University of Zurich UZH

ROBOTICS & PERCEPTION GROUP

Vision Algorithms for Mobile Robotics

Lecture 01
Introduction

Davide Scaramuzza

http://rpg.ifi.uzh.ch

Today's Outline

- About me and my research lab
- What is Computer Vision?
- Why study Computer Vision?
- Example of vision applications
- Organization of the course
- Start: Visual Odometry overview

Who am I?

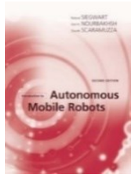
Current position

- Professor of Robotics & computer vision since 2012
- Dep. of Informatics (UZH) and Neuroinformatics (UZH & ETH)
- Director of the Master's program in Artificial Intelligence at the Dep. of Informatics (UZH)
- Adjunct Professor of the ETH Master in Robotics, Systems and Control and Associate faculty of the ETH AI Center

Education

- Master in Electronics Engineering at the University of Perugia, Italy, 2004
- PhD in Robotics and Computer Vision at ETH Zurich, Switzerland, 2008
- Post-doc at the University of Pennsylvania, USA
- Visiting professor at Stanford University, 2019

Book



- "Autonomous Mobile Robots, 2nd Edition" MIT Press, 2011

Hobbies

- Running, piano, magic tricks

My lab: the Robotics and Perception Group

- **Address**: Andreasstrasse 15, 2nd floor, next to **Zurich Oerlikon** train station
- **Webpage**: http://rpg.ifi.uzh.ch

Research Topics

Real-time, Onboard Computer Vision and Control for Autonomous Drone Navigation:

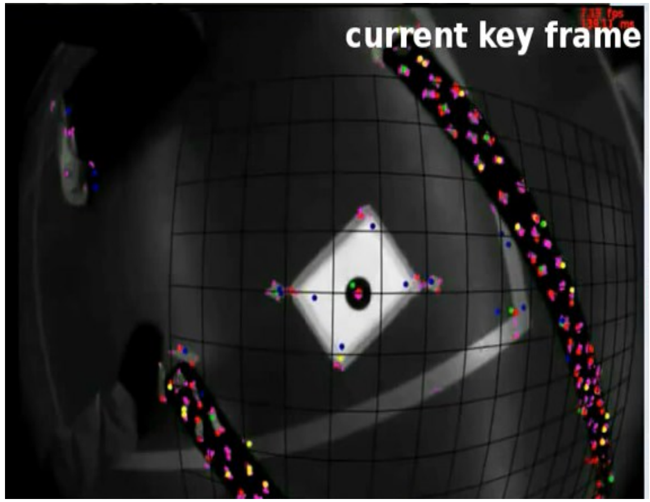
- Robot Learning
- Robot Vision
- Motion Planning & Control

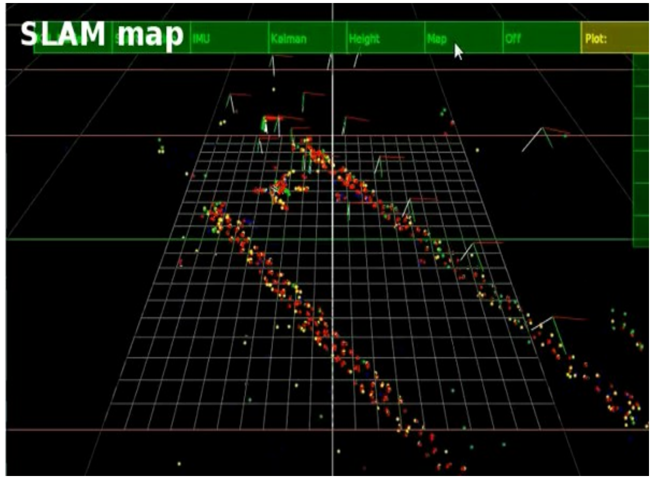
Motivation:

- Search and rescue applications

For an overview on our research, watch this keynote at the MIT Robotics Today Seminar Series:
https://youtu.be/LhO5WSFH7ZY

2009: First Vision-based Autonomous Flight





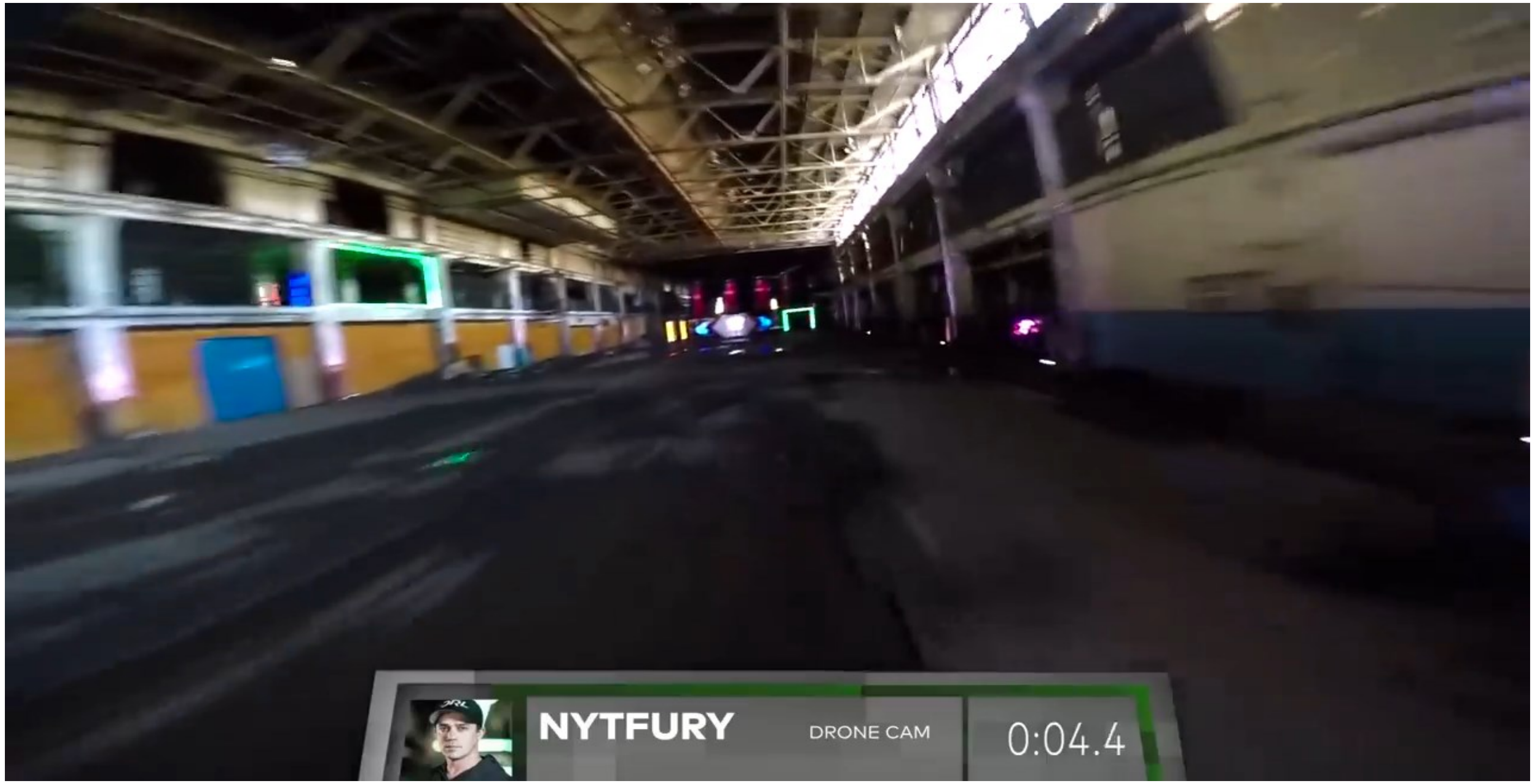
European Micro Aerial Vehicle competition, Sep. 9, 2009

Bloesch, Weiss, Scaramuzza, Siegwart, *Vision Based MAV Navigation in Unknown and Unstructured Environment*, **ICRA'10** [PDF]

Today

NASA Ingenuity helicopter performing autonomous vision-based flight on Mars

What does it take to fly as **good as or better** than human pilots?



WARNING! This drone is NOT autonomous; it is operated by a human pilot.

Human pilots take years to become **agile**

Pfeiffer, Scaramuzza (2021) *Human-piloted drone racing: Perception and control*, **RAL'21**

Vision-based High-Speed Flight in the Wild

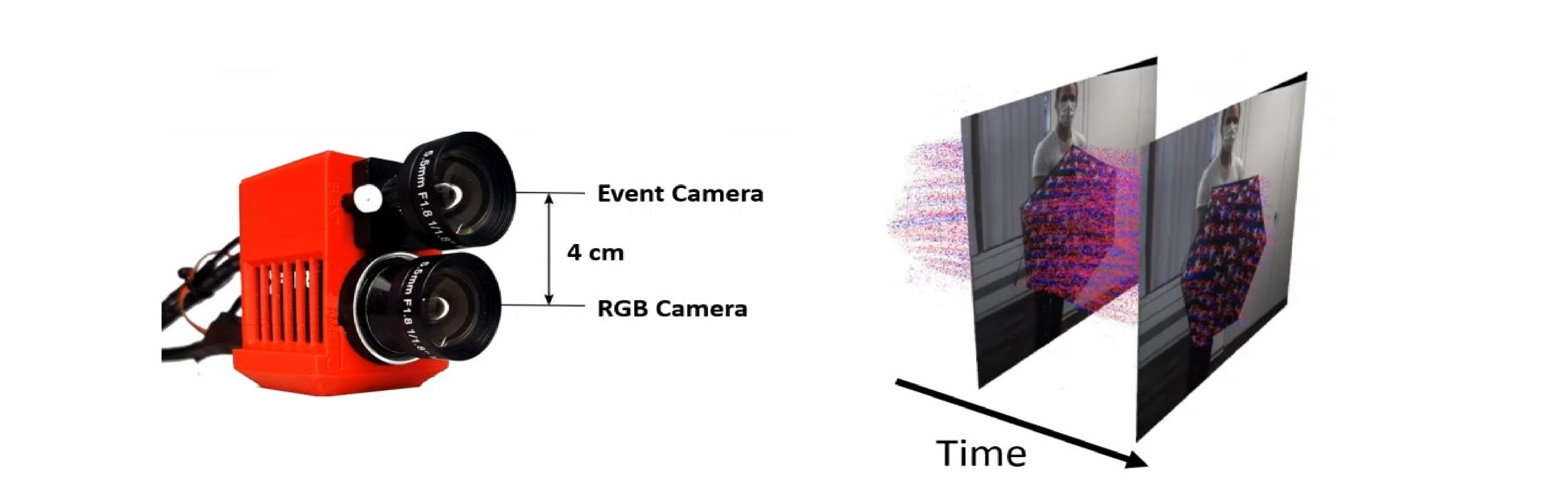
This AI-controlled drone is fully autonomous and uses onboard vision and computation

Loquercio, Kaufmann, Ranftl, Mueller, Koltun, Scaramuzza, *Learning High Speed Flight in the Wild*, **Science Robotics, 2021**
[PDF](). [Video](). [Code & Datasets]()

Autonomous Drone Racing

Kaufmann, Bauersfeld, Loquercio, Mueller, Koltun, Scaramuzza,
Champion-Level Drone Racing using Deep Reinforcement Learning, **Nature, 2023**

Event Cameras



Tulyakov, Gehrig, et al., TimeLens: *Event-based Video Frame Interpolation*, CVPR'21. PDF. Video. Code. Featured on Two-Minute-Papers: Video.

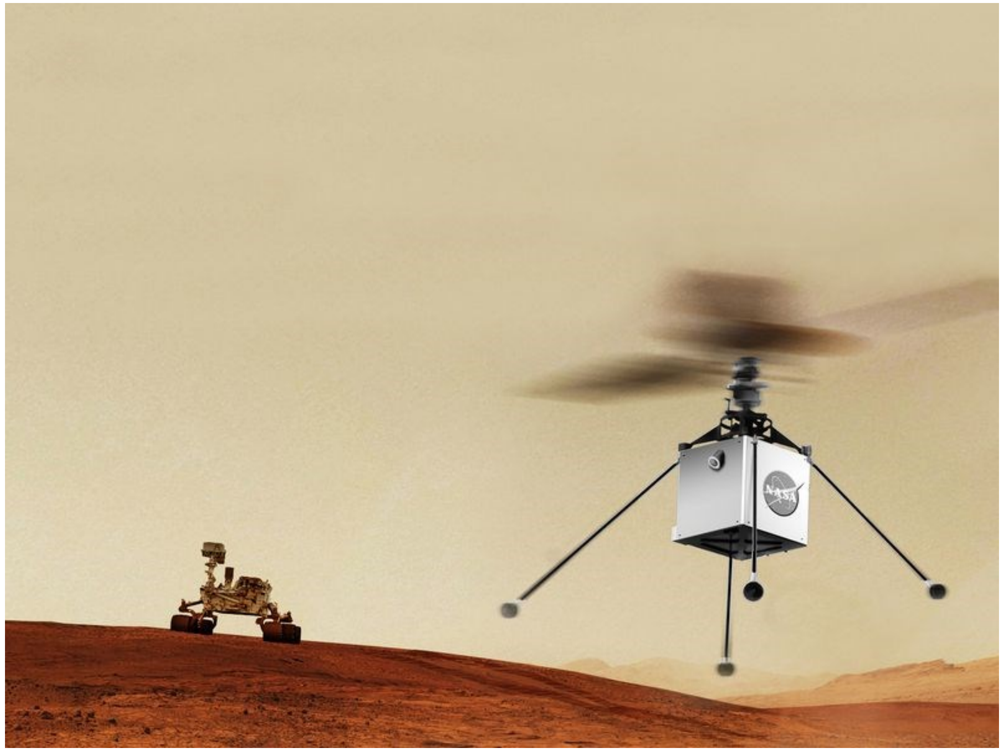
5273 FPS

Tulyakov, Gehrig, et al., TimeLens: *Event-based Video Frame Interpolation*, CVPR’21. PDF. Video. Code. Featured on Two-Minute-Papers: Video.

Tech Transfer and Spin-offs

Collaboration with NASA/JPL for future Mars missions

Jet Propulsion Laboratory
California Institute of Technology



Read the details on [this Swissinfo article]

SUIND

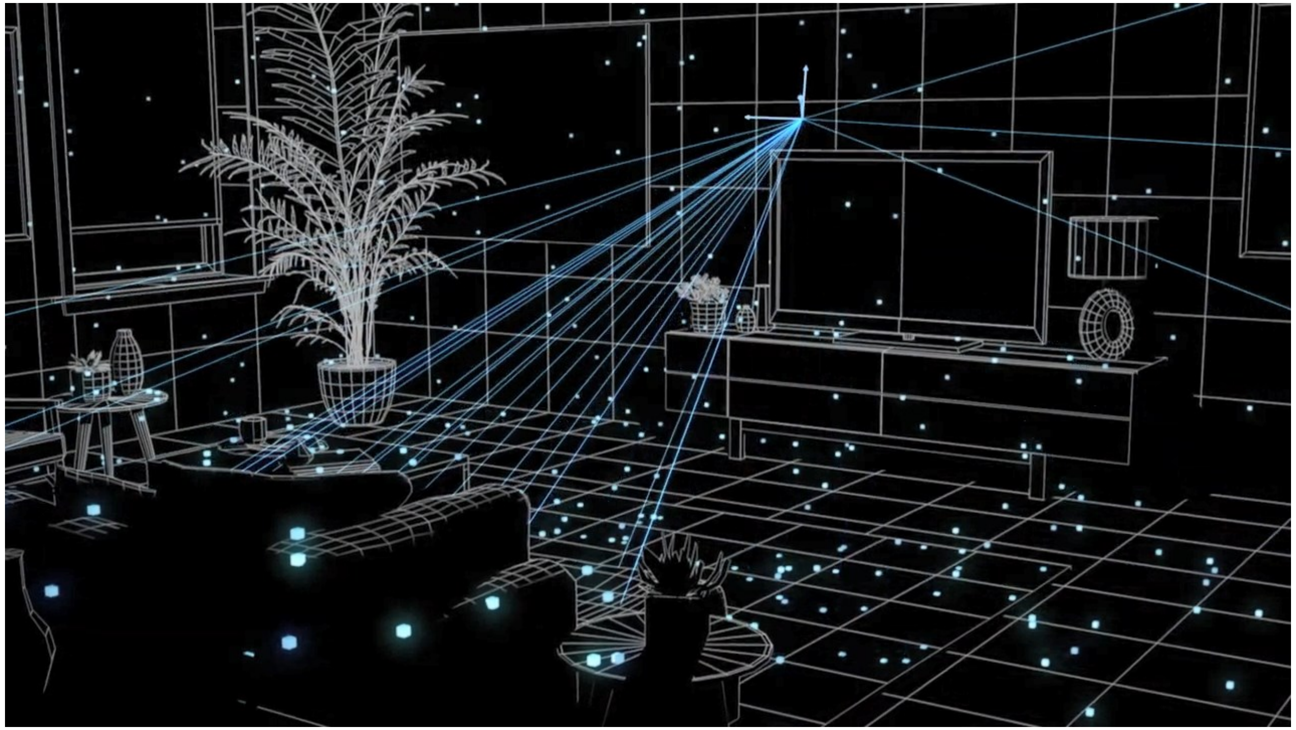
Autonomous Crop Spraying and Forest Mmonitoring

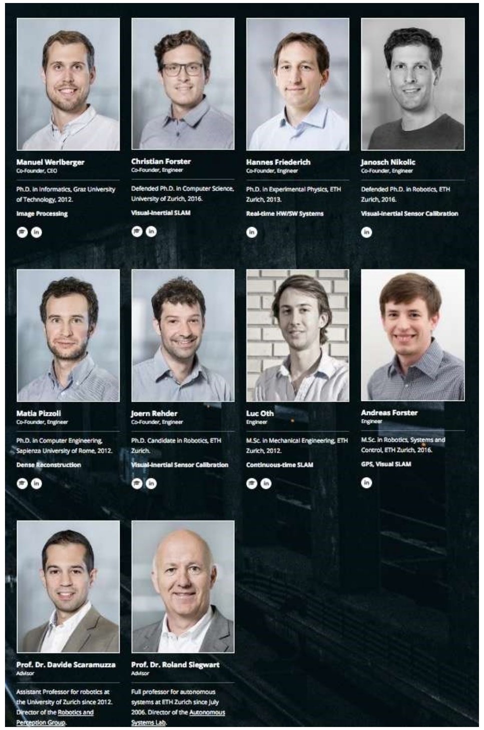
Fotokite A tethered drone for first response

The drone receives electrical power over-tether from the ground so that it can fly “forever”

“Zurich-Eye” – Today: Meta Zurich

- **Vision-based Localization and Mapping** systems for mobile robots
- Born in Sep. 2015, became **Facebook-Oculus Zurich** in Sep. 2016. Today, **200 employees**.
- In 2018, Zurich-Eye launched **Oculus Quest** (10 million units sold so far)

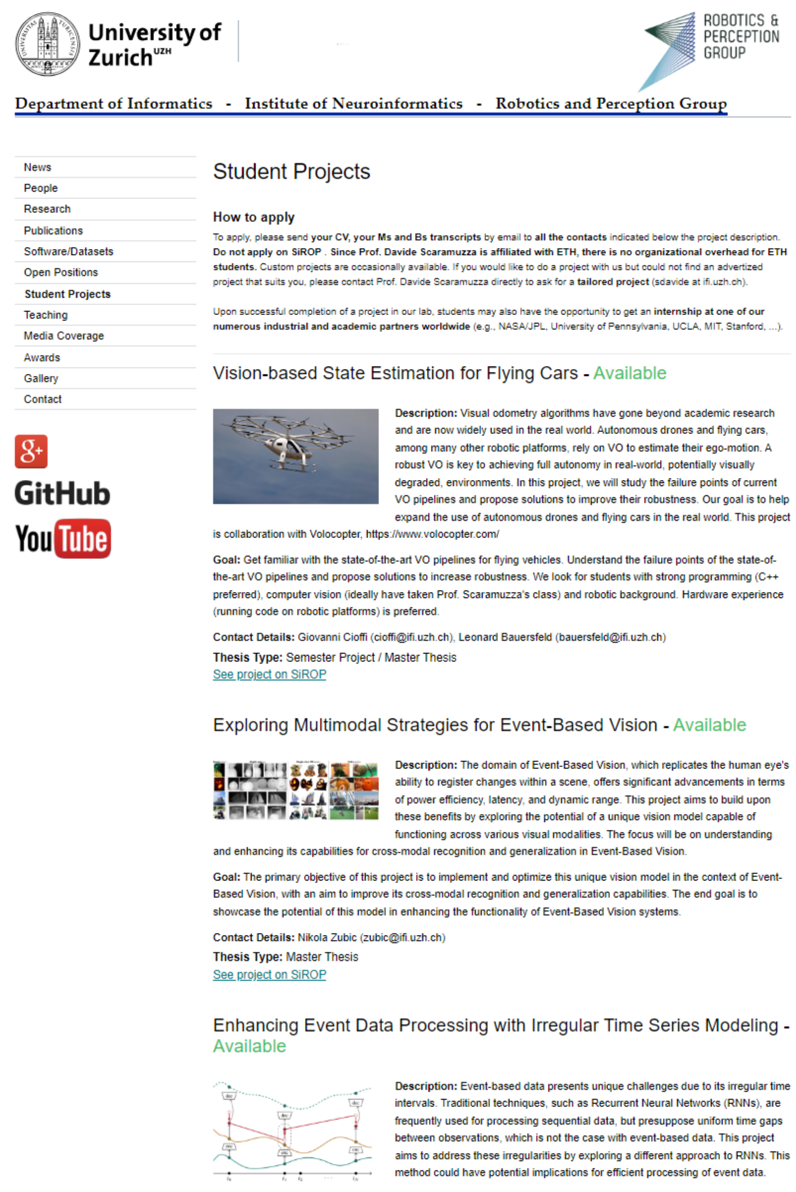




“**From the lab to the living room**”: The story behind Facebook’s Oculus Insight technology from Zurich-Eye to Oculus Quest:
https://tech.fb.com/the-story-behind-oculus-insight-technology/

Student Projects: http://rpg.ifi.uzh.ch/student_projects.php

- **Topics**: machine learning, computer vision, control, planning, system integration
- **Highlights**: many of our Master students have published their thesis in international conferences, won prestigious awards (e.g., ETH Medal, Fritz-Kutter Award, conference paper awards), got a PhD at prestigious institutions (MIT), worked at NASA/JPL, etc.


University of Zurich[UZH]

ROBOTICS & PERCEPTION GROUP

Department of Informatics - Institute of Neuroinformatics - Robotics and Perception Group

News
People
Research
Publications
Software/Datasets
Open Positions
Student Projects
Teaching
Media Coverage
Awards
Gallery
Contact

GitHub
YouTube

Student Projects

How to apply

To apply, please send **your CV, your Ms and Bs transcripts** by email to **all the contacts** indicated below the project description. **Do not apply on SiROP . Since Prof. Davide Scaramuzza is affiliated with ETH, there is no organizational overhead for ETH students.** Custom projects are occasionally available. If you would like to do a project with us but could not find an advertized project that suits you, please contact Prof. Davide Scaramuzza directly to ask for a **tailored project** (sdavide at ifi.uzh.ch).

Upon successful completion of a project in our lab, students may also have the opportunity to get an **internship at one of our numerous industrial and academic partners worldwide** (e.g., NASA/JPL, University of Pennsylvania, UCLA, MIT, Stanford, ...).

Vision-based State Estimation for Flying Cars - Available

Description: Visual odometry algorithms have gone beyond academic research and are now widely used in the real world. Autonomous drones and flying cars, among many other robotic platforms, rely on VO to estimate their ego-motion. A robust VO is key to achieving full autonomy in real-world, potentially visually degraded, environments. In this project, we will study the failure points of current VO pipelines and propose solutions to improve their robustness. Our goal is to help expand the use of autonomous drones and flying cars in the real world. This project is collaboration with Volocopter, https://www.volocopter.com/

Goal: Get familiar with the state-of-the-art VO pipelines for flying vehicles. Understand the failure points of the state-of-the-art VO pipelines and propose solutions to increase robustness. We look for students with strong programming (C++ preferred), computer vision (ideally have taken Prof. Scaramuzza's class) and robotic background. Hardware experience (running code on robotic platforms) is preferred.

Contact Details: Giovanni Cioffi (cioffi@ifi.uzh.ch), Leonard Bauersfeld (bauersfeld@ifi.uzh.ch)

Thesis Type: Semester Project / Master Thesis

See project on SiROP

Exploring Multimodal Strategies for Event-Based Vision - Available

Description: The domain of Event-Based Vision, which replicates the human eye's ability to register changes within a scene, offers significant advancements in terms of power efficiency, latency, and dynamic range. This project aims to build upon these benefits by exploring the potential of a unique vision model capable of functioning across various visual modalities. The focus will be on understanding and enhancing its capabilities for cross-modal recognition and generalization in Event-Based Vision.

Goal: The primary objective of this project is to implement and optimize this unique vision model in the context of Event-Based Vision, with an aim to improve its cross-modal recognition and generalization capabilities. The end goal is to showcase the potential of this model in enhancing the functionality of Event-Based Vision systems.

Contact Details: Nikola Zubic (zubic@ifi.uzh.ch)

Thesis Type: Master Thesis

See project on SiROP

Enhancing Event Data Processing with Irregular Time Series Modeling - Available

Description: Event-based data presents unique challenges due to its irregular time intervals. Traditional techniques, such as Recurrent Neural Networks (RNNs), are frequently used for processing sequential data, but presuppose uniform time gaps between observations, which is not the case with event-based data. This project aims to address these irregularities by exploring a different approach to RNNs. This method could have potential implications for efficient processing of event data.

Today’s Outline

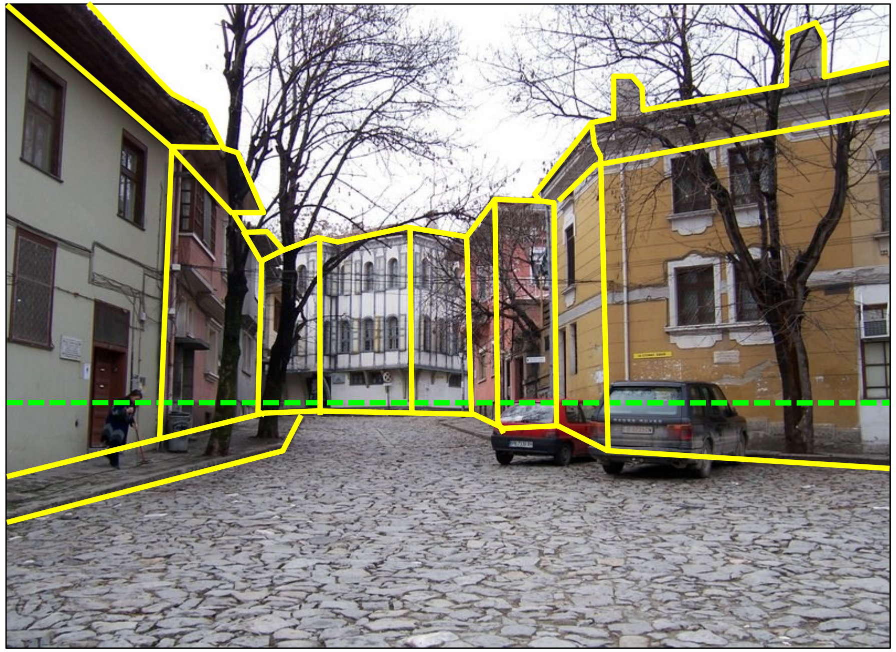
- About me and my research lab
- What is Computer Vision?
- Why study computer vision?
- Example of Vision Applications
- Organization of the course
- Start: Visual Odometry overview

What is computer vision?

Automatic extraction of “meaningful” information from images and videos

Semantic information

(“Image Analysis and Computer Vision” course)



Geometric information

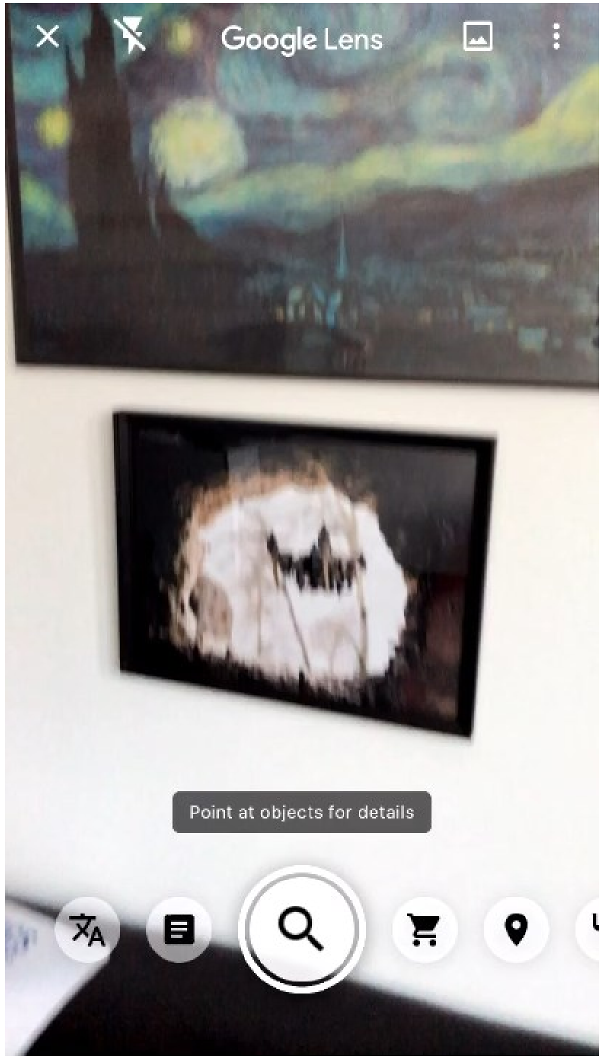
(this course)

Vision Demo?

Terminator 2

Are we there? Almost!

Google App



Today’s Outline

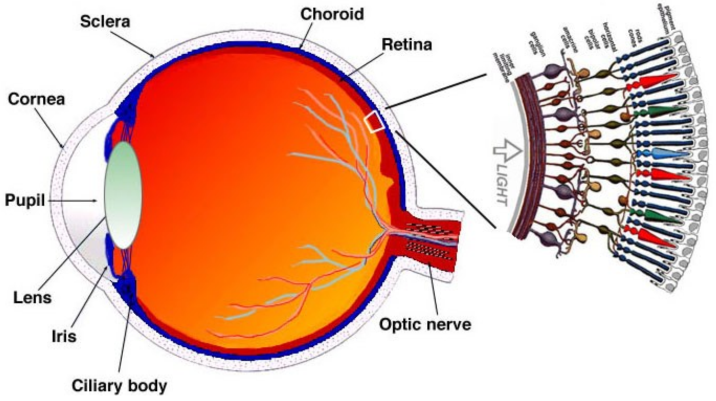
- About me and my research lab
- What is Computer Vision?
- Why study computer vision?
- Example of Vision Applications
- Organization of the course
- Start: Visual Odometry overview

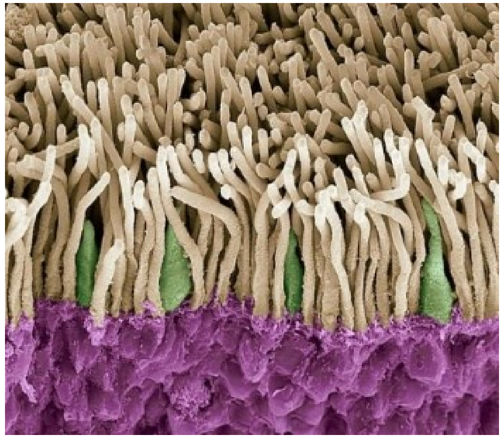
Why study computer vision?

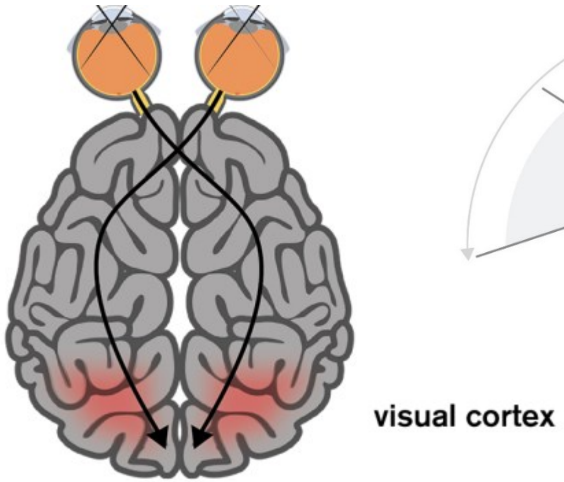
- **Relieve** humans of boring, easy tasks
- **Enhance** human abilities: human-computer interaction, visualization, augmented reality (AR)
- Perception for autonomous **robots**
- **Organize** and give access to visual **content**
- Lots of computer-vision **companies and jobs in Switzerland** (Zurich & Lausanne):
  - Meta (Zurich): AR/VR, Instagram
  - Huawei (Zurich): automotive, autonomous cars, event cameras, computational photography
  - Verity (Zurich): SLAM engineer
  - Perspective Robotics (Zurich): Computer vision engineer
  - Fixposition (Zurich): Sensor fusion engineer
  - Magic-Leap (Zurich): AR/VR
  - Microsoft Research (Zurich): Robotics and Hololens AR
  - Google (Zurich): Brain, Positioning Services, Street View, YouTube
  - Apple (Zurich): Autonomous Driving, face tracking
  - NVIDIA (Zurich): simulation, autonomous driving
  - Logitech (Zurich, Lausanne)
  - Disney-Research (Zurich)
  - VIZRT (Zurich): sport broadcasting, 3D replay
  - Pix4D (Lausanne): 3D reconstruction from drones
  - More on glassdoor.ch

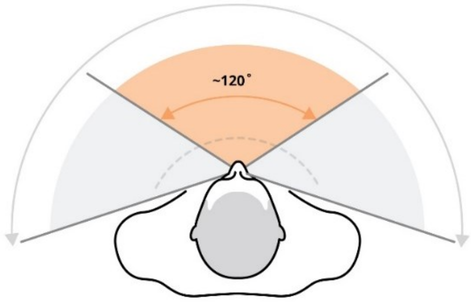
Vision in humans

- **Vision** is our most powerful sense. **Half of the primate cerebral cortex** is devoted to visual processing
- The retina is ~1,000 mm^2. Contains **130 million photoreceptors** (120 mil. rods for low light vision and 10 mil. cones for color sampling) covering a **visual field** of $\mathbf{220 \times 135}$ **degrees**
- Provides enormous amount of information: **data-rate of ~3GBytes/s**
- To match the eye resolution, we would need a **500 Megapixel** camera. But in practice the acuity of an eye is **8 Megapixels** within a **18-degree field of view** (5.5 mm diameter) around a small depression called **fovea**





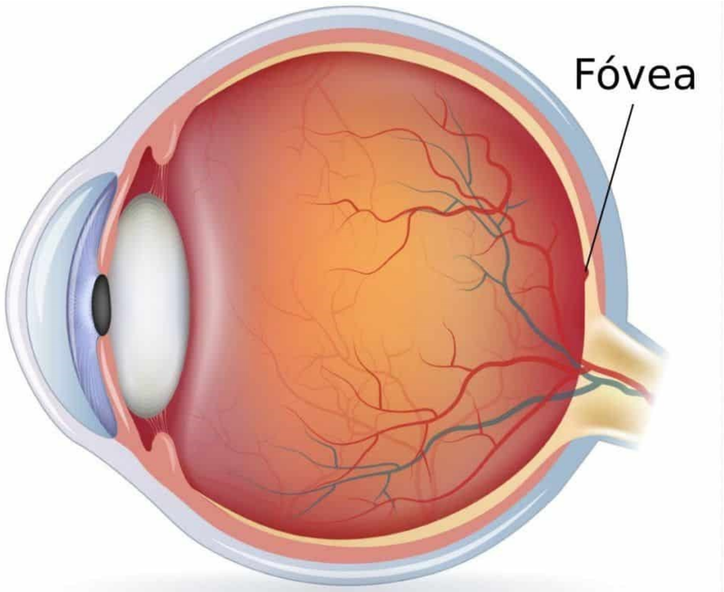




Vision in humans: how we see

- The **area we see in focus** and in **full color** represents the part of the visual field that is covered by the **fovea**
- The **fovea** is 0.35 mm in diameter, covers a visual field of **1-2 degrees**, has **high density of cone cells**
- Within the rest of the **peripheral visual field**, the image we perceive becomes more **blurry** (**rod cells**)

How we actually see. This principle is used in foveated rendering



If you are interested to study human perception, check out the UZH course "Computational Vision" (this semester)

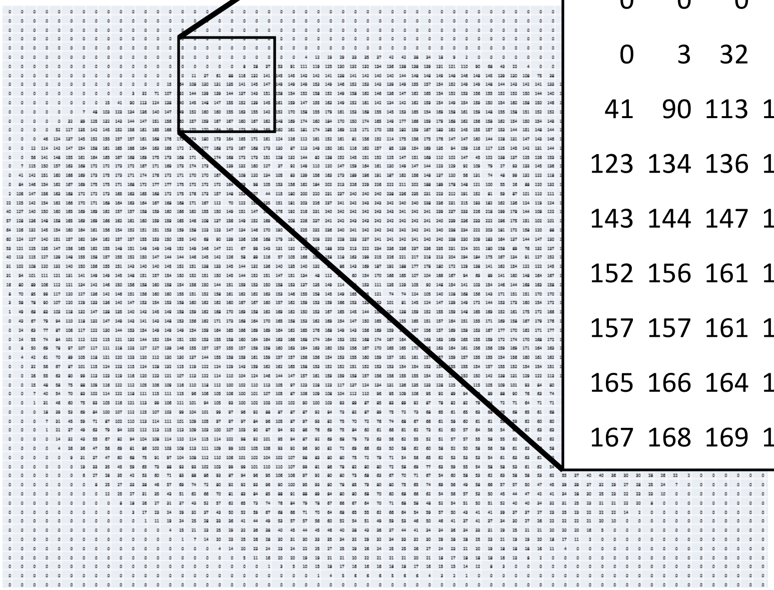
What a newborn sees every month in the first year

“Your baby sees things best from 15 to 30 cm away. This is the perfect distance for gazing up into the eyes of mom or dad. Any farther than that, and the newborn sees mostly blurry shapes because they're nearsighted. At birth, a newborn's eyesight is between 20/200 and 20/400.”

http://uk.businessinsider.com/what-a-baby-can-see-every-month-for-the-first-year-of-its-life-2017-1?r=US&IR=T

Why is vision hard?

How do we go from an array of number to recognizing a fruit?



0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	8	28
0	0	0	0	0	0	11	37	61	88	116	132
0	0	0	0	15	64	108	130	131	135	141	145
0	3	32	71	107	132	144	139	139	144	137	143
41	90	113	124	138	140	145	148	147	155	152	139
123	134	136	140	147	149	152	160	160	155	163	155
143	144	147	151	156	160	157	159	167	167	160	167
152	156	161	165	166	169	170	170	164	169	173	164
157	157	161	168	176	175	174	180	173	164	165	171
165	166	164	163	166	172	179	177	168	173	167	168
167	168	169	175	173	168	171	177	174	168	172	173

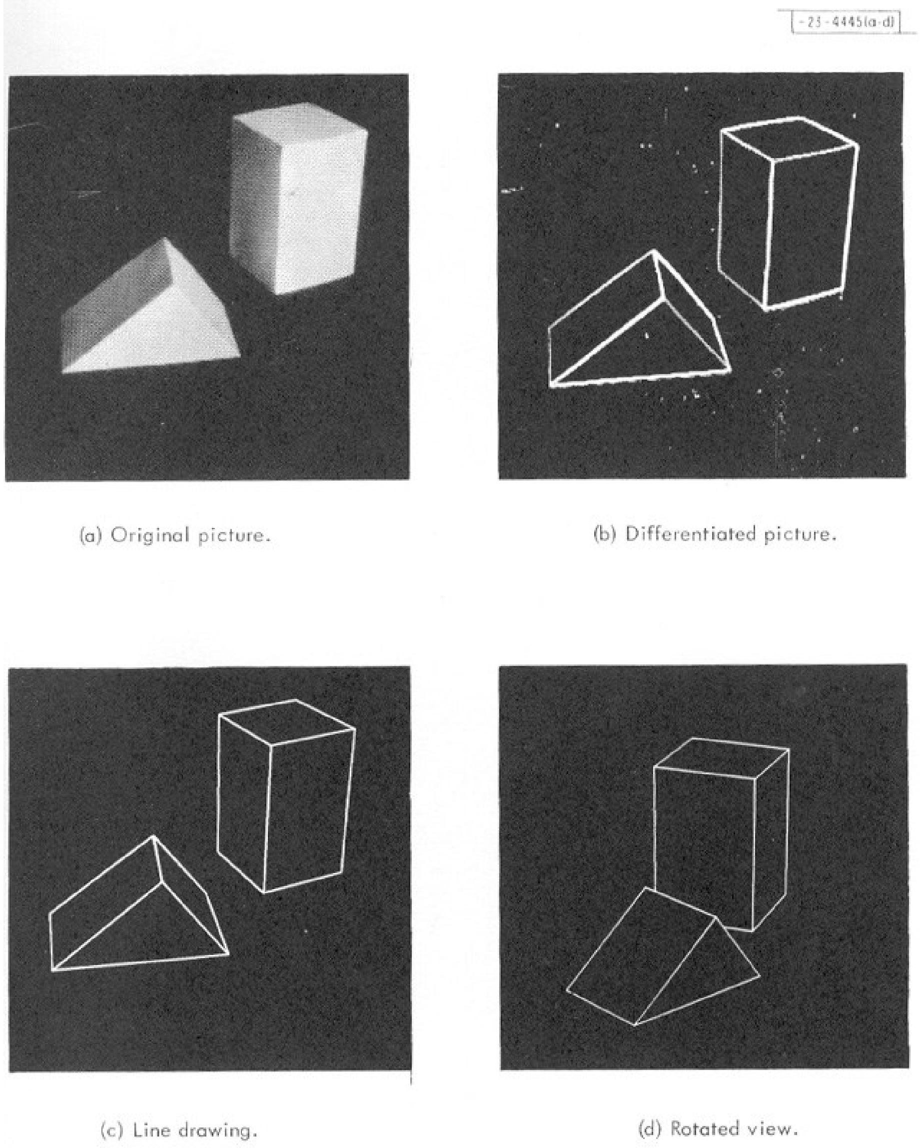
What a computer sees

What we see

Origins of computer vision

- **1963** - L. G. Roberts publishes his PhD thesis on *Machine Perception of Three Dimensional Solids*, thesis, MIT Department of Electrical Engineering

- He is the **inventor of ARPANET, the current Internet**



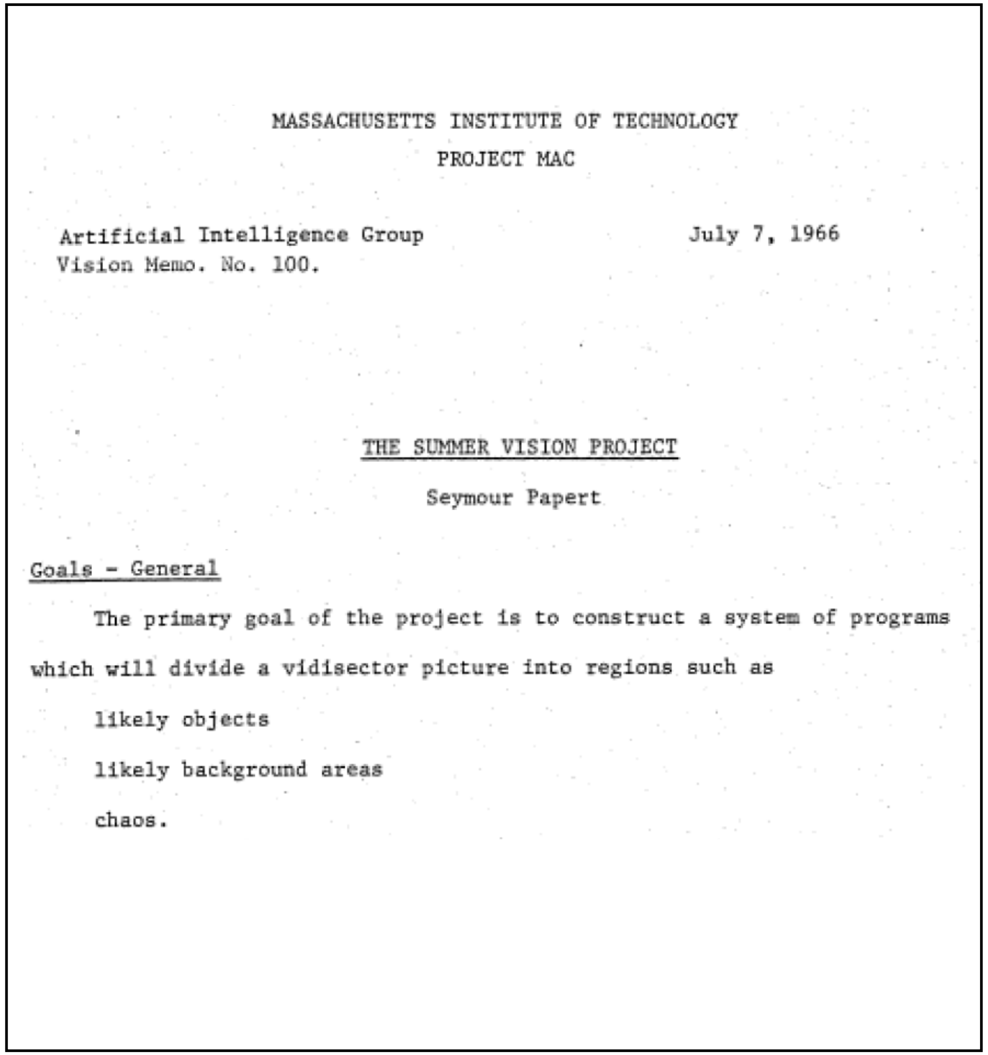
Origins of computer vision

- **1963** - L. G. Roberts publishes his PhD thesis on *Machine Perception of Three Dimensional Solids*, thesis, MIT Department of Electrical Engineering

- He is the **inventor of ARPANET, the current Internet**

- **1966** – Seymour Papert, MIT, publishes the Summer Vision Project asking students to design an algorithm to segment an image into objects and background… within summer!

- **1969** – David Marr starts developing a framework for processing visual information



MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

Artificial Intelligence Group   July 7, 1966
Vision Memo. No. 100.

THE SUMMER VISION PROJECT

Seymour Papert

Goals - General

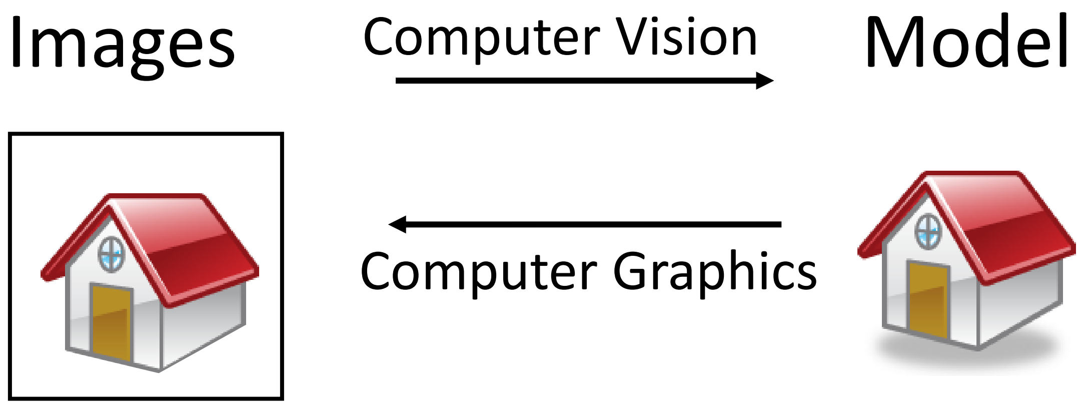
The primary goal of the project is to construct a system of programs which will divide a vidisector picture into regions such as

likely objects

likely background areas

chaos.

Computer Vision vs Computer Graphics

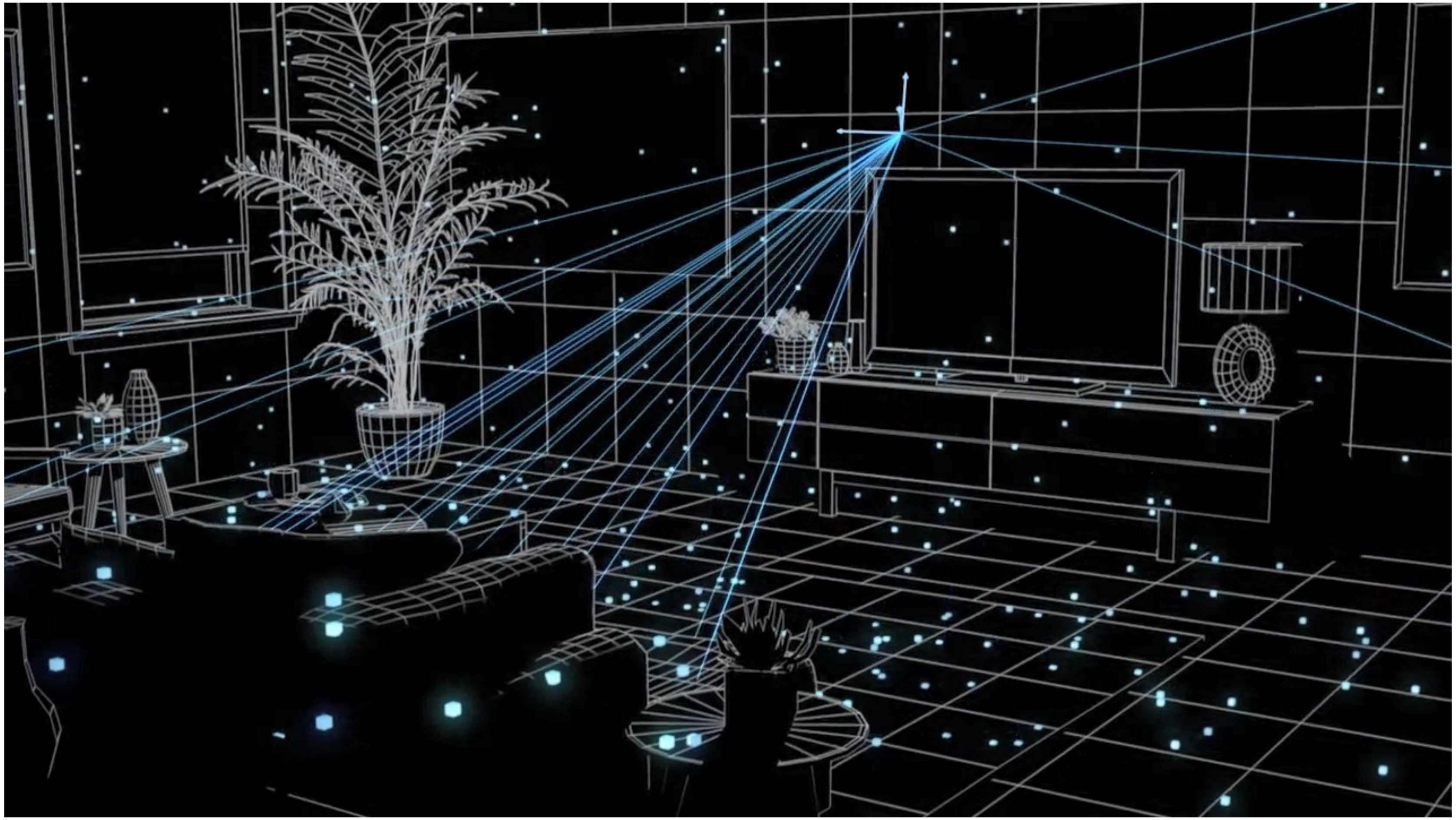


Inverse problems: analysis and synthesis.

Today’s Outline

- About me and my research lab
- What is Computer Vision?
- Why study computer vision?
- Example of Vision Applications
- Organization of the course
- Start: Visual Odometry overview

VR/AR



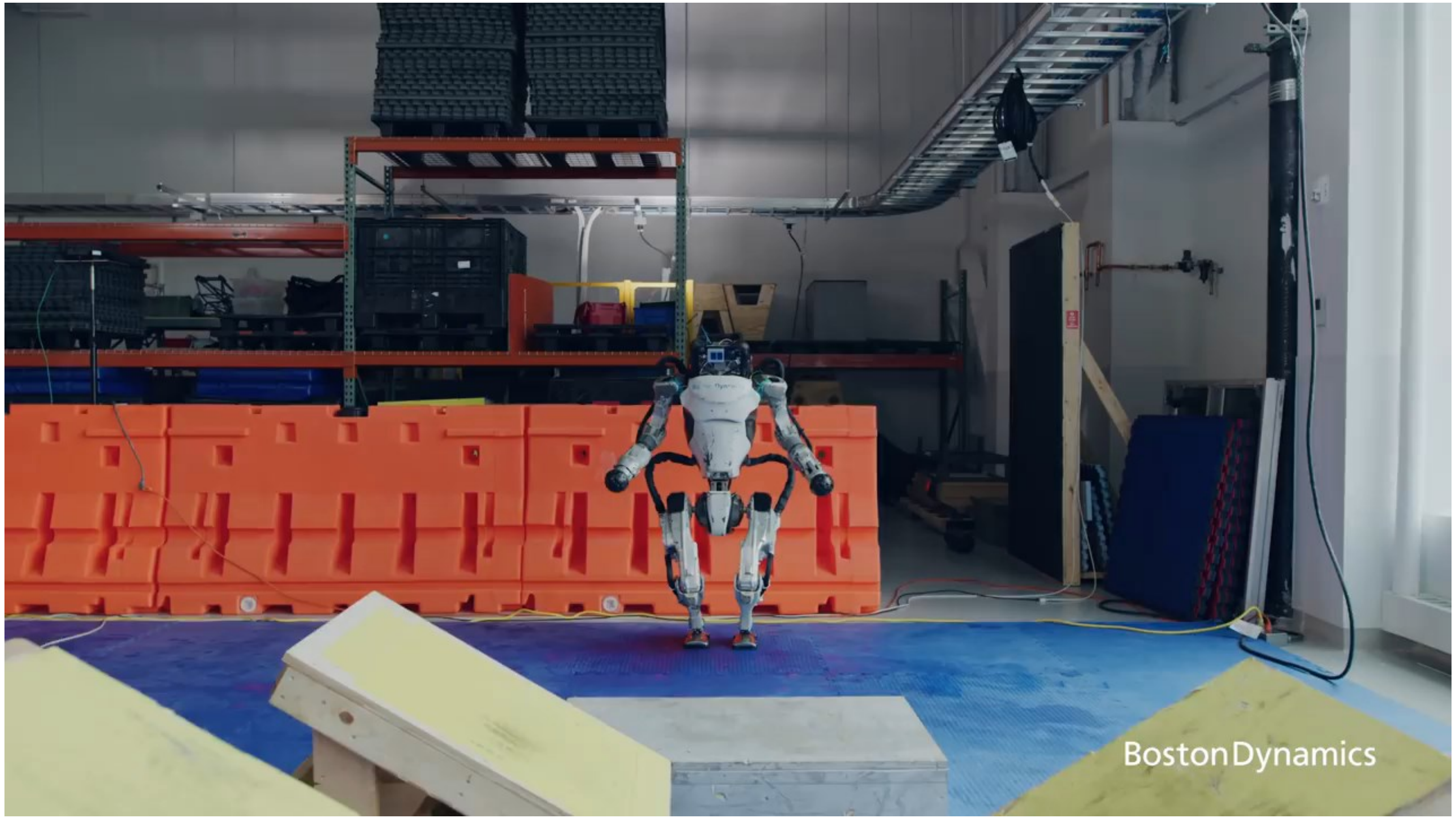
Oculus Quest uses four cameras to track the pose of the head and the controllers

Advanced Driving Assistance Systems (ADAS)

Mobileye: Vision system used at **BMW, GM, Volvo** models. Bought by **Intel in 2017 for 15 billion USD**!

- **Pedestrian & car** collision warning
- **Lane departure** warning
- **Safety distance** monitoring and warning

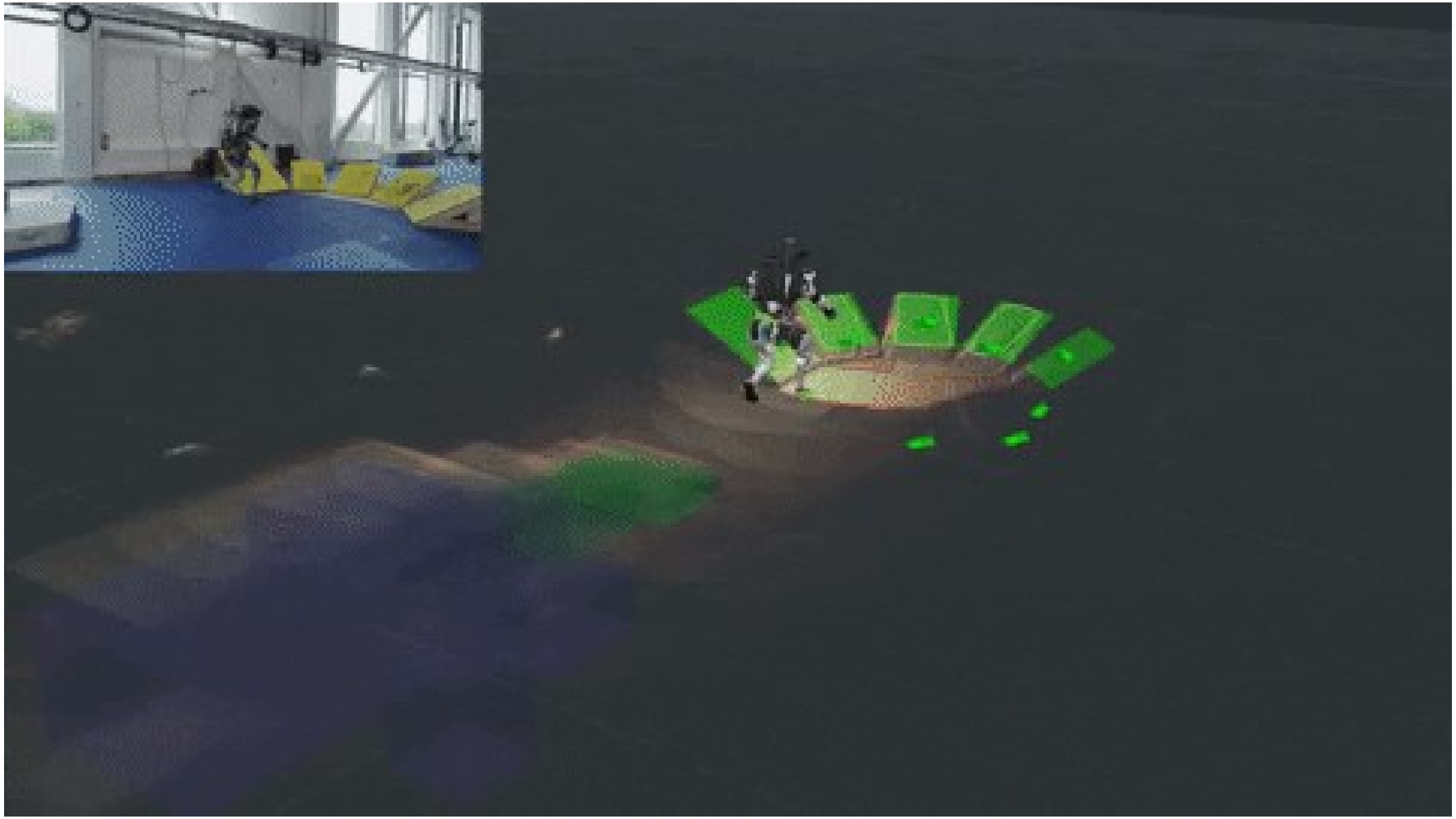
Boston Dynamics ATLAS Robot



https://youtu.be/tF4DML7FIWk

Watch Boston Dynamics keynote at the MIT Robotics Today Seminar Series: https://youtu.be/EGABAx52GKI

Boston Dynamics ATLAS Robot

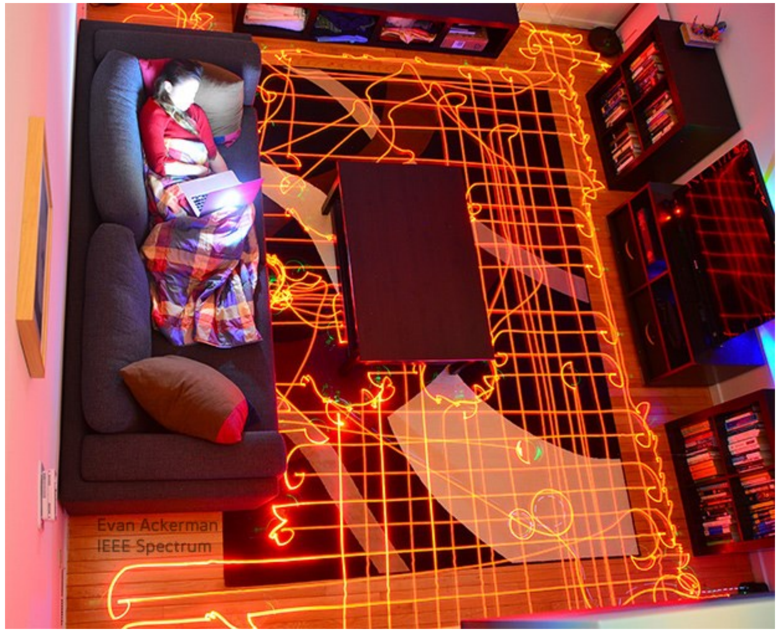


https://blog.bostondynamics.com/flipping-the-script-with-atlas

Roomba Vacuum Cleaner

- Introduced in 2002 by iRobot
- More than 40 million Roombas sold so far
- Fully autonomous, uses camera to recognize places

The Roomba 880 navigates by zigzagging randomly across the room. Average cleaning time: 20 minutes



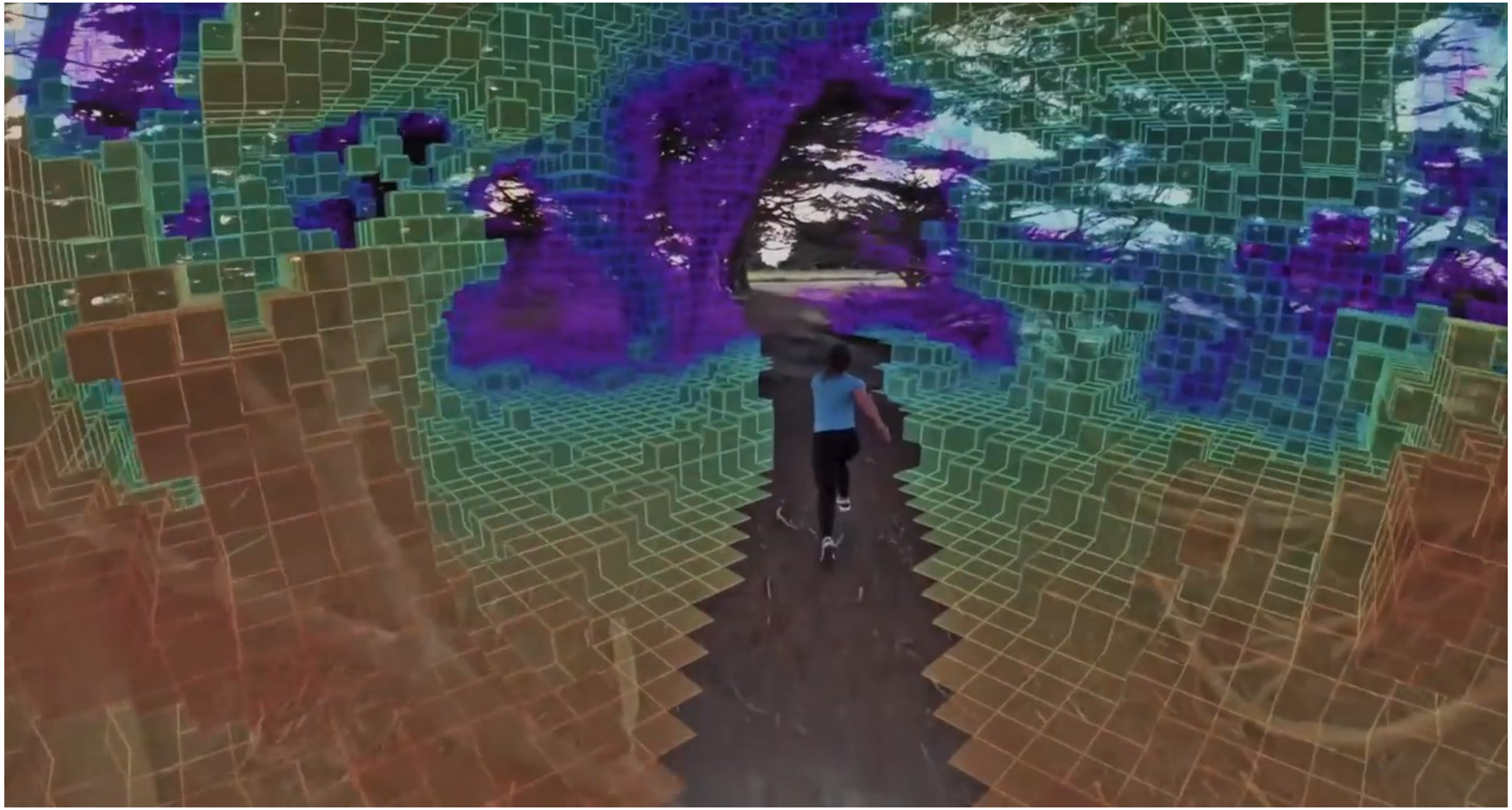
The Roomba 980 navigates by following a pre-defined path optimized thanks to visual SLAM - Average cleaning time: 5 minutes

Skydio and DJI Drones

The Skydio-2 drone features 7 cameras for obstacle avoidance, visual odometry, and person following

Watch Skydio keynote at the MIT Robotics Today Seminar Series: https://youtu.be/ncZmnfIRIWE

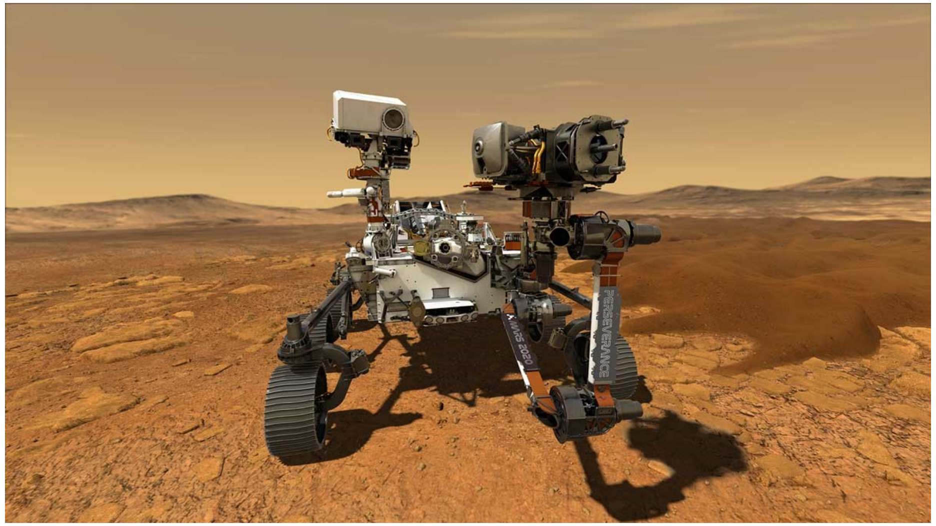
Skydio and DJI Drones

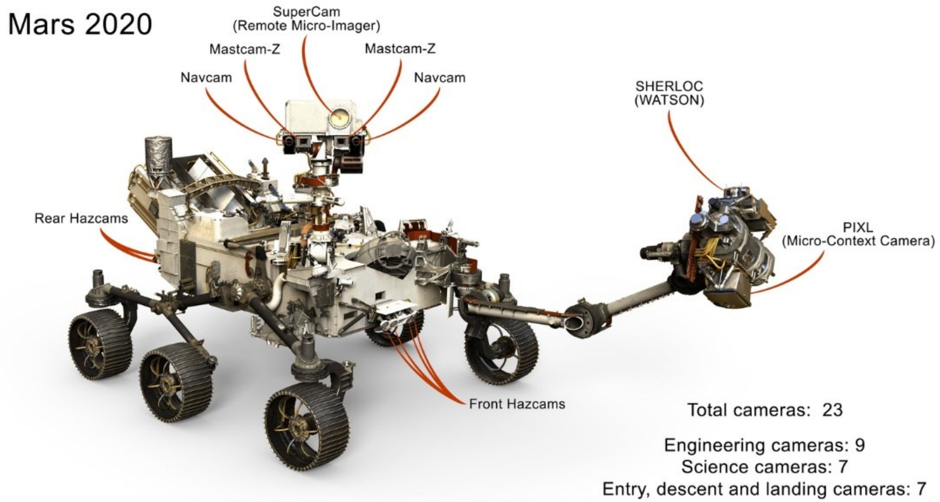


The Skydio-2 drone features 7 cameras for obstacle avoidance, visual odometry, and person following

Watch Skydio keynote at the MIT Robotics Today Seminar Series: https://youtu.be/ncZmnfIRIWE

NASA Mars Rovers





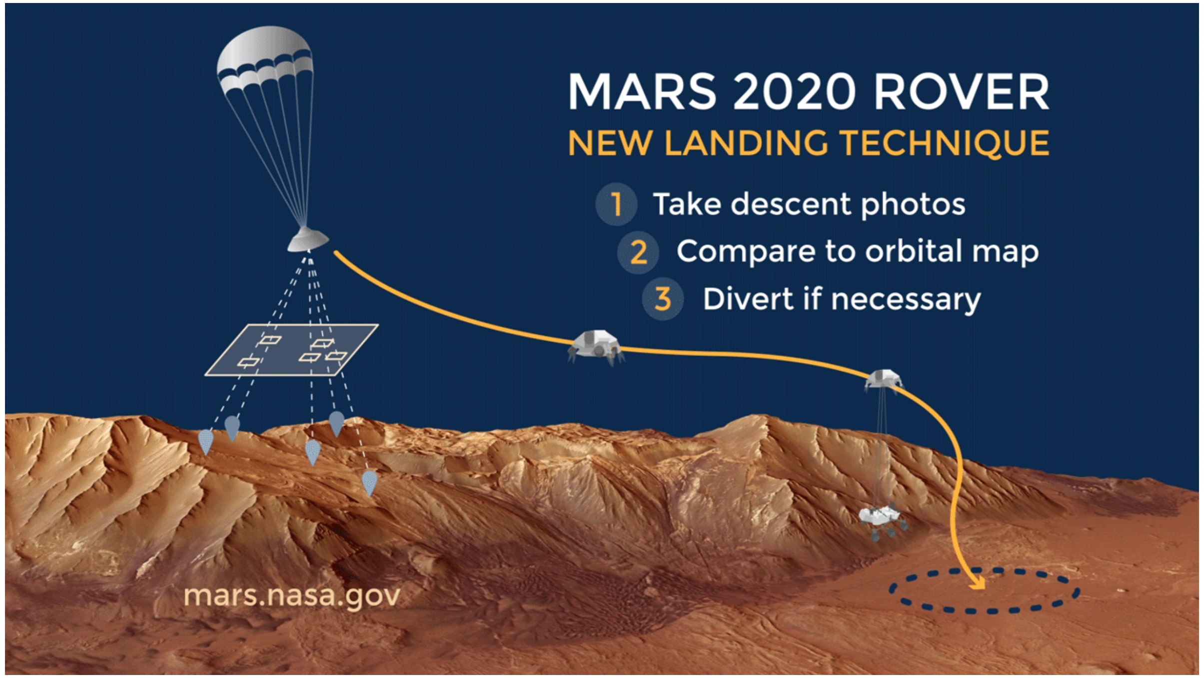
NASA'S Perseverance Rover landed in 2021 features 23 cameras used for:

- Autonomous landing on Mars (Terrain Relative Navigation)
- Autonomous navigation and positioning of the robotic arm
- Science: 3D photos and videos, analysis of chemical components of the soil

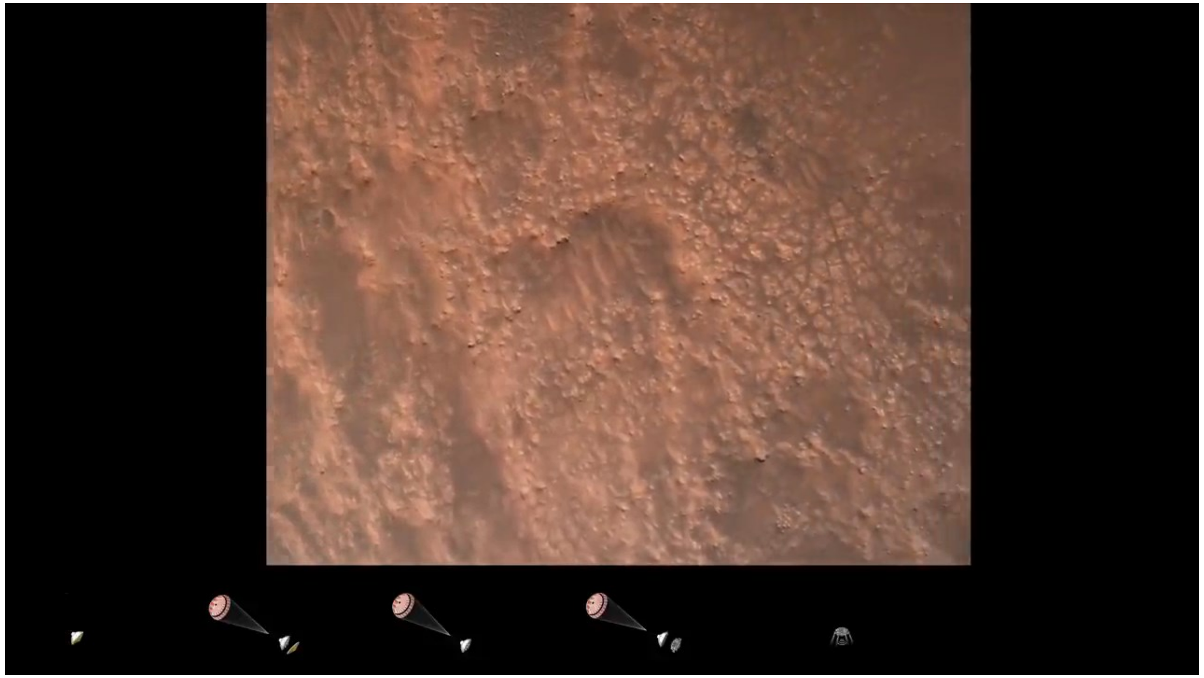
For more info, watch the RSS'21 keynote by Larry Matthies, head of the Computer Vision Group at NASA/JPL: https://youtu.be/NcI6fJOzBsU

Perseverance Descent via Vision-based Terrain Relative Navigation

Landing accuracy: 40 meters.



https://mars.nasa.gov/mars2020/mission/technology/#Terrain-Relative-Navigation



Real footage recorded by Perseverance during descent https://youtu.be/4czjS9h4Fpg

Vision-based Flight on Mars

The NASA Ingenuity helicopter performs the first autonomous vision-based flight on April 19, 2021, on Mars.
https://youtu.be/p1KolyCqICI?t=2502
https://mars.nasa.gov/technology/helicopter/#

On November 30, we will have a lecture by Jeff Delaune, from NASA/JPL,
who developed the visual navigation of Ingenuity

Today’s Outline

- About me and my research lab
- What is Computer Vision?
- Why study computer vision?
- Example of Vision Applications
- Organization of the course
- Start: Visual Odometry overview

Instructors

Lecturer: Davide Scaramuzza

- **Contact**: sdavide (at) ifi (dot) uzh (dot) ch
- **Office hours**: every **Thursday from 16:00 to 18:00**
  both in person or via ZOOM possible (**please announce yourself by email**)

- **Teaching Assistants**: Jiaxu Xing and Leonard Bauersfeld

Jiaxu Xing
jixing (at) ifi (dot) uzh (dot) ch

Leonard Bauersfeld
bauersfeld (at) ifi (dot) uzh (dot) ch

http://rpg.ifi.uzh.ch/people.html

Lectures and Exercises

Lectures:

- **08:00 to 09:45** every week. **After class**, **I usually stay for 10 more minutes** for questions
- **Breaks**: always but can vary between 5-15 min
- Room: SOC-F-106, Rämistrasse 69, 8001 Zurich

Exercises:

- **12:15 to 13:45** every week: starting today with a tutorial on camera notation
- Room: same as above

Course & Exam Registration and Cancelation

- Registration and exam cancelation deadline for the course is **October 10, 23:59 hrs**
- NB: at UZH, when you register for a course, you are also automatically registered for the exam. If you want to cancel the exam, you must unbook the course by October 10. Afterward, it will no longer be possible to cancel the exam. No show at the exam will be graded as 1.0. If you cannot take the exam because you fell ill, you must submit a petition with medical certificate no later than five business days after the examination date. If you are a student with a disability, you must request assistance in due time. Further info here

Tentative Course Schedule

For updates, slides, and additional material: http://rpg.ifi.uzh.ch/teaching.html

21.09.2023	**Lecture 01 - Introduction to Computer Vision and Visual Odometry** Exercise: Camera Notation Tutorial	Scaramuzza Leonard, Jiaxu
28.09.2023	**Lecture 02 - Image Formation: perspective projection and camera models** Exercise 01- Augmented reality wireframe cube	Scaramuzza Leonard, Jiaxu
05.10.2023	**Lecture 03 - Camera Calibration** Exercise 02 - PnP problem	Leonard Leonard, Jiaxu
12.10.2023	**Lecture 03 continued** **Lecture 04 - Filtering & Edge detection** Exercise session replaced by continuation of Lecture 4	Scaramuzza
19.10.2023	**Lecture 05 - Point Feature Detectors, Part 1** Exercise 03 - Harris detector + descriptor + matching	Scaramuzza Leonard, Jiaxu
26.10.2023	**Lecture 06 - Point Feature Detectors, Part 2** Exercise 04 - SIFT detector + descriptor + matching	Leonard Leonard, Jiaxu
02.11.2023	**Lecture 07 - Multiple-view Geometry 1** Exercise 05 - Stereo vision: rectification, epipolar matching, disparity, triangulation	Scaramuzza Leonard, Jiaxu
09.11.2023	**Lecture 08 - Multiple-view Geometry 2** Exercise 06 - Eight-Point Algorithm	Scaramuzza Leonard, Jiaxu
16.11.2023	**Lecture 09 - Multiple-view Geometry 3** Exercise 07 - P3P algorithm and RANSAC	Scaramuzza Leonard, Jiaxu
23.11.2023	**Lecture 10 - Multiple-view Geometry 4** Continuation of Lecture 10 + Exercise session on Intermediate VO Integration	Scaramuzza Leonard, Jiaxu
30.11.2023	**1st hour: seminar by Dr. Jeff Delaune from NASA-JPL: "Vision-Based Navigation for Mars Helicopters."** **2nd hour: Lecture 11 - Optical Flow and KLT Tracking** Exercise 08 - Lucas-Kanade tracker	NASA Leonard Leonard, Jiaxu
07.12.2023	**Lecture 12a (1st hour) - Place Recognition** **Lecture 12b (2nd hour) - Dense 3D Reconstruction** **Lecture 12c (3rd and 4th hour, replaces exercise) - Deep Learning Tutorial** Optional Exercise on Place Recogntion	Scaramuzza Scaramuzza Leonard
14.12.2023	**Lecture 13 - Visual inertial fusion** Exercise 09 - Bundle Adjustment	Scaramuzza Leonard, Jiaxu
21.12.2023	**Lecture 14 - Event-based vision + lab visit after the lecture** Exercise session: Final VO Integration	Scaramuzza Leonard, Jiaxu

Study Material

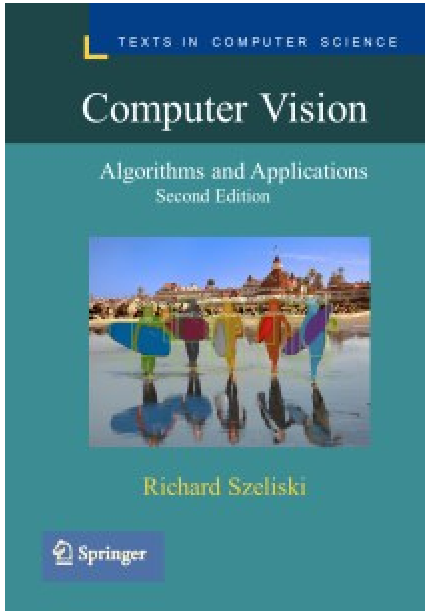
- **Schedule**, **lecture slides, exercise download, mini projects, course info** on the official course website**:** http://rpg.ifi.uzh.ch/teaching.html

- **Video Recordings** of lectures and exercises will be uploaded to **OLAT**: https://lms.uzh.ch/auth/RepositoryEntry/17430413374/CourseNode/85421310414617

- Post any **questions** related to lectures or exercises in the **OLAT Forum**

Reference Textbooks

- **Computer Vision: Algorithms and Applications**, **2nd Edition**, by Richard Szeliski. **Freely downloadable** from the author webpage: http://szeliski.org/Book/
- **Chapter 4 of Autonomous Mobile Robots,** 2nd edition, 2011, by R. Siegwart, I.R. Nourbakhsh, D. Scaramuzza. PDF
- **Additional readings** (i.e., **optional and not requested at the exam**) for interested students will be provided along with the slides and linked directly from the course website



- Further readings:
  - *Robotics, Vision and Control: Fundamental Algorithms*, 2nd edition, by Peter Corke
  - *An Invitation to 3D Vision*: Y. Ma, S. Soatto, J. Kosecka, S.S. Sastry
  - *Multiple view Geometry*: R. Hartley and A. Zisserman

Prerequisites

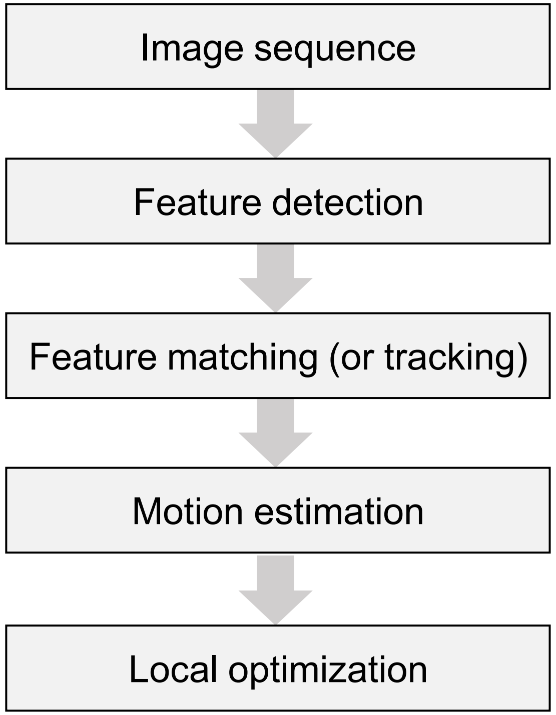
- **Linear algebra**
- **Matrix calculus**: matrix multiplication, inversion, singular value decomposition
  - Check out this Linear Algebra Primer from Stanford University
  - Check out this Immersive Linear Algebra interactive tool by Ström, Åström, and Akenine-Möller
  - Check out this tutorial on camera pose notation
- **No prior knowledge** of **computer vision** and **image processing** is required

Learning Objectives

- **High-level goal:** <u>learn to implement the visual-inertial odometry algorithms</u> used in current mobile robots (drones, cars, planetary robots), AR/VR products (Meta Quest, Microsoft HoloLens, Magic Leap), and Google Visual Positioning Service (e.g., Google Map Live View).
- You will also learn **to implement the fundamental computer vision algorithms** used in mobile robotics, in particular:
  - image formation,
  - filtering,
  - feature extraction,
  - multiple view geometry,
  - dense reconstruction,
  - feature and template tracking,
  - image retrieval,
  - event-based vision,
  - visual-inertial odometry, Simultaneous Localization And Mapping (SLAM),
  - and some basics of deep learning.

Exercises

- **Learning Goal** of the exercises: **Implement a full visual odometry pipeline** (like the one running on Mars rovers).
- **Each week** you will learn how to implement a **building block** of visual odometry.
- Two exercises will be dedicated to **system integration**.
- **NB: Questions about the implementation details of each exercise can be asked at the exam.**

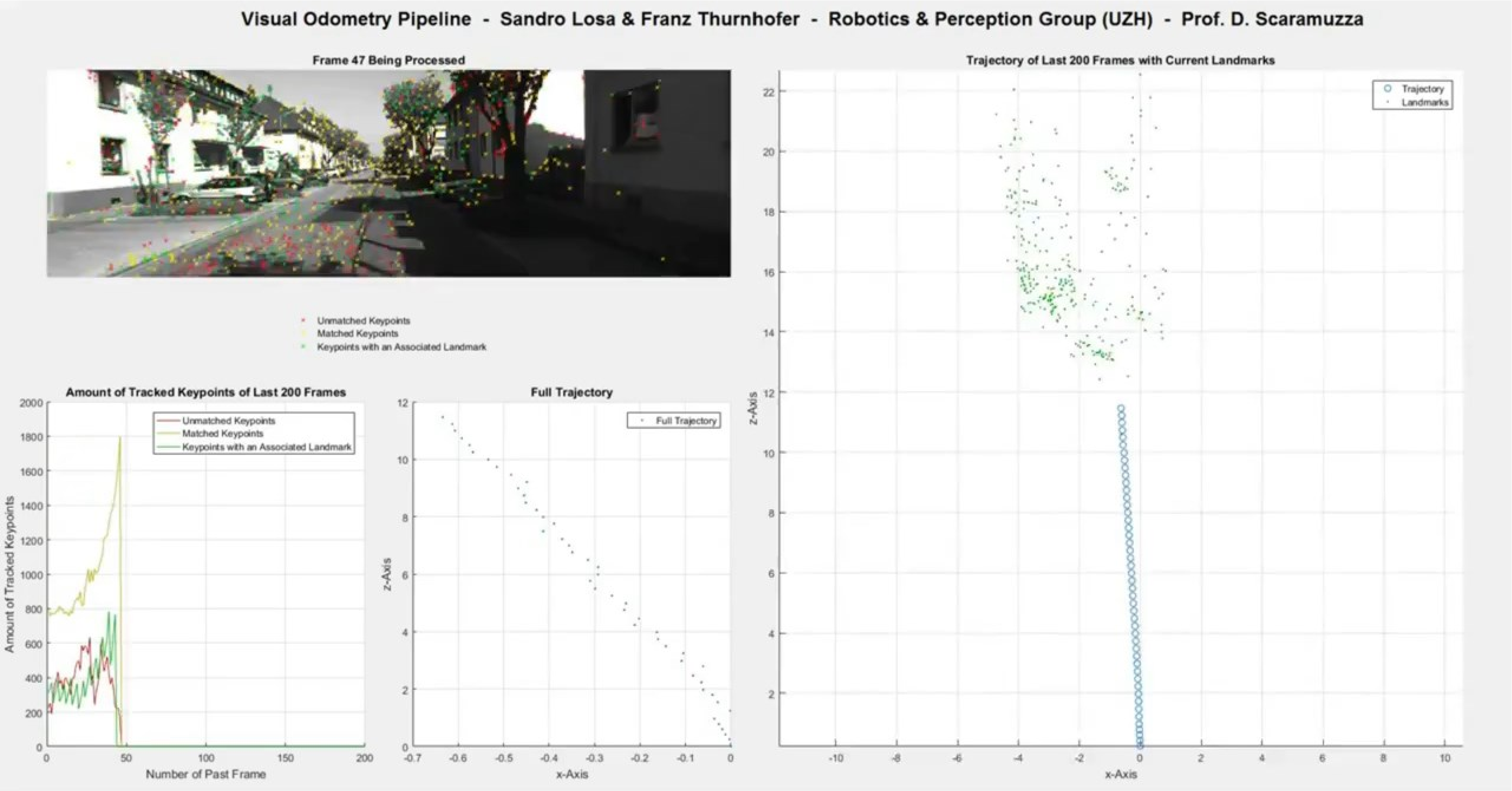


Building blocks of visual odometry along with information flow

Exercises

- **Bring your own laptop**
- Exercises in **Python or Matlab**. You will need to have Matlab or Python already pre-installed on your machine for the exercises.
- Python can be downloaded from here.
- You can download Matlab from:
  - **ETH:** Download: https://itshop.ethz.ch/EndUser/Items/Home
  - **UZH:** Download: https://www.zi.uzh.ch/de/students/software-elearning/campussoft.html
  - An introductory tutorial on Matlab can be found here: http://rpg.ifi.uzh.ch/docs/teaching/2023/MatlabPrimer.pdf
  - **Please install all the toolboxes included in the license.** If you don't have enough space in your PC, then install at least the Image Processing, Computer Vision, and Optimization toolboxes

Outcome of last year exercises



Grading and Exam

- The **final grade is based on a written exam** (2 hours)
  - Exam date: **January 11, 2024, from 08:00 to 10:00 on site**
  - **Closed-book exam**
  - **The last exams can be found on OLAT**

- **Optional mini project:**
  - you have the **option** (i.e., not mandatory) to do a **mini project**, which consists of implementing a working visual odometry algorithm in **Matlab** or **Python** (but C++ or are also accepted)
  - If the algorithm runs smoothly, producing a reasonable result, you will be rewarded with an **up to 0.5 grade increase on the final grade**. However, notice that the mini project can be very time consuming!
  - The **deadline** to hand in the mini project is **07.01.2024**.
  - **Group work: minimum 2, max 4 people.**

Class Participation

- **Strong class participation is encouraged!**

- Class participation includes
  - **ask** and **answer questions**
  - being able to **articulate key points from last lecture**

Today’s Outline

- About me and my research lab
- What is Computer Vision?
- Why study computer vision?
- Example of Vision Applications
- Organization of the course
- Start: Visual Odometry overview

What is Visual Odometry (VO) ?

VO is the process of incrementally estimating the pose of the vehicle by examining the changes that motion induces on the images of its onboard cameras

input

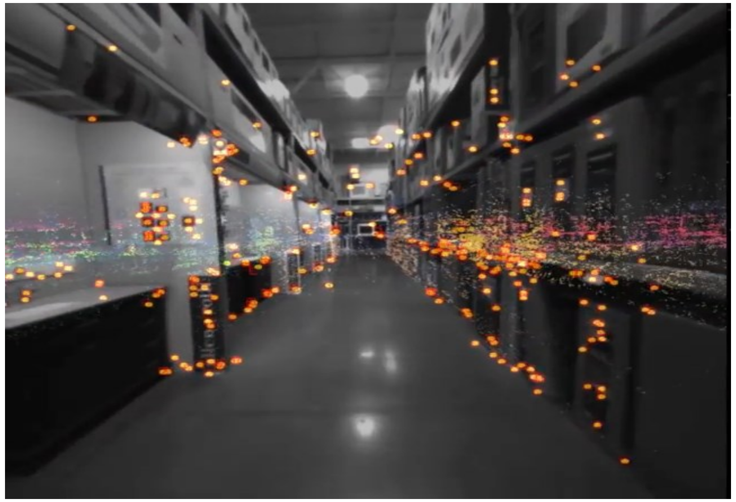
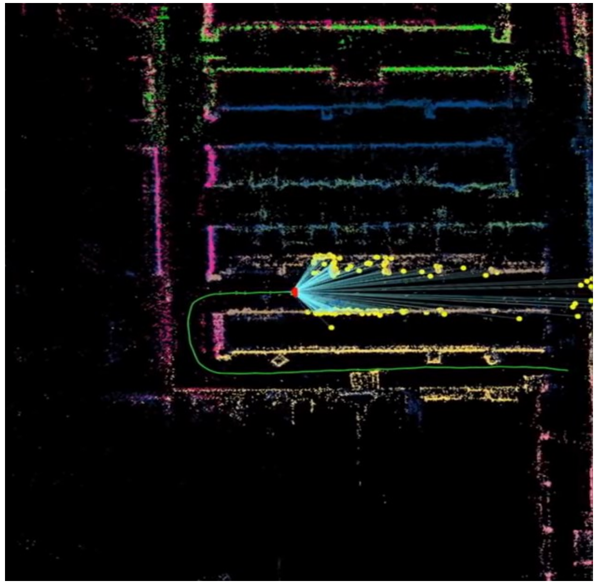


Image sequence (or video stream)
from one or more cameras attached to a moving vehicle

output



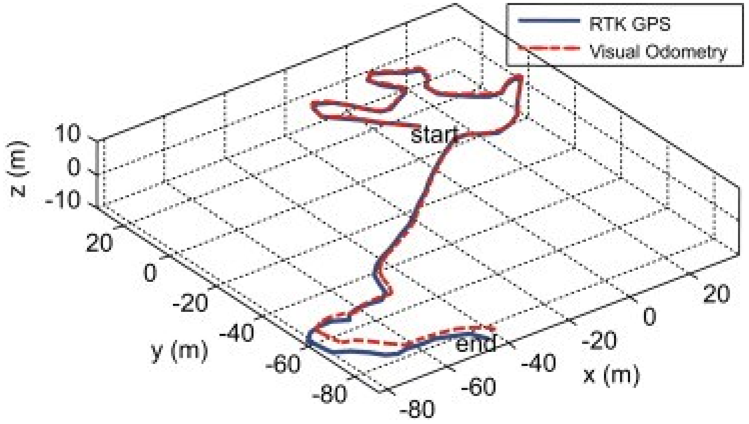
Camera trajectory (3D structure is a plus)

$R_0, R_1, \ldots, R_i$

$t_0, t_1, \ldots, t_i$

Why VO?

- VO is crucial for **flying**, **walking**, and **underwater** robots
- Contrary to wheel odometry, VO is **not affected by wheel slippage** (e.g., on sand or wet floor)
- Very accurate:
  relative position error is 0.1% – 2% of the travelled distance
- VO can be used as a complement to
  - wheel encoders (wheel odometry)
  - GPS (when GPS is degraded)
  - Inertial Measurement Units (IMUs)
  - laser odometry



Assumptions

- **Sufficient illumination** in the environment
- **Dominance of static scene** over moving objects
- **Enough texture** to allow apparent motion to be extracted
- Sufficient **scene overlap** between consecutive frames



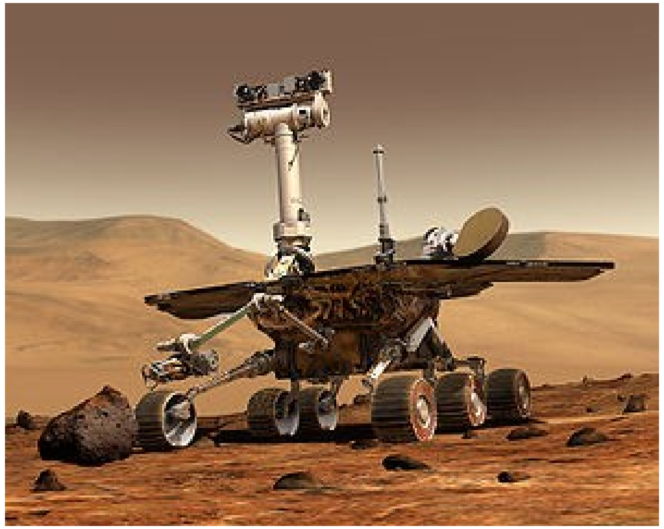

Is any of these scenes good for VO? Why?

A Brief history of VO

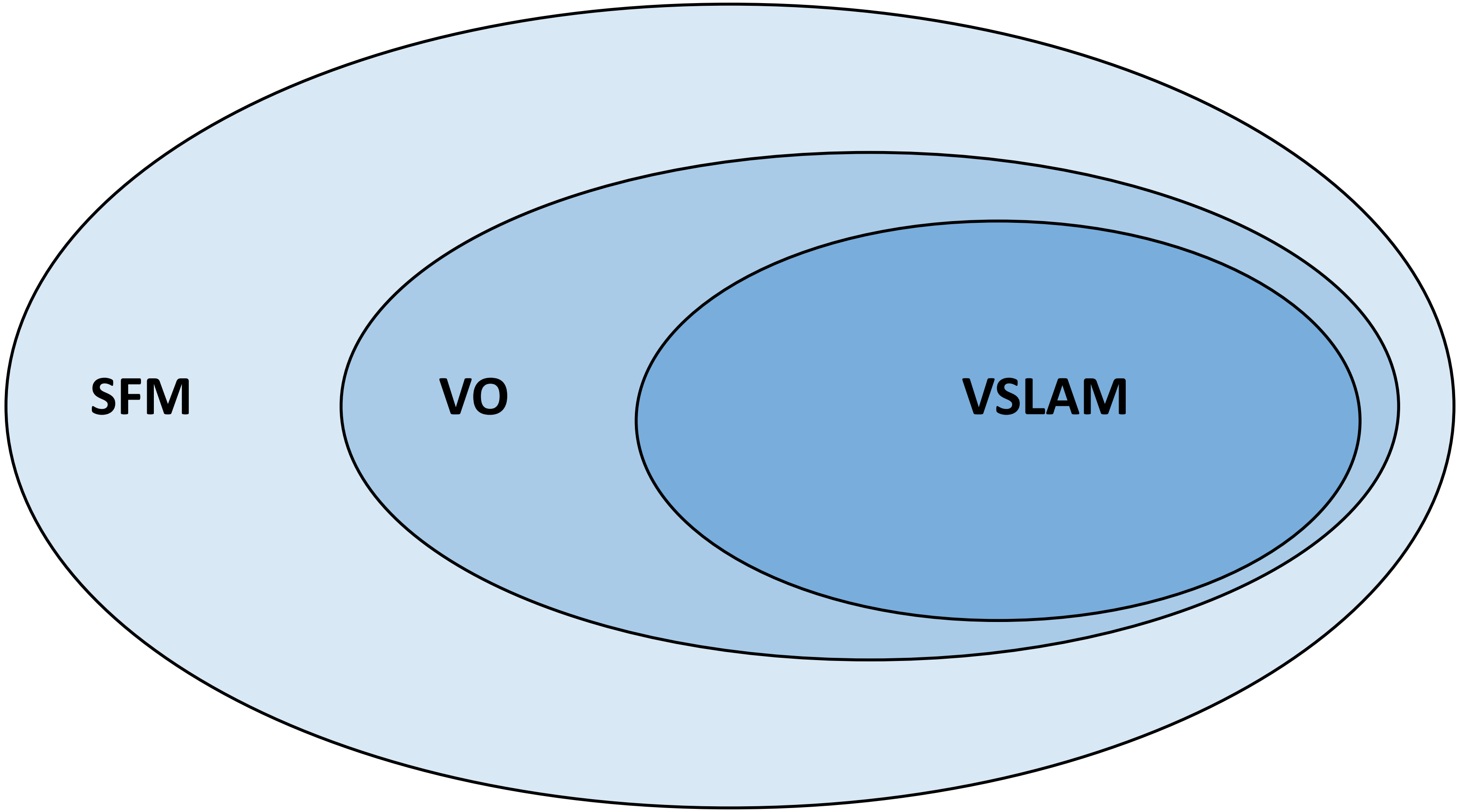
- **1980**: First known VO real-time implementation on a robot by **Hans Moraveck** PhD thesis **(NASA/JPL)** for Mars rovers using one sliding camera (*sliding stereo*).

A Brief history of VO

- **1980**: First known VO real-time implementation on a robot by **Hans Moraveck** PhD thesis **(NASA/JPL)** for Mars rovers using one sliding camera (*sliding stereo*).
- **1980 to 2000**: The VO research was dominated by **NASA/JPL** in preparation of the **2004 mission to Mars**
- **2004**: VO was used on a robot on another planet: Mars rovers Spirit and Opportunity (see seminal paper from NASA/JPL, 2007)
- **2004**: VO was revived in the academic environment by **David Nister**'s «Visual Odometry» paper. The term VO became popular.
- **2015-today**: VO becomes a **fundamental tool of several products**: VR/AR, drones, smartphones
- **2021**: VO is used on the **Mars helicopter**

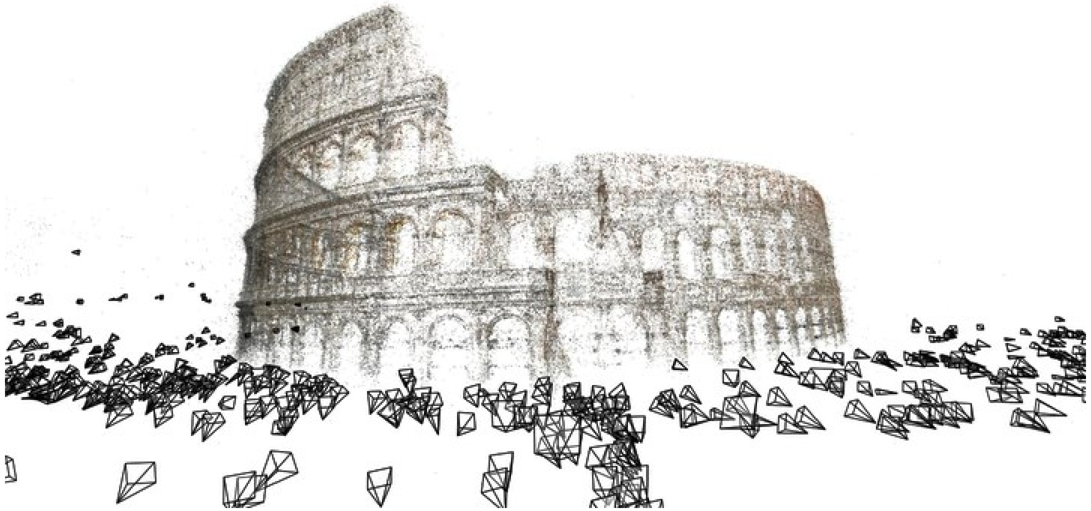


VO vs VSLAM vs SFM



Structure from Motion (SFM)

SFM is more general than VO and tackles the problem of 3D reconstruction and 6DOF pose estimation from **unordered image sets**



Reconstruction from 3 million images from Flickr.com on a cluster of 250 computers, 24 hours of computation
Paper: “Building Rome in a Day”, ICCV’09.
State of the art software: COLMAP

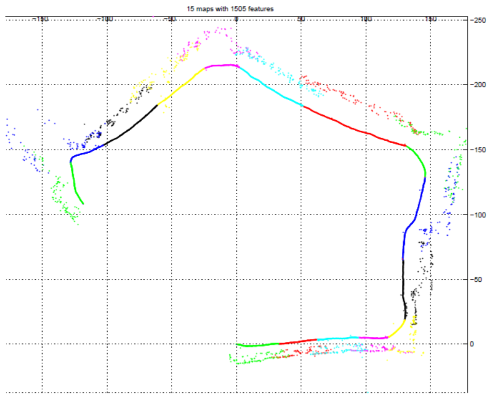
VO vs SFM

- VO is a **particular case** of SFM
- VO focuses on estimating the 6DoF motion of the camera **sequentially** (as a new frame arrives) and in **real time**
- Terminology: sometimes **SFM** is used as a **synonym** of **VO**

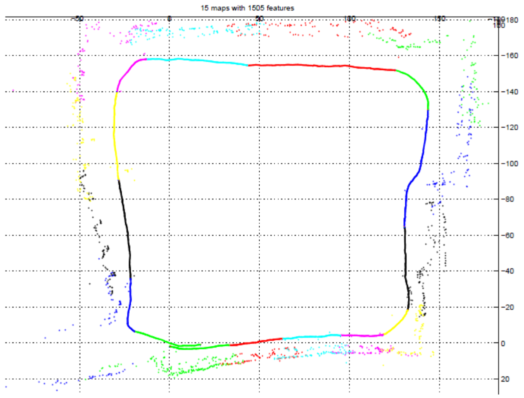
VO vs. Visual SLAM

- **Visual Odometry**
  - Focus on incremental estimation
  - **Guarantees local consistency** (i.e., estimated trajectory is locally correct, but not globally, i.e. from the start to the end)

- **Visual SLAM** (Simultaneous Localization And Mapping)
  - **SLAM = visual odometry + loop detection & closure**
  - **Guarantees global consistency** (the estimated trajectory is globally correct, i.e. from the start to the end)



Visual odometry



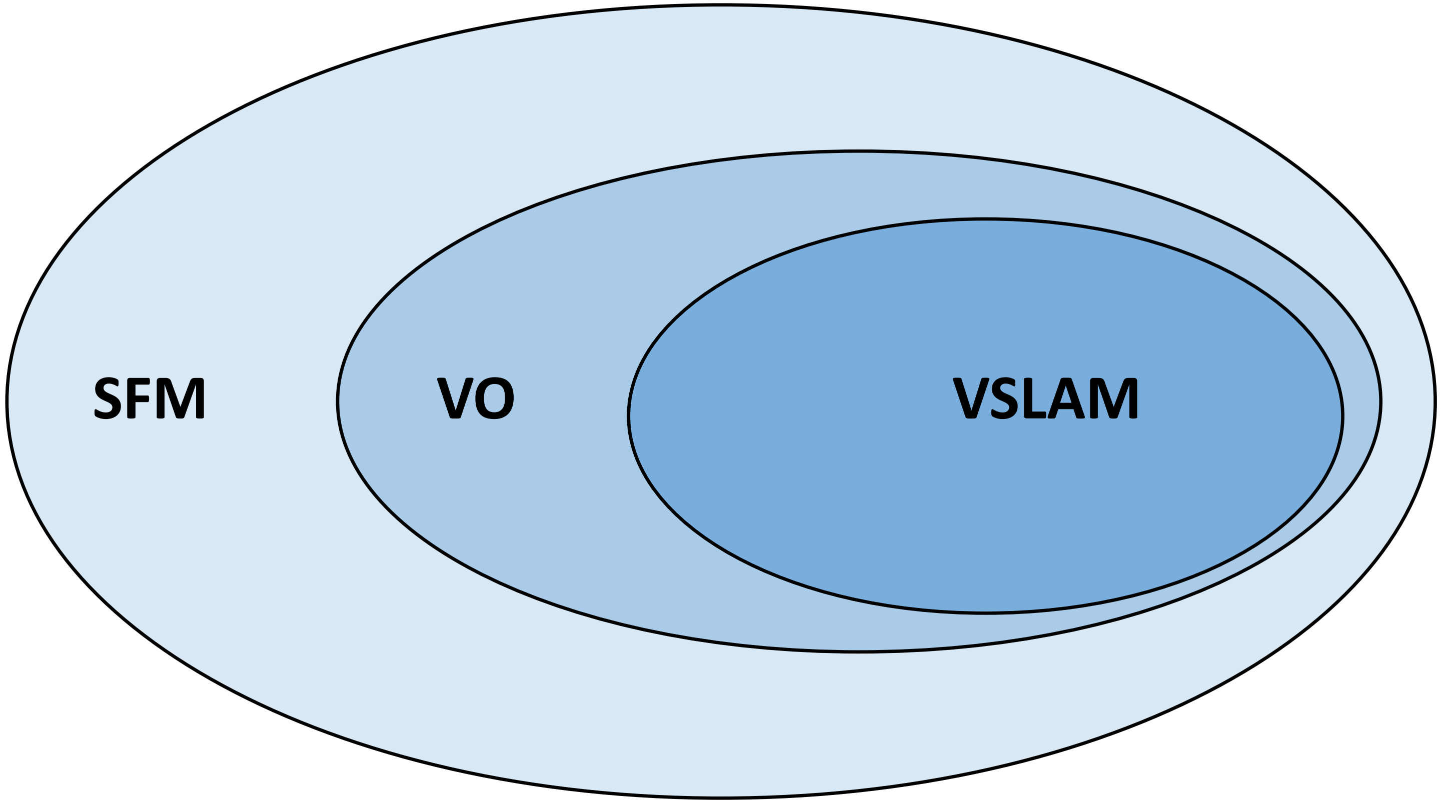
Visual SLAM

Image courtesy of [Clemente et al., RSS’07]

VSLAM ⊆ VO ⊆ SFM

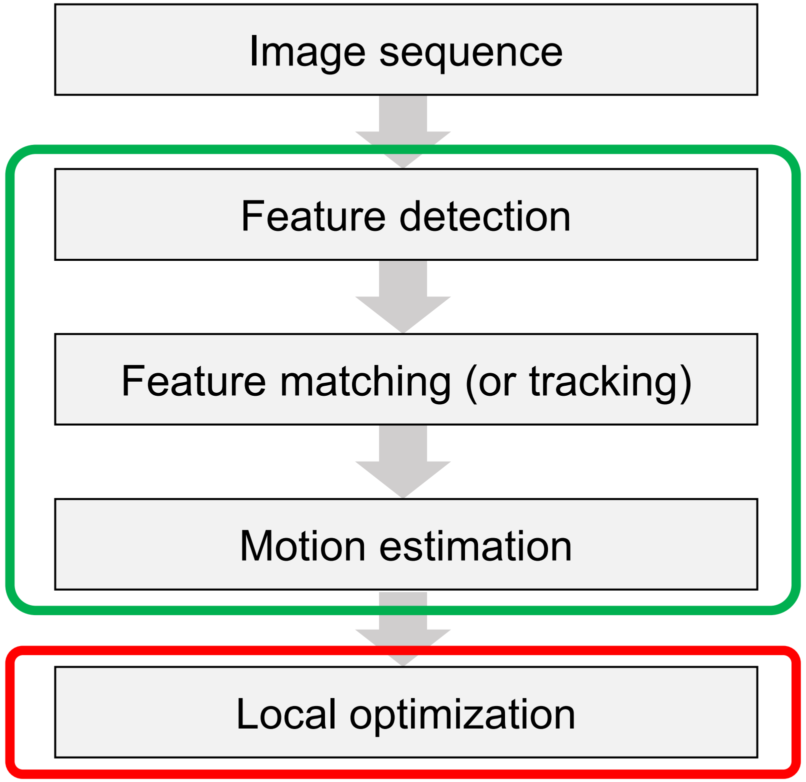
Why?

- **because every VSLAM and VO are SFM**, but not every SFM is VO or SLAM
- **because every VSLAM is a VO**, but not every VO is a SLAM
  - VSLAM applies more stringent requirements, such as loop detection and closure, than VO, making it a particular case. Every VSLAM functions as a VO, given that VSLAM, like VO, incrementally estimates poses (although Bundle Adjustment may further refine these estimations). Moreover, if VSLAM achieves global consistency, it inherently ensures local consistency as well.



VO Flow Chart

VO computes the camera path incrementally (pose after pose)



Front-end: outputs the *relative pose* between the *last two frames*

Back-end: “*adjusts*” the relative poses among *multiple recent frames*

VO Flow Chart

VO computes the camera path incrementally (pose after pose)

Image sequence

Feature detection

Feature matching (or tracking)

Motion estimation

Local optimization

Features tracked over multiple recent frames overlaid on the last frame

VO Flow Chart

VO computes the camera path incrementally (pose after pose)

Image sequence

↓

Feature detection

↓

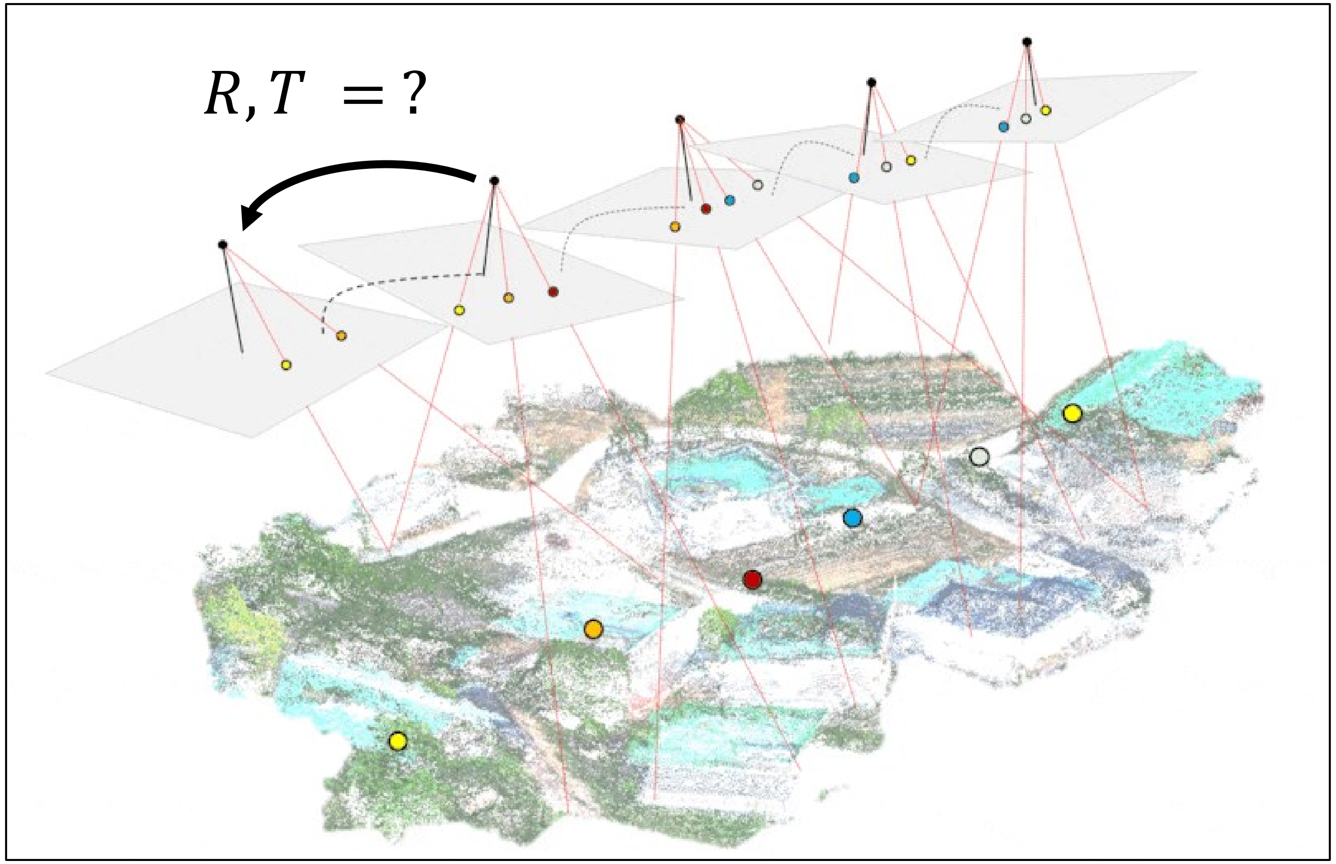
Feature matching (or tracking)

↓

Motion estimation

↓

Local optimization



VO Flow Chart

VO computes the camera path incrementally (pose after pose)

Image sequence

↓

Feature detection

↓

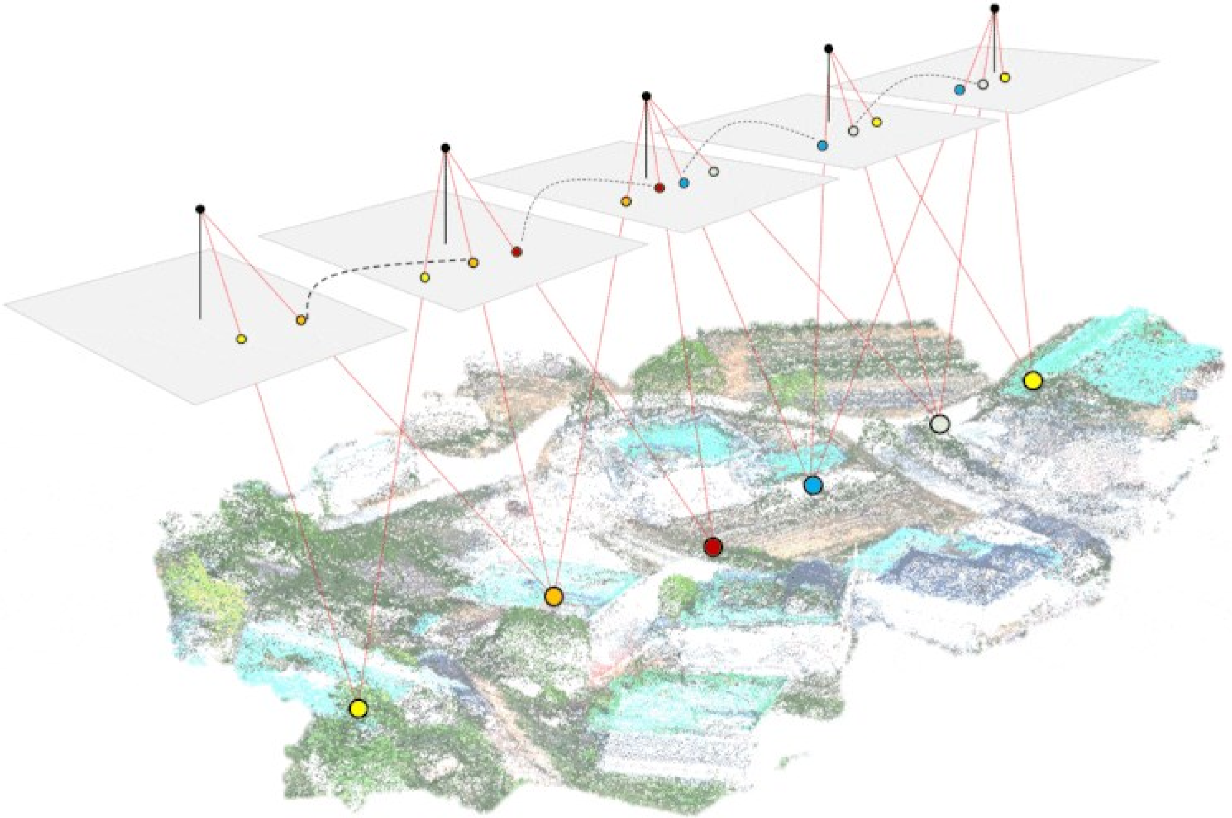
Feature matching (or tracking)

↓

Motion estimation

↓

Local optimization



Course Topics

- Principles of image formation
- Image filtering
- Feature detection and matching
- Multi-view geometry
- Dense reconstruction
- Visual place recognition
- Deep learning
- Visual inertial fusion
- Event-based Vision

Course Topics

- Principles of image formation
  - Perspective projection
  - Camera calibration

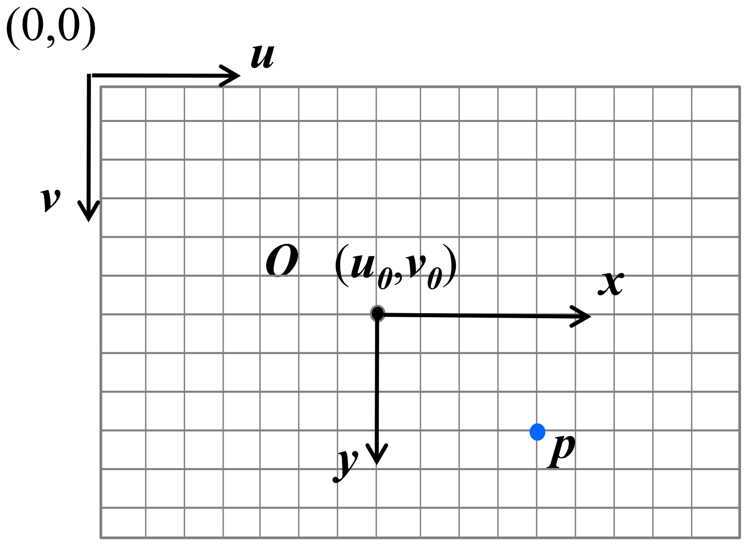


Image plane

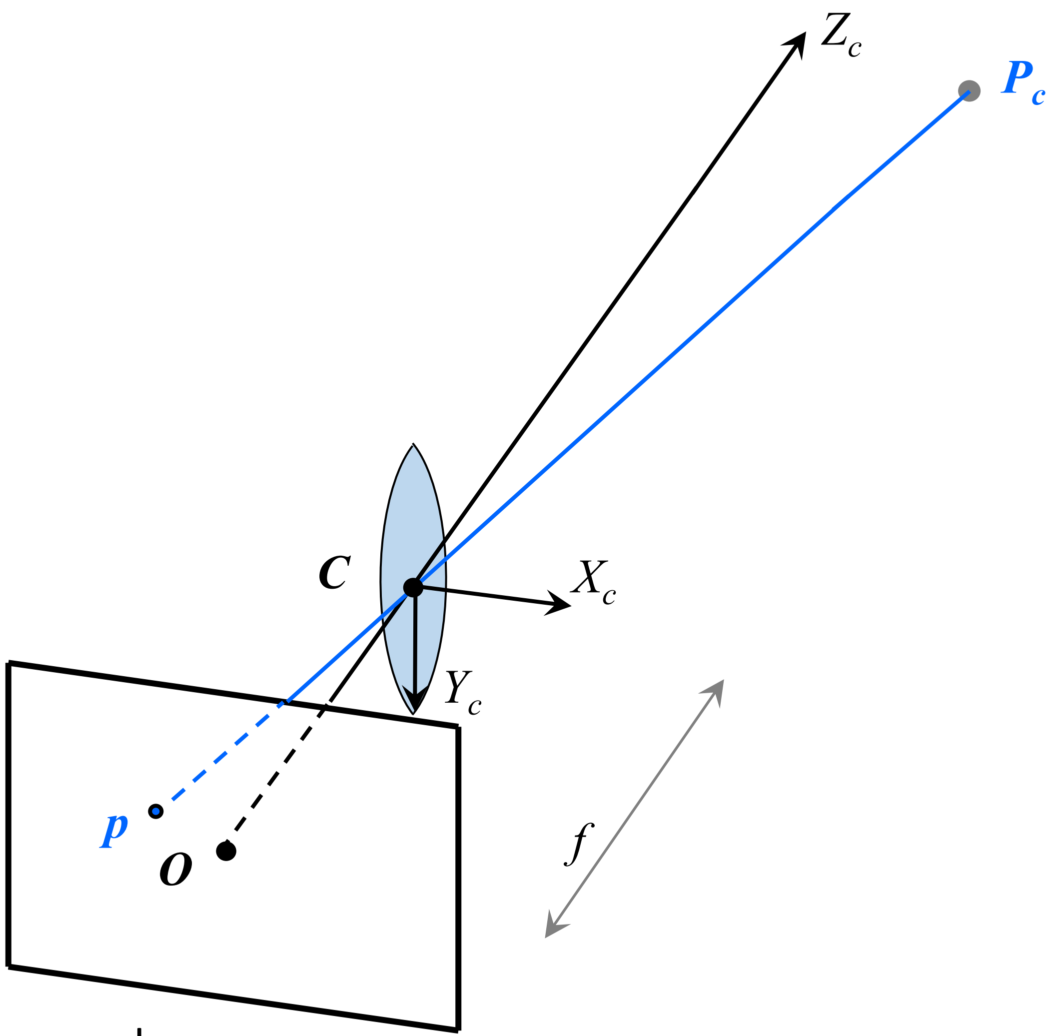
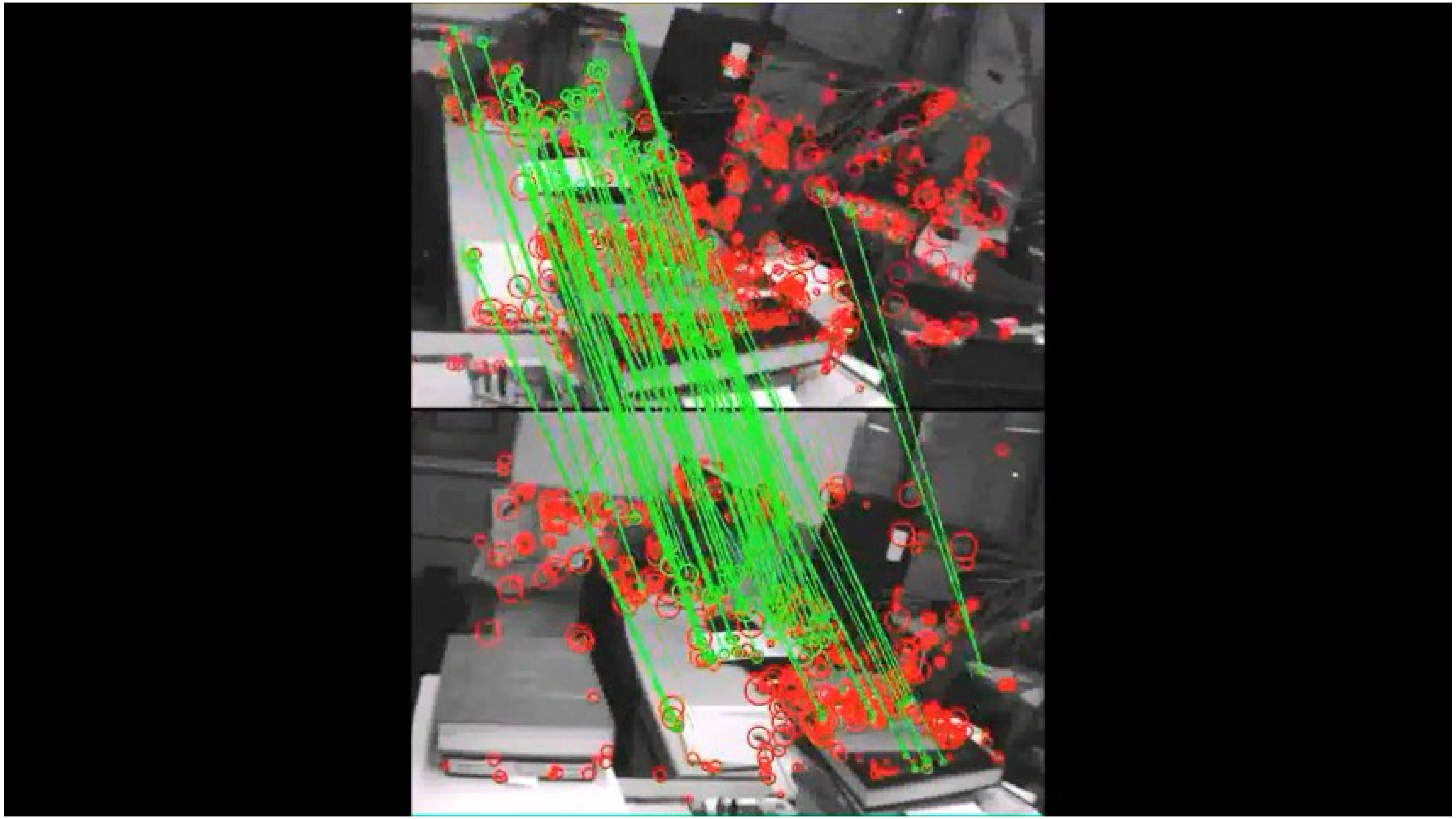


Image plane

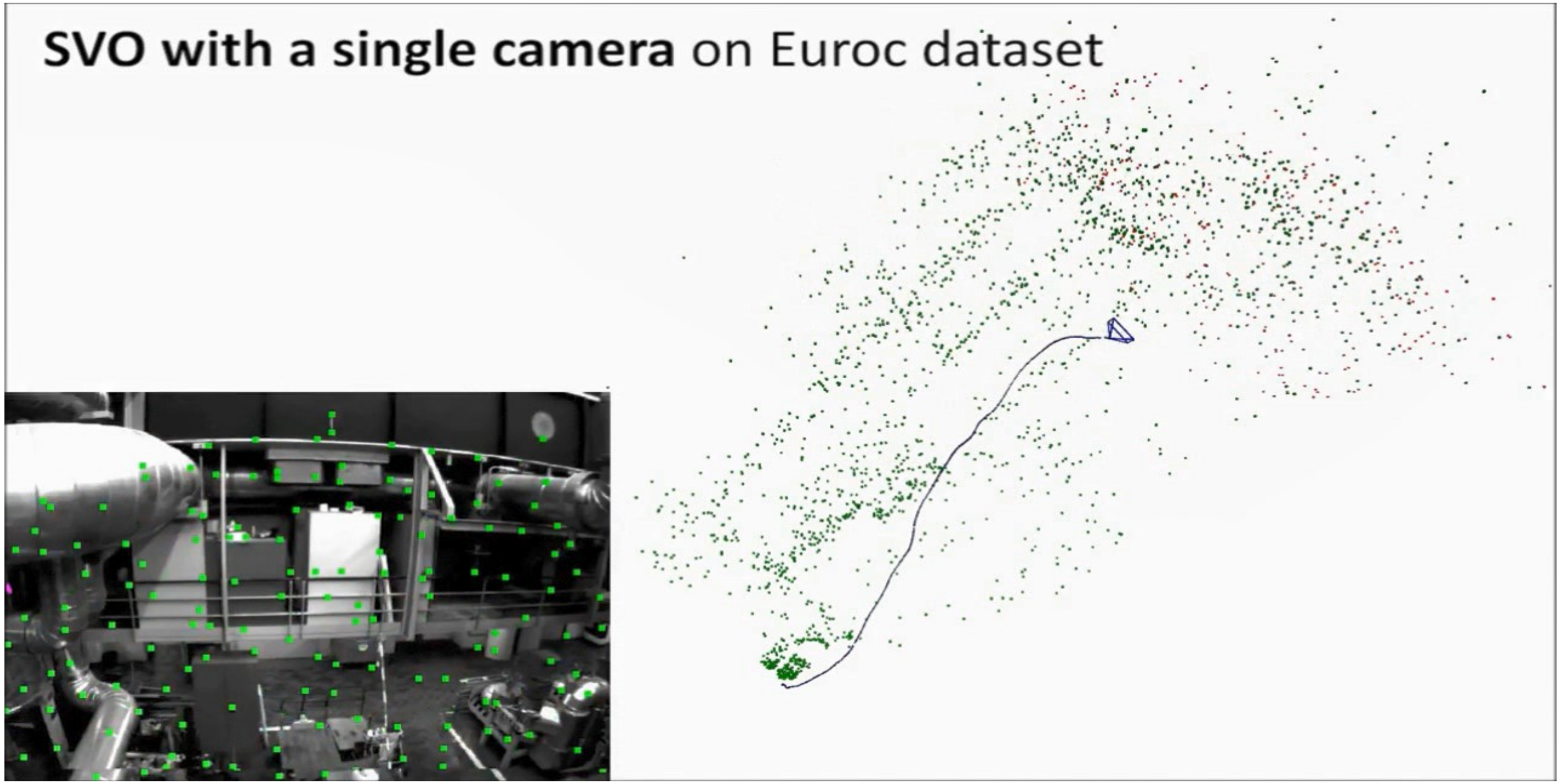
Course Topics

- Feature detection and matching



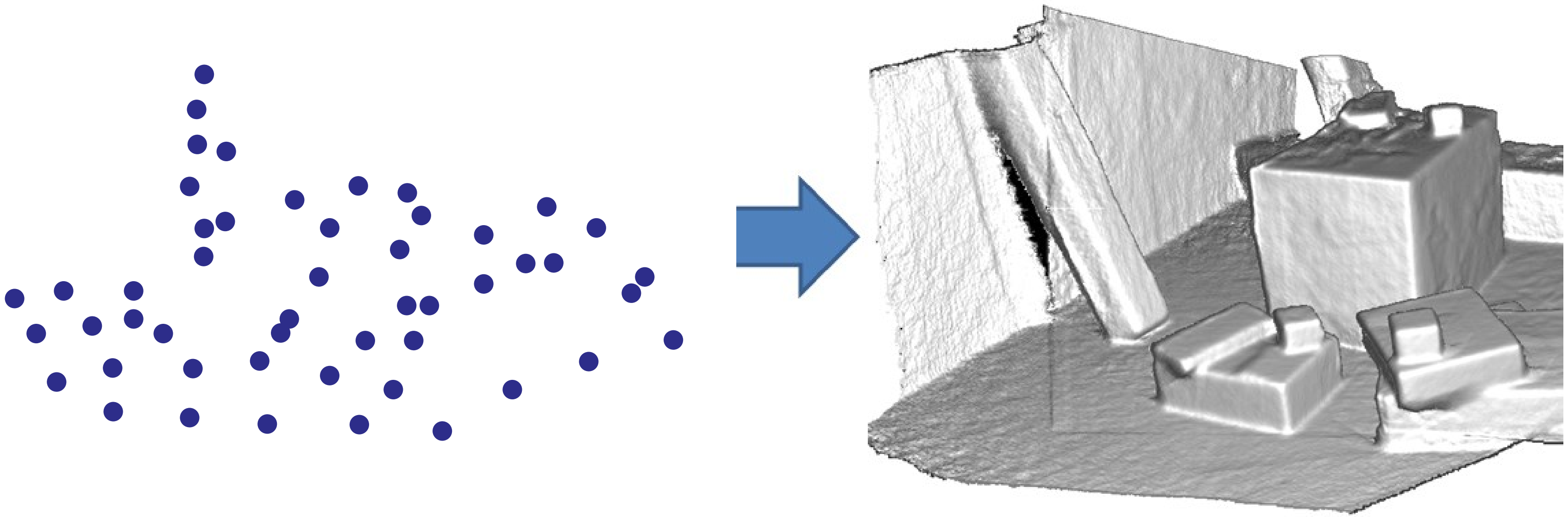
Course Topics

- Multi-view geometry and sparse 3D reconstruction



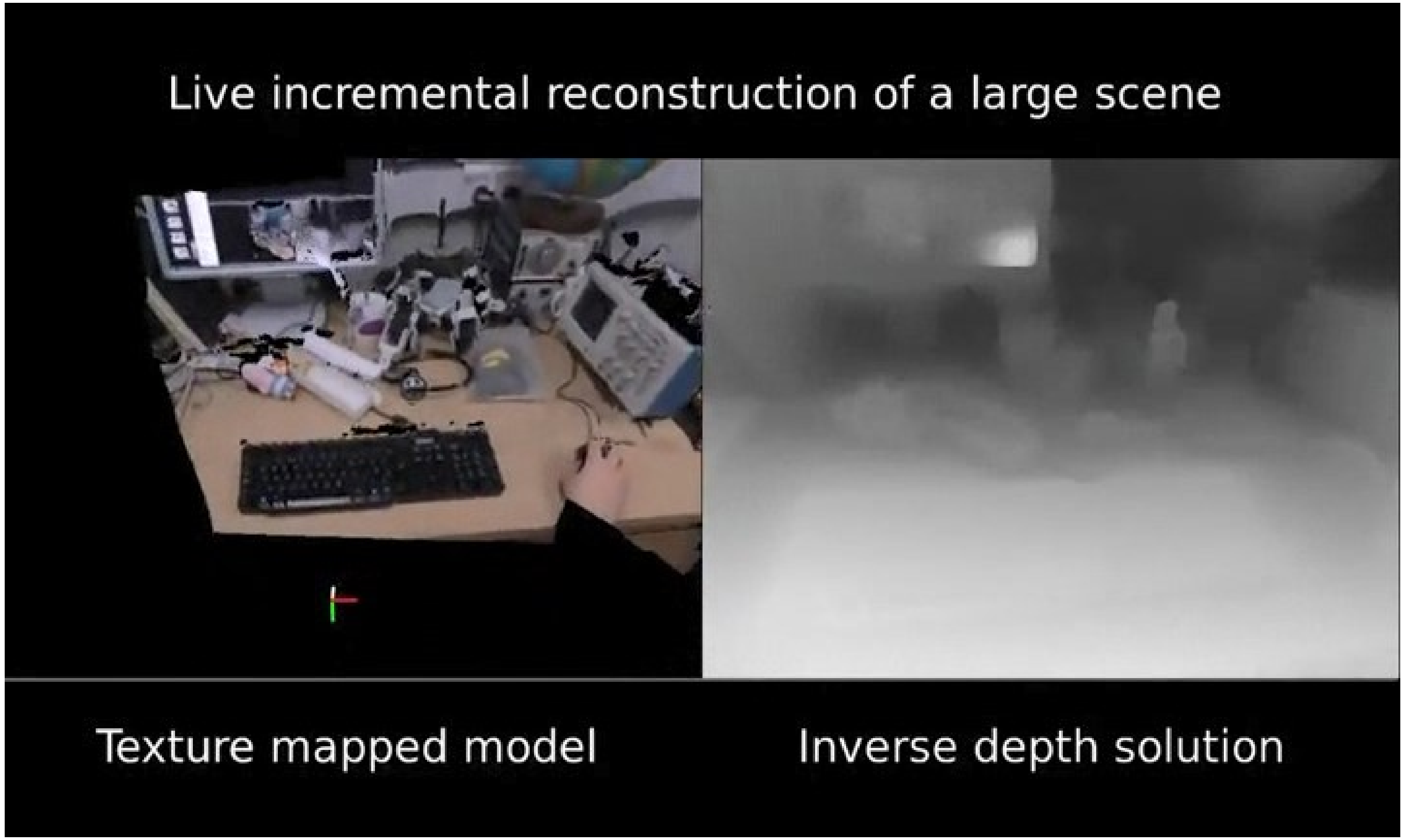
Course Topics

- Dense 3D reconstruction



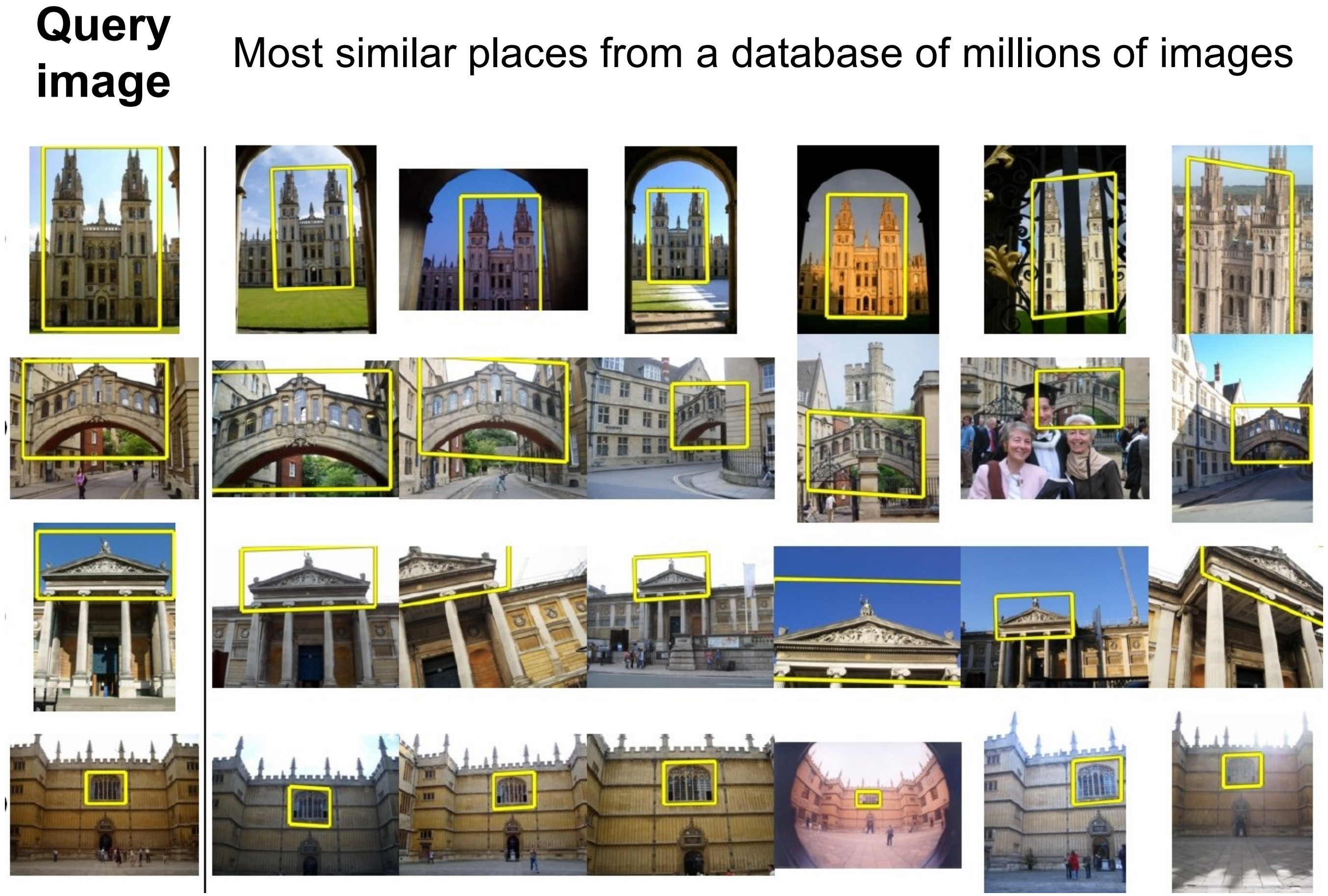
Course Topics

- Dense 3D reconstruction



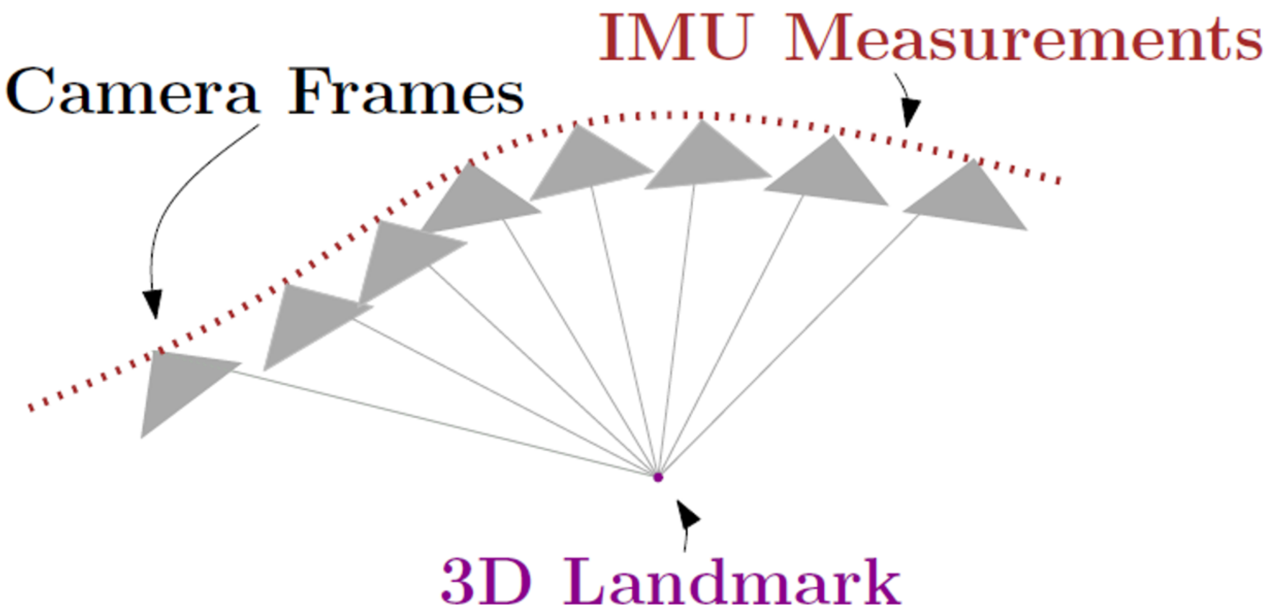
Course Topics

- Place recognition and deep learning



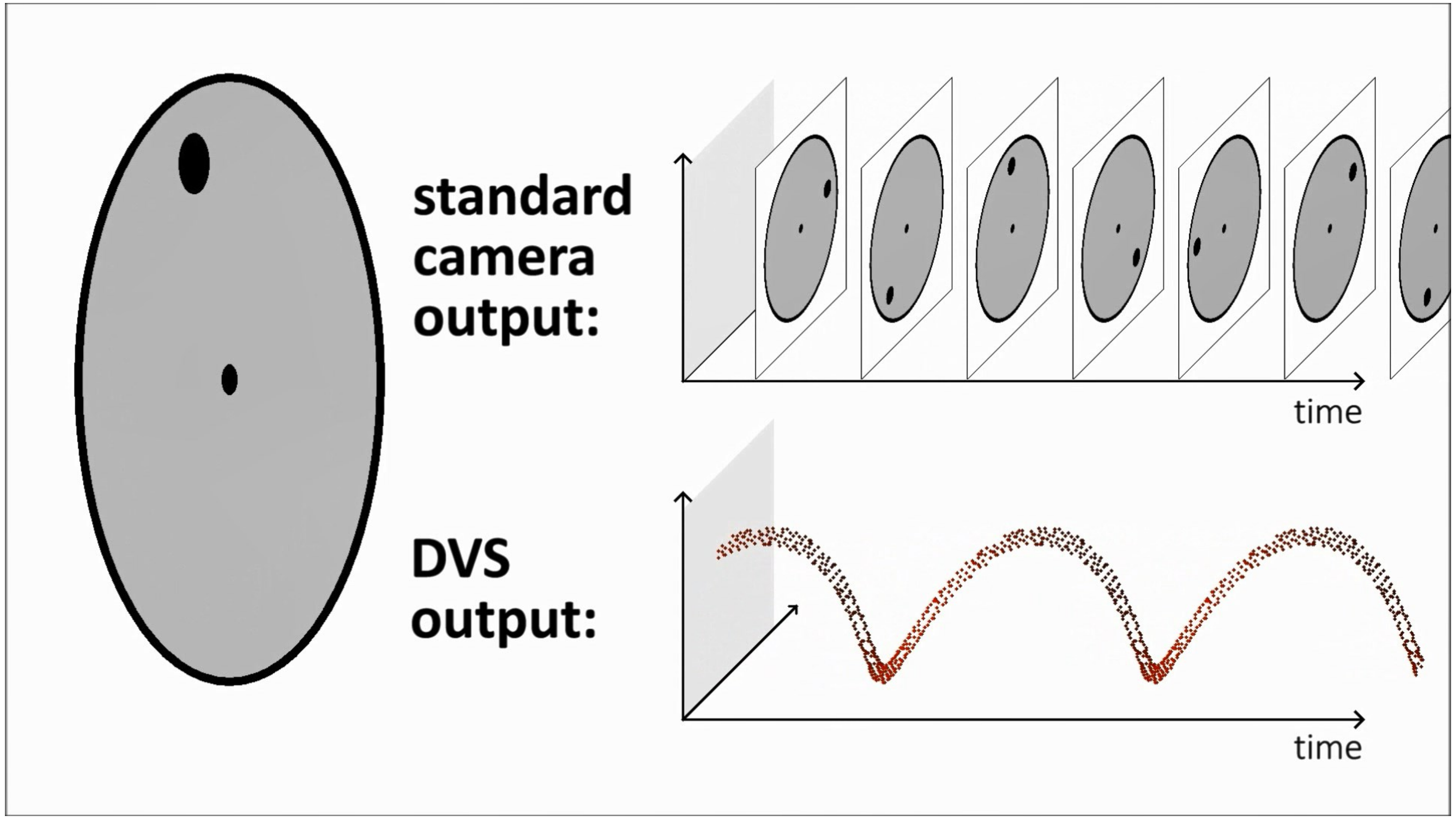
Course Topics

- Visual-inertial fusion

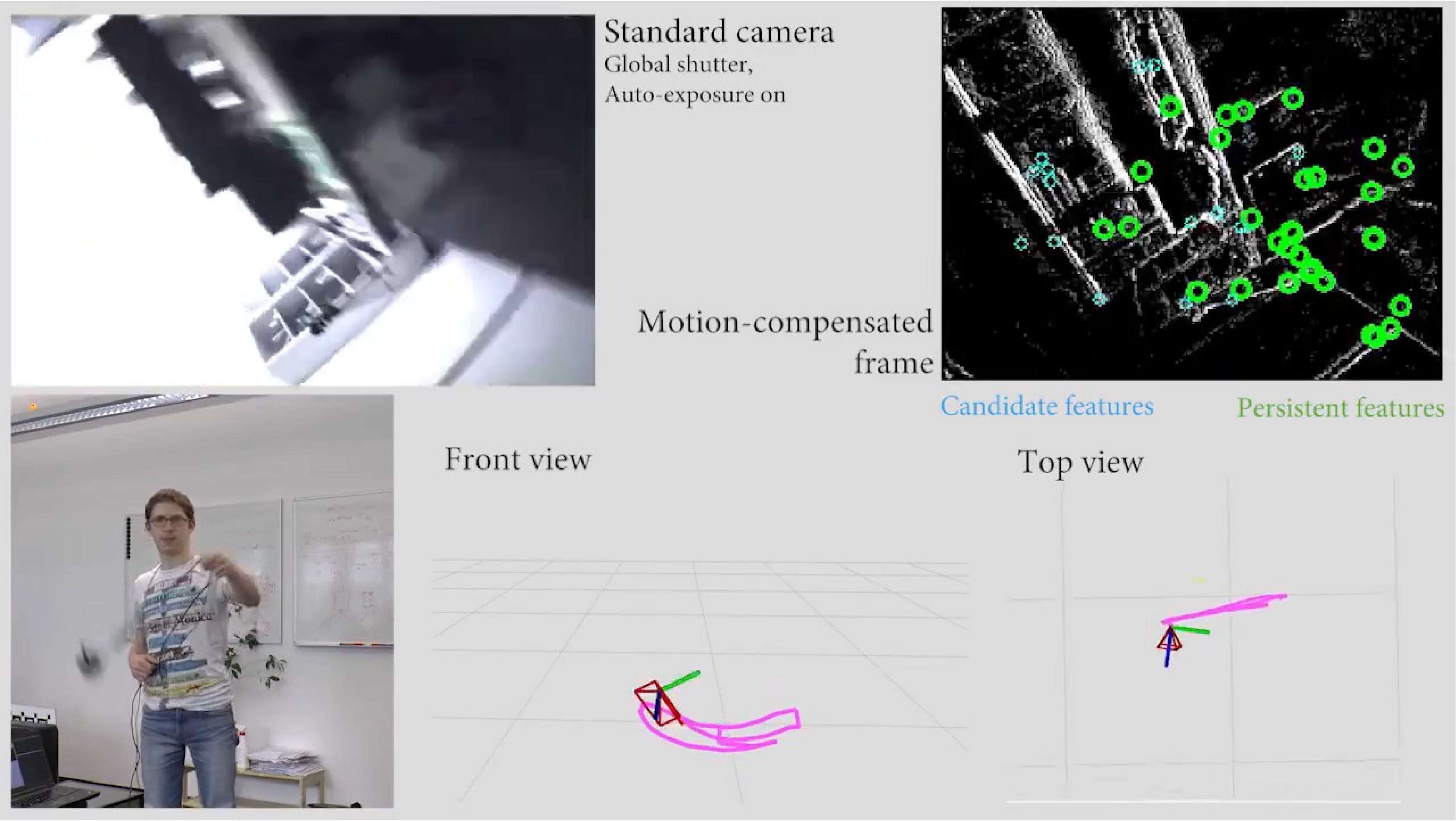


Course Topics

- Event cameras



Application of event cameras: high-speed VO



Rosinol et al., *Ultimate SLAM?* **IEEE RAL'18 best Paper Award Honorable Mention** [PDF](). [Video](). [IEEE Spectrum]().

Reading

- Scaramuzza, D., Fraundorfer, F., **Visual Odometry: Part I - The First 30 Years and Fundamentals**, *IEEE Robotics and Automation Magazine*, Volume 18, issue 4, 2011. PDF

- Fraundorfer, F., Scaramuzza, D., **Visual Odometry: Part II - Matching, Robustness, and Applications**, *IEEE Robotics and Automation Magazine*, Volume 19, issue 1, 2012. PDF

- C. Cadena, L. Carlone, H. Carrillo, Y. Latif, D. Scaramuzza, J. Neira, I.D. Reid, J.J. Leonard, **Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age**, *IEEE Transactions on Robotics*, Vol. 32, Issue 6, 2016. PDF

Understanding Check

Are you able to:

- Provide a definition of Visual Odometry?
- Explain the most important differences between VO, VSLAM, and SFM?
- What assumptions does VO rely on?
- Illustrate the flow chart of VO?