asynchronous Sensor, Low Latency, High Dynamic Range, Low Power.

1 Introduction and Applications

"The *brain is imagination, and that was exciting to me; I wanted to build a chip that could imagine something*[1]."

as well as new computer vision and robotic tasks. Sight is, by far, the dominant sense in humans to perceive the world, and, together with the brain, learn new things. In recent

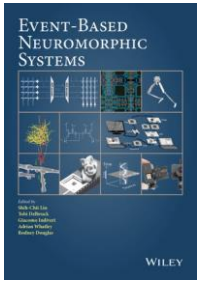
Materials

- ISIS Webpage of the course:
  https://isis.tu-berlin.de/course/view.php?id=19385

ISIS INFORMATION SYSTEM FOR INSTRUCTORS AND STUDENTS

- Overview paper:
  Gallego et al., Event-based Vision: A Survey, arXiv 2019.

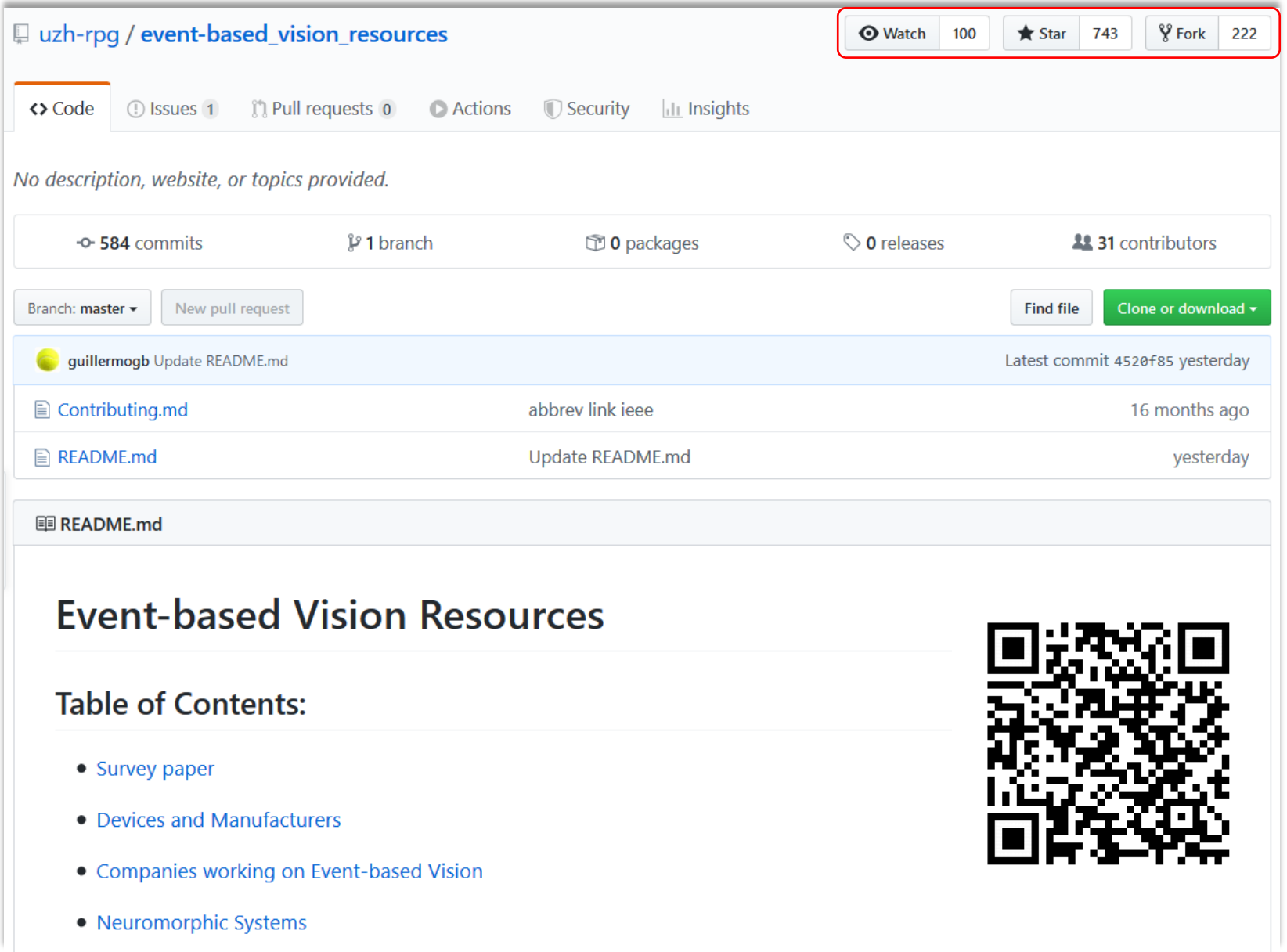
- List of Event-based Vision Resources:
  - Links to papers, books, videos, datasets, cameras, code…
  - Topical reviews
  - Research talks at International Workshops and Tutorials
  - PhD and Master theses on event-based vision



Event-Based Neuromorphic Systems

- General computer vision & robotics textbooks:
  - R. Szeliski's book is freely available
  - P. Corke's book: Robotics, Vision and Control (2nd Ed)

List of Event-based Vision resources



Schedule

- Fully online, unless TU Berlin decides otherwise.
- 14 weeks.
  - **Theory** (Tu.): We will presumably follow the topics in the order covered in the Survey paper
  - **Exercises** (Th.): Start simple, data reading and processing. Review some image processing. Then, increase complexity.
  - Equipment: Computer + Linux + Python (+Matlab?) + ROS (Robot Operating System in C++ / Python)

- Interested in you **learning the fundamentals** rather than on covering a large amount of material.

Grading

- No plan about examinations yet (originally, July 22nd).
  This is being coordinated by TU Berlin.
  https://www.pruefungen.tu-berlin.de/menue/sommersemester_2020_digital/studierende/
  https://www.pruefungen.tu-berlin.de/menue/sommersemester_2020_digital/lehrende/

- Grading scale:

Note:	1.0	1.3	1.7	2.0	2.3	2.7	3.0	3.3	3.7	4.0
Punkte:	86.0	82.0	78.0	74.0	70.0	66.0	62.0	58.0	54.0	50.0

- Original plan:
  - Two written test: 30% + 40%
  - Practice (exercises): 30%

Enrollment

- Currently, the class is full
- Maximum number of students: 30
- If people drop class, then use the waiting list.

Next steps

- Skim through the material on ISIS
  - Specially, the overview paper.

- Prepare equipment (computer & software)
  - Get familiarized with Zoom

- Ask questions
  - During the online session or on ISIS (between sessions)

Know your Audience

- What's your major?
- What's your experience in Computer Vision, ML and Robotics? (What courses have you taken?)
- What are your coding / programming skills?
  - What languages? What level?

- Why did you enroll in the course?
- What do you expect from the course?