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

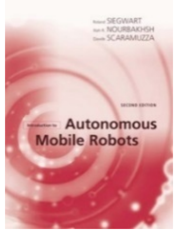
Who am I?

Current position

- Professor of Robotics and Perception since 2012
- Dep. of Informatics (UZH) and Neuroinformatics (UZH & ETH)
- Adjunct Professor of the ETH Master in Robotics, Systems and Control

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



Book

- “Autonomous Mobile Robots,” 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, Agile Drone Flight:

- Machine Learning
- Computer Vision
- Motion Planning & Control

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

Autonomous Drone Racing

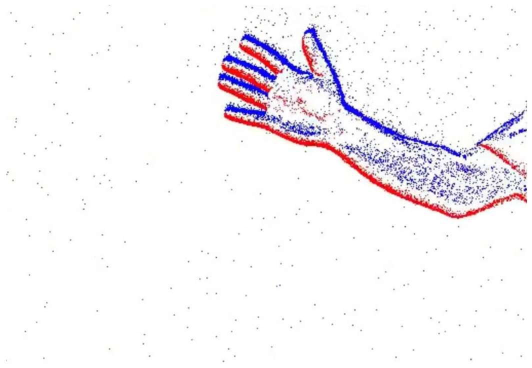
Foehn et al., **AlphaPilot: Autonomous Drone Racing,** RSS 2020, **Best System Paper Award**. PDF Video

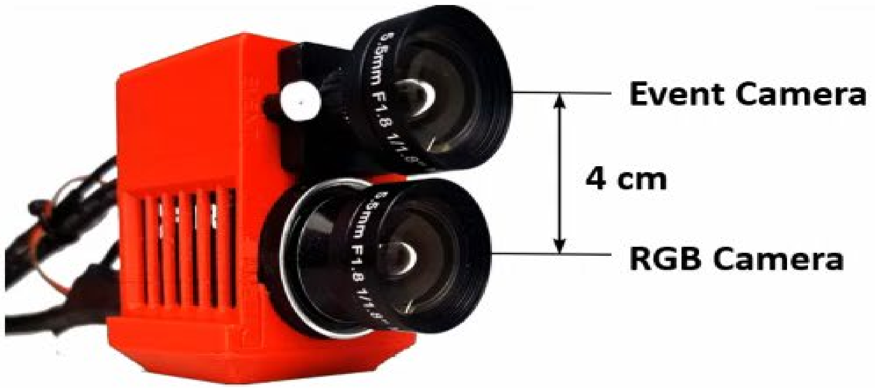
Drone Acrobatics

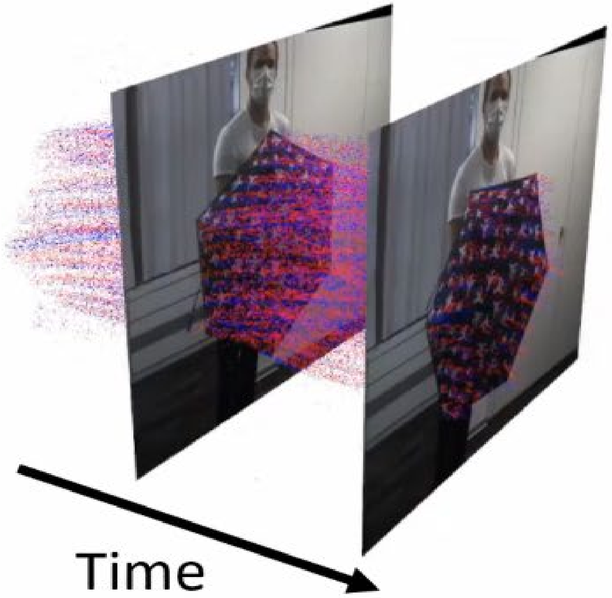
Kaufmann et al., **Deep Drone Acrobatics,** RSS 2020, **Best Paper Award finalist.** PDF. Video.

Event Cameras

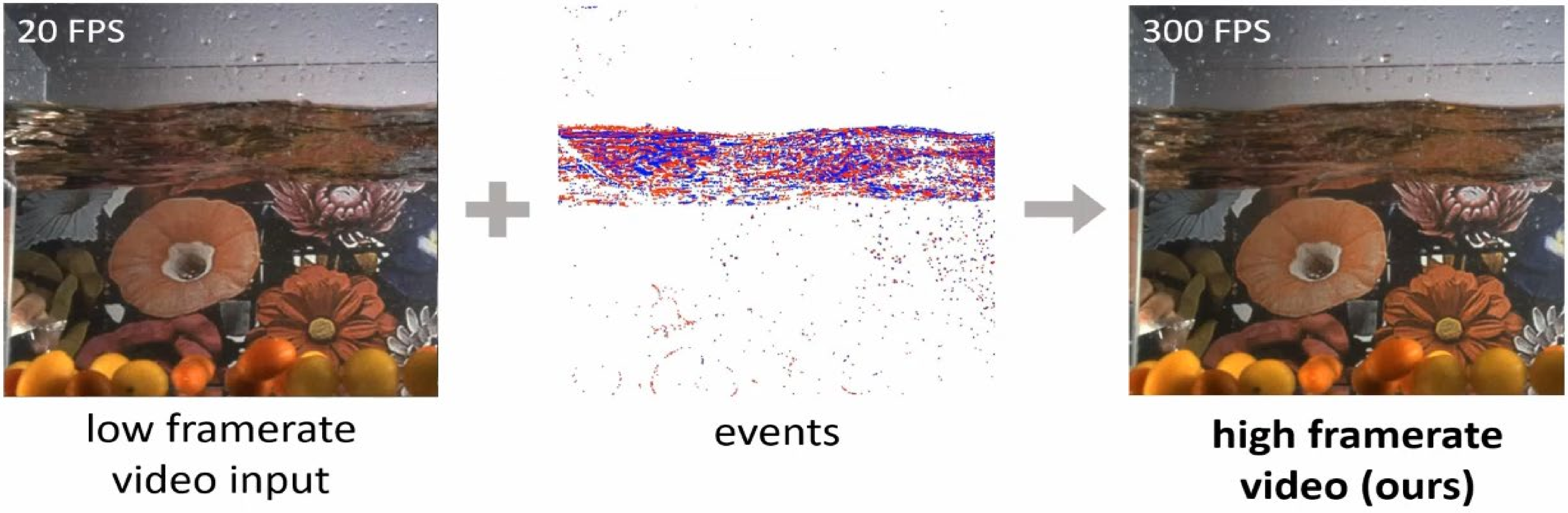
An **event camera** is a sensor that only measures **motion in the scene**







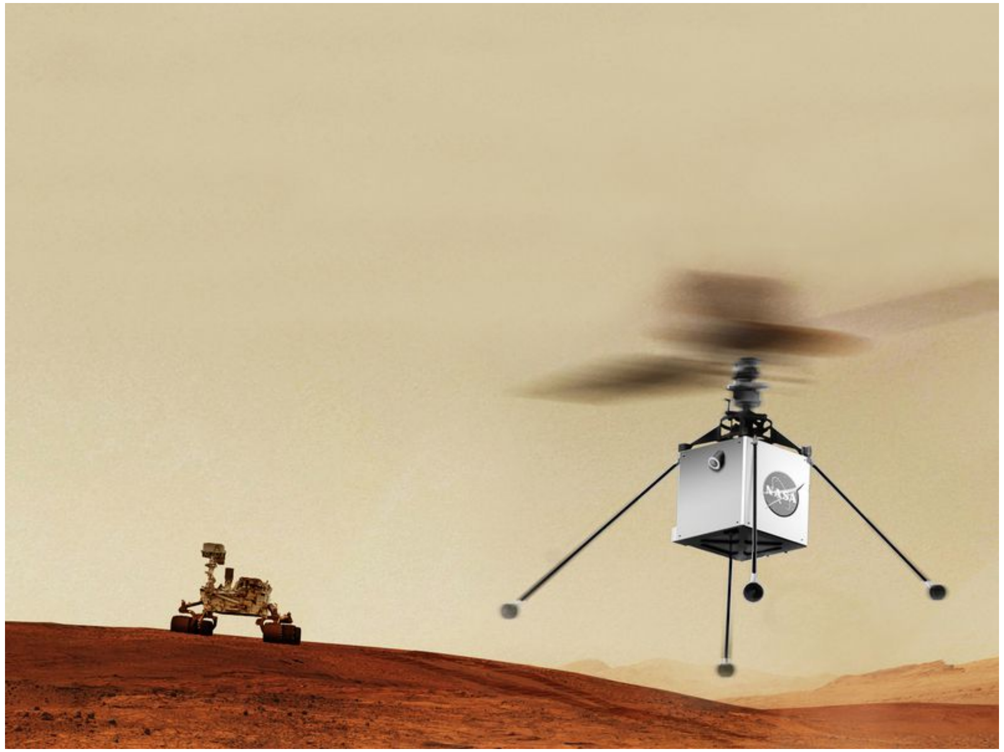
Computational Photography with Event Cameras



Tulyakov et al., TimeLens: Event-based Video Frame Interpolation, **CVPR’21**. [PDF](). [Video](). [Code]().

Collaboration with NASA/JPL for future Mars missions

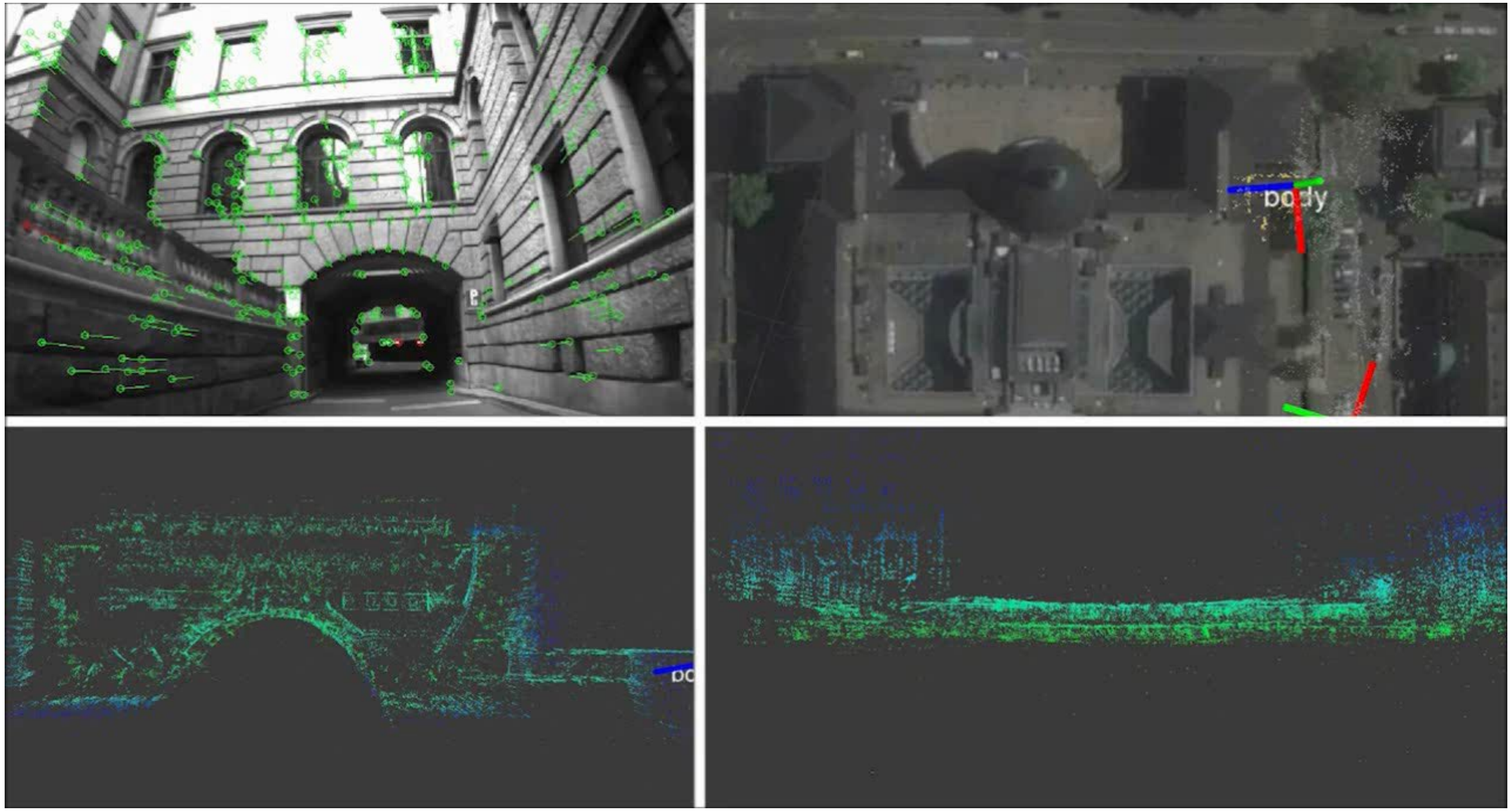
Jet Propulsion Laboratory
California Institute of Technology



Read the details on [this Swissinfo article]

Startup: "Zurich-Eye" – Today: Facebook-Oculus Zurich

- **Vision-based Localization and Mapping** systems for mobile robots
- Born in Sep. 2015, became **Facebook-Oculus Zurich** in Sep. 2016. Today, **200 employees**.



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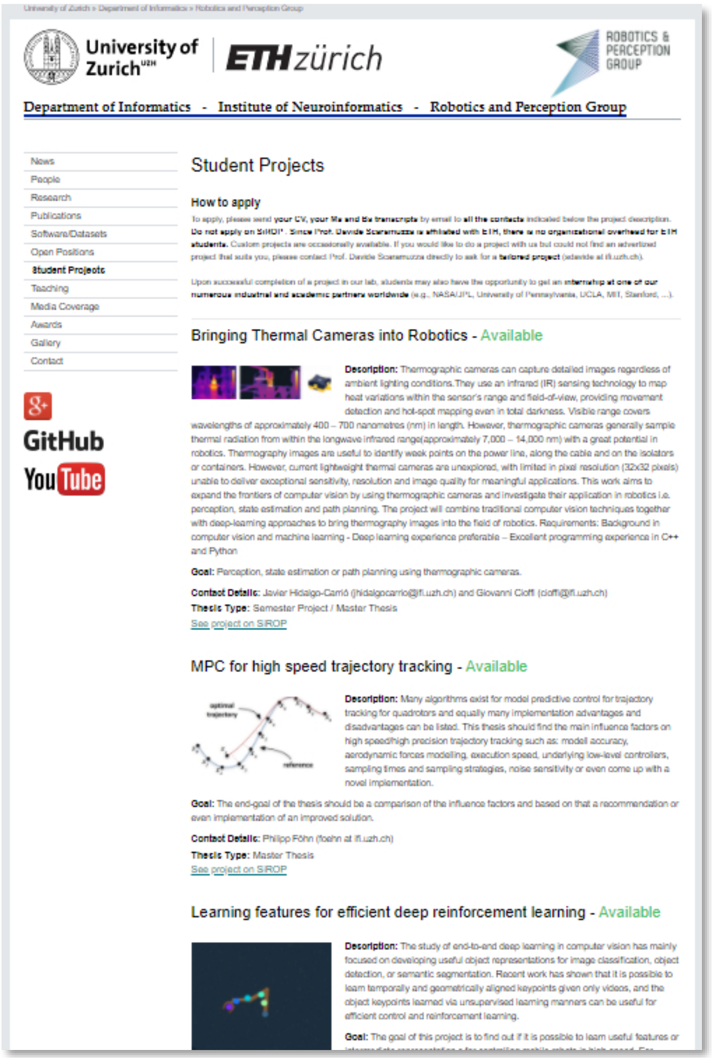
- Born in Sep. 2015, became **Facebook-Oculus Zurich** in Sep. 2016. Today, **200 employees**.
- In 2018, Zurich-Eye launched **Oculus Quest** (2 million units sold so far)

https://youtu.be/xwW-1mbemGc

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

- **Topics**: machine learning, computer vision, control, planning, robot 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.



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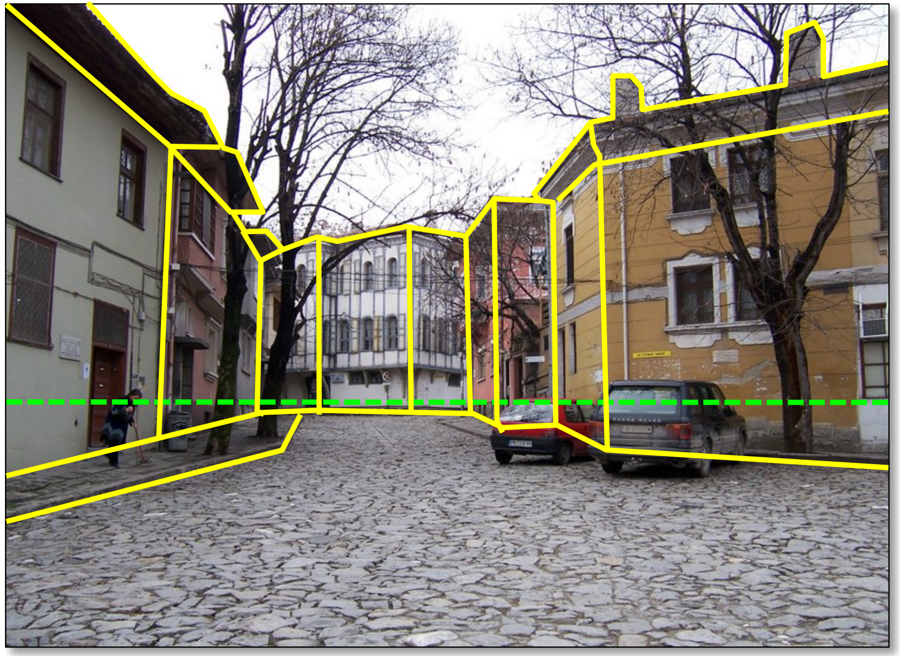
What is computer vision?

Automatic extraction of "meaningful" information from images and videos

Semantic information



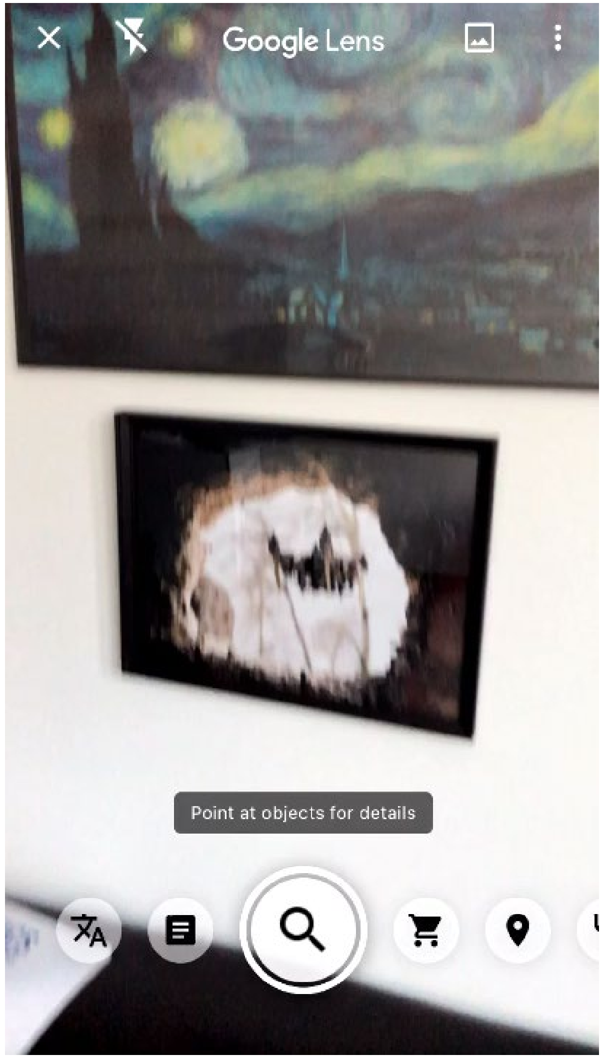
Geometric information
(this course)

Vision Demo?

Terminator 2

We are almost there!

Google App



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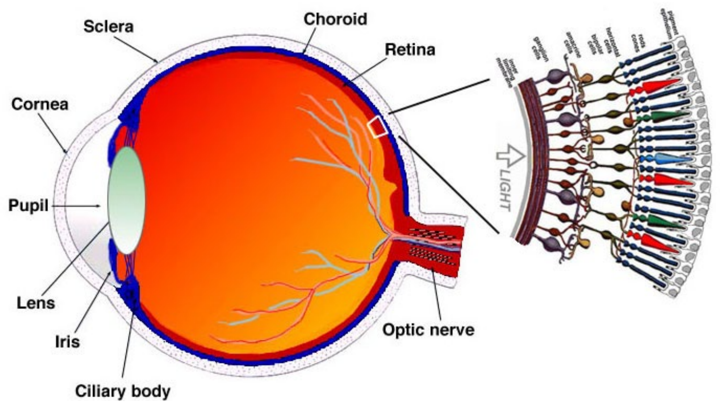
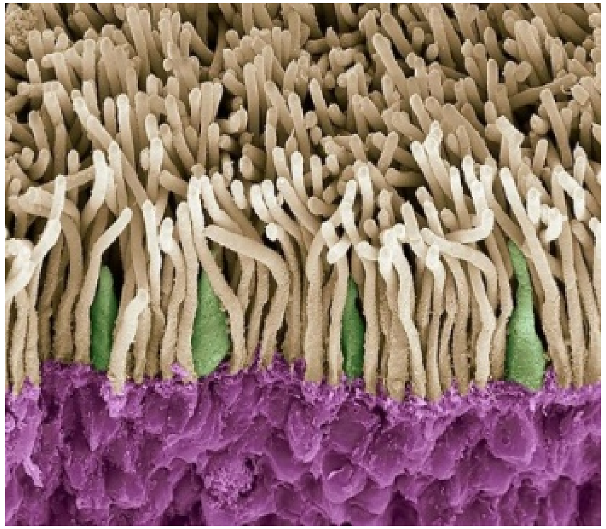
Why study computer vision?

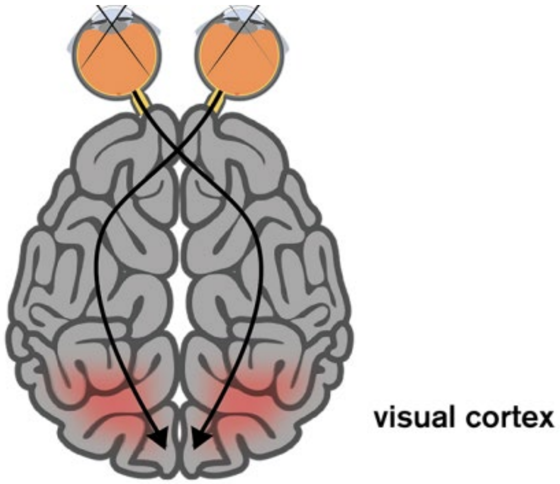
- **Relieve** humans of boring, easy tasks
- **Enhance** human abilities: human-computer interaction, visualization, augmented reality (AR)
- Perception for autonomous **robots**
- **Organize** and give access to visual **content**
- Lots of computer-vision **companies and jobs in Switzerland** (Zurich & Lausanne):
  - Facebook-Oculus (Zurich): AR/VR
  - Huawei (Zurich): 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 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**



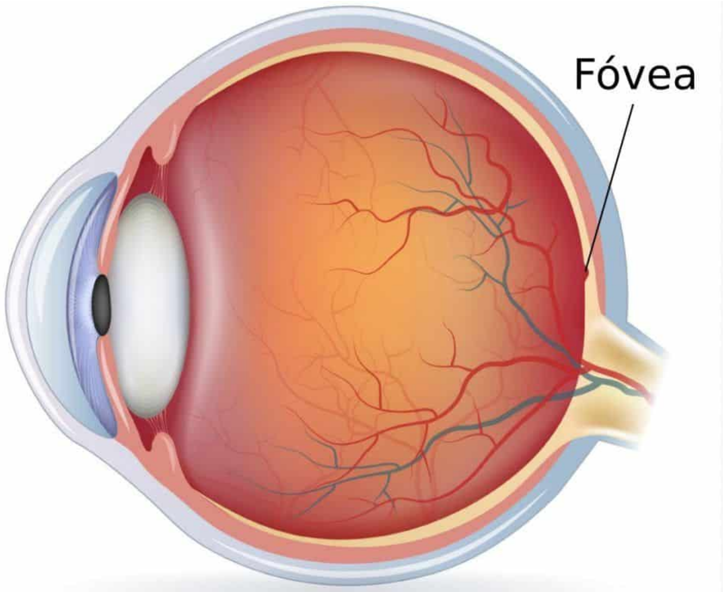




Vision in humans: how we see

- 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]



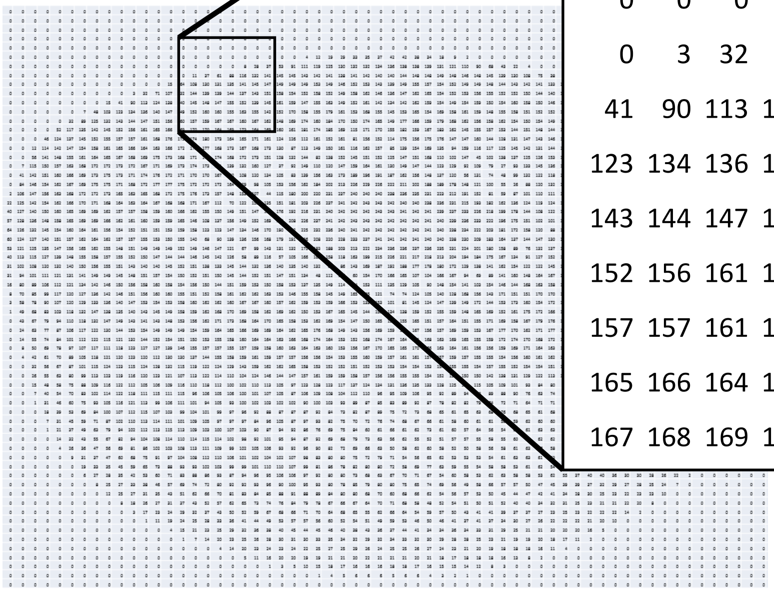
What a newborn sees every month in the first year

“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?



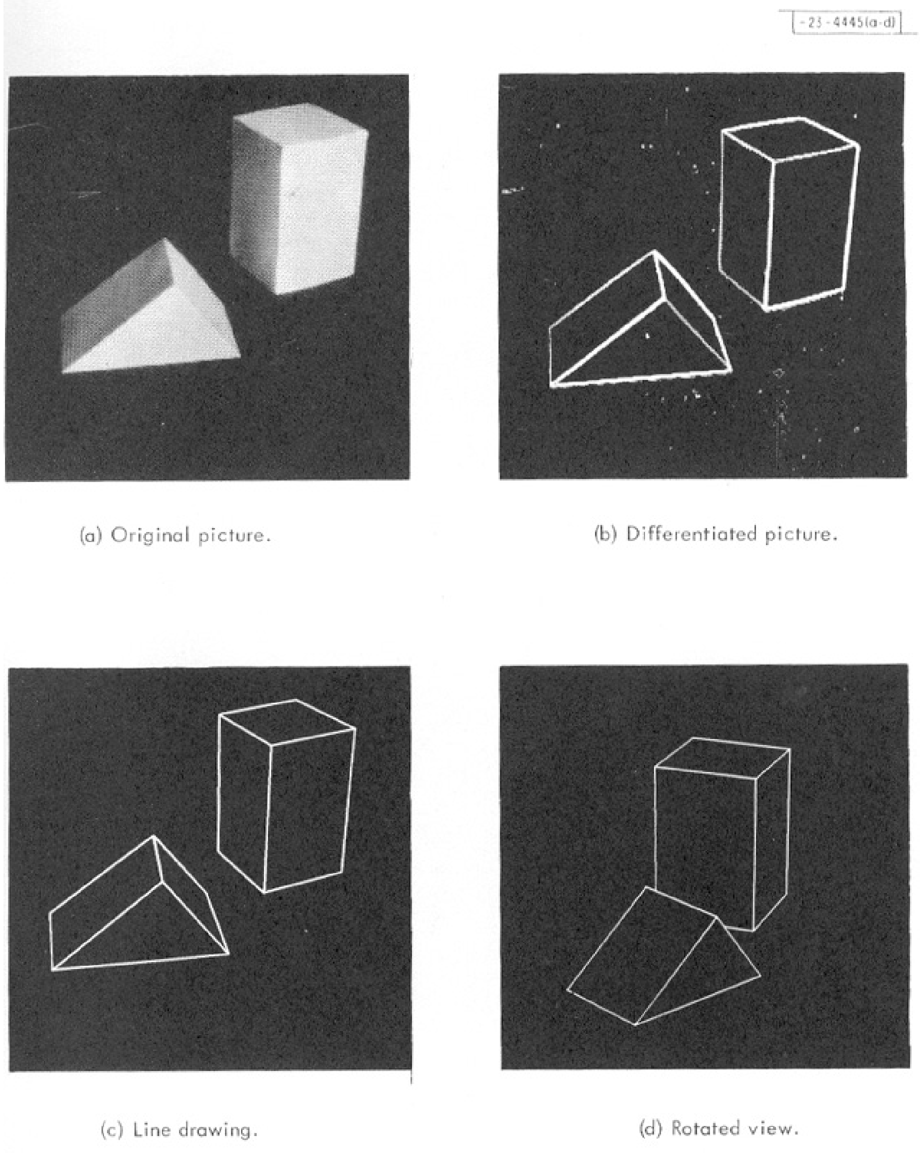
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	8	28
0	0	0	0	0	0	11	37	61	88	116	132
0	0	0	0	15	64	108	130	131	135	141	145
0	3	32	71	107	132	144	139	139	144	137	143
41	90	113	124	138	140	145	148	147	155	152	139
123	134	136	140	147	149	152	160	160	155	163	155
143	144	147	151	156	160	157	159	167	167	160	167
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

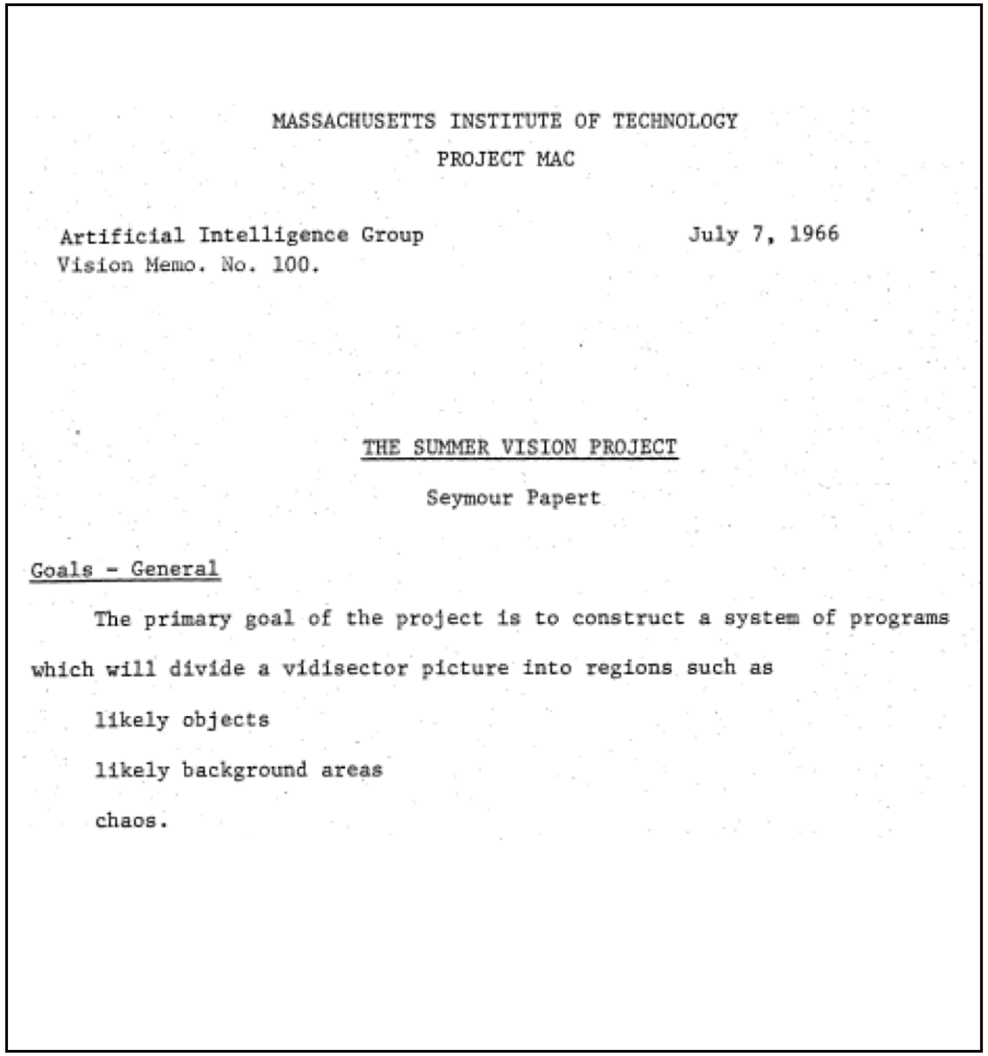
Origins of computer vision

- **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

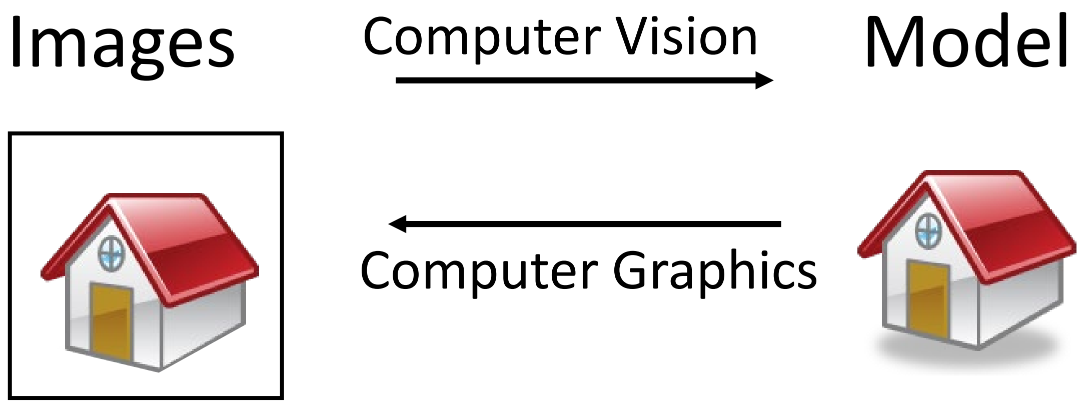
The primary goal of the project is to construct a system of programs which will divide a vidisector picture into regions such as

likely objects

likely background areas

chaos.

Computer Vision vs Computer Graphics



Inverse problems: analysis and synthesis.

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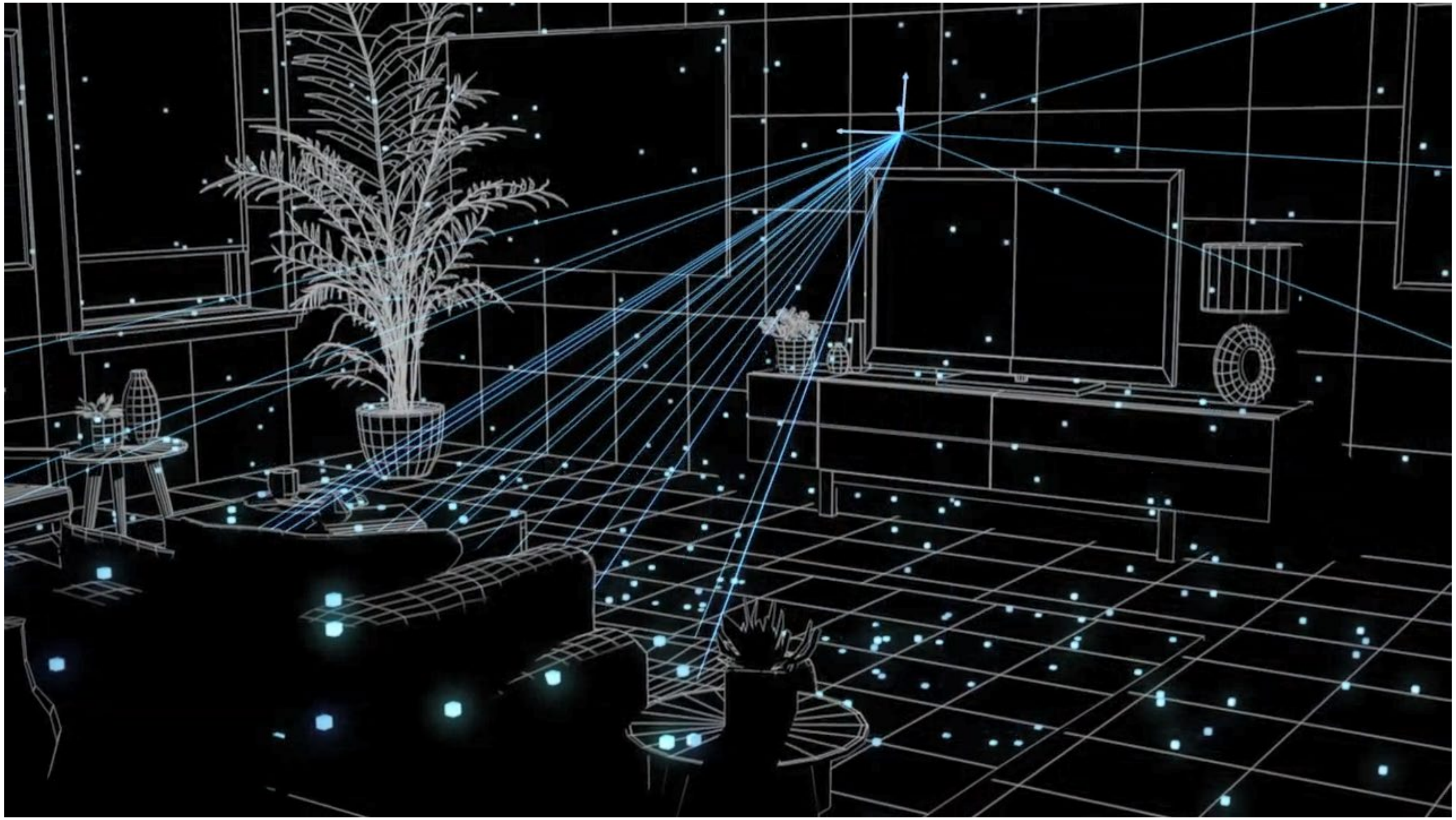
VR/AR



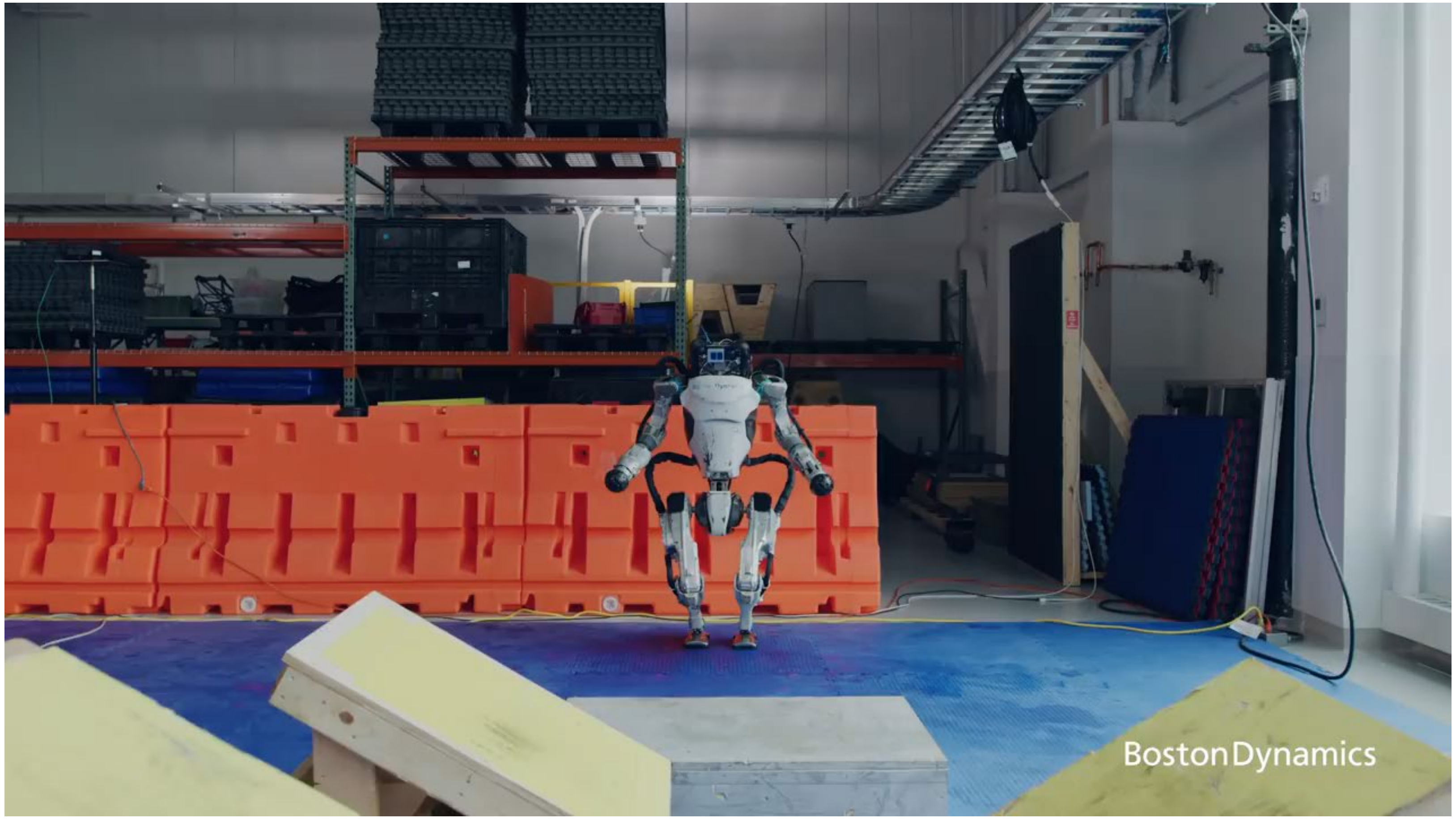
Oculus Quest uses four cameras to track the pose of the head and the controllers

Advanced Driving Assistance Systems (ADAS)

Mobileye: Vision system used at **Tesla, 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

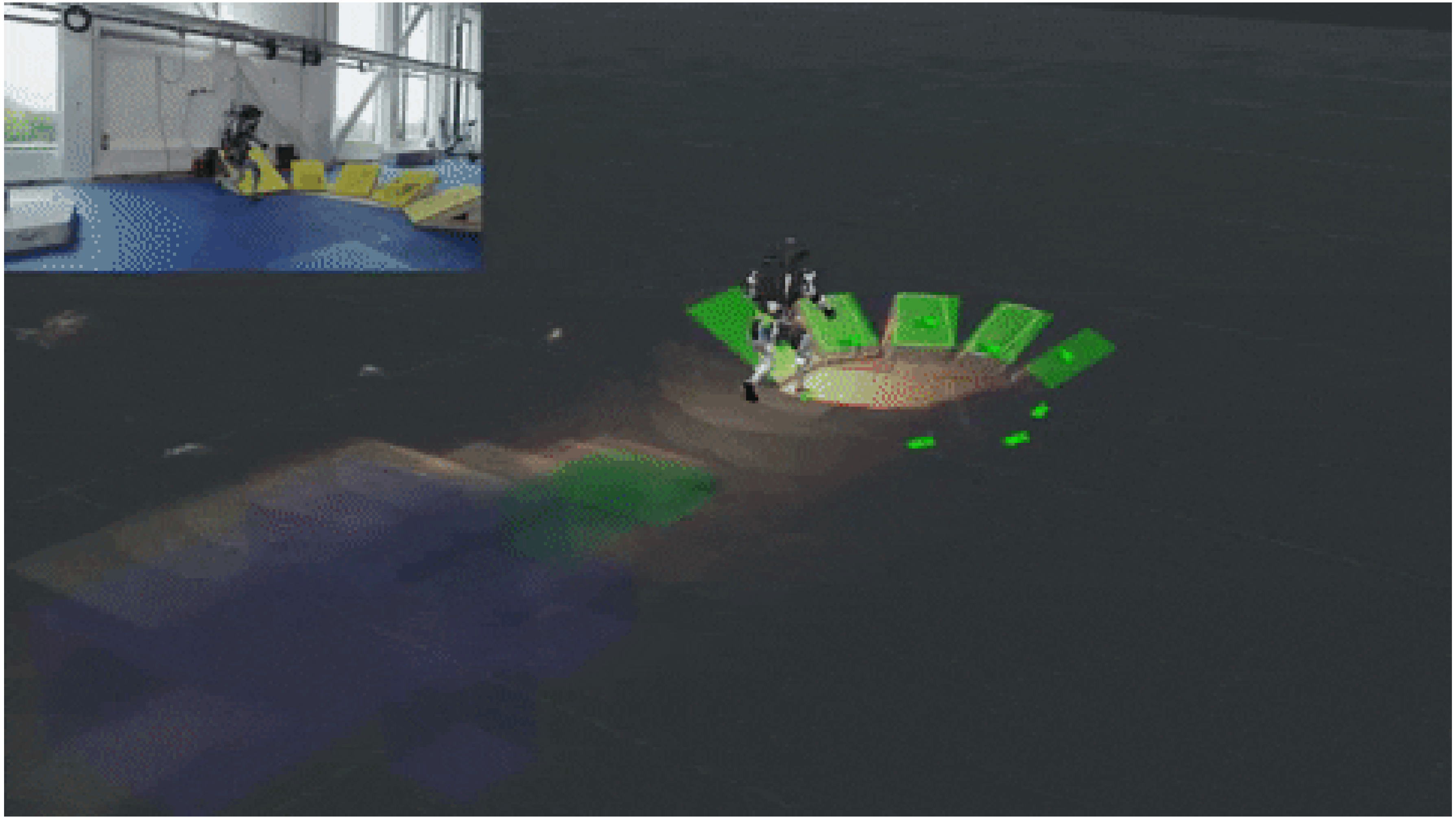
Boston Dynamics ATLAS Robot



https://youtu.be/tF4DML7FIWk

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

Boston Dynamics ATLAS Robot



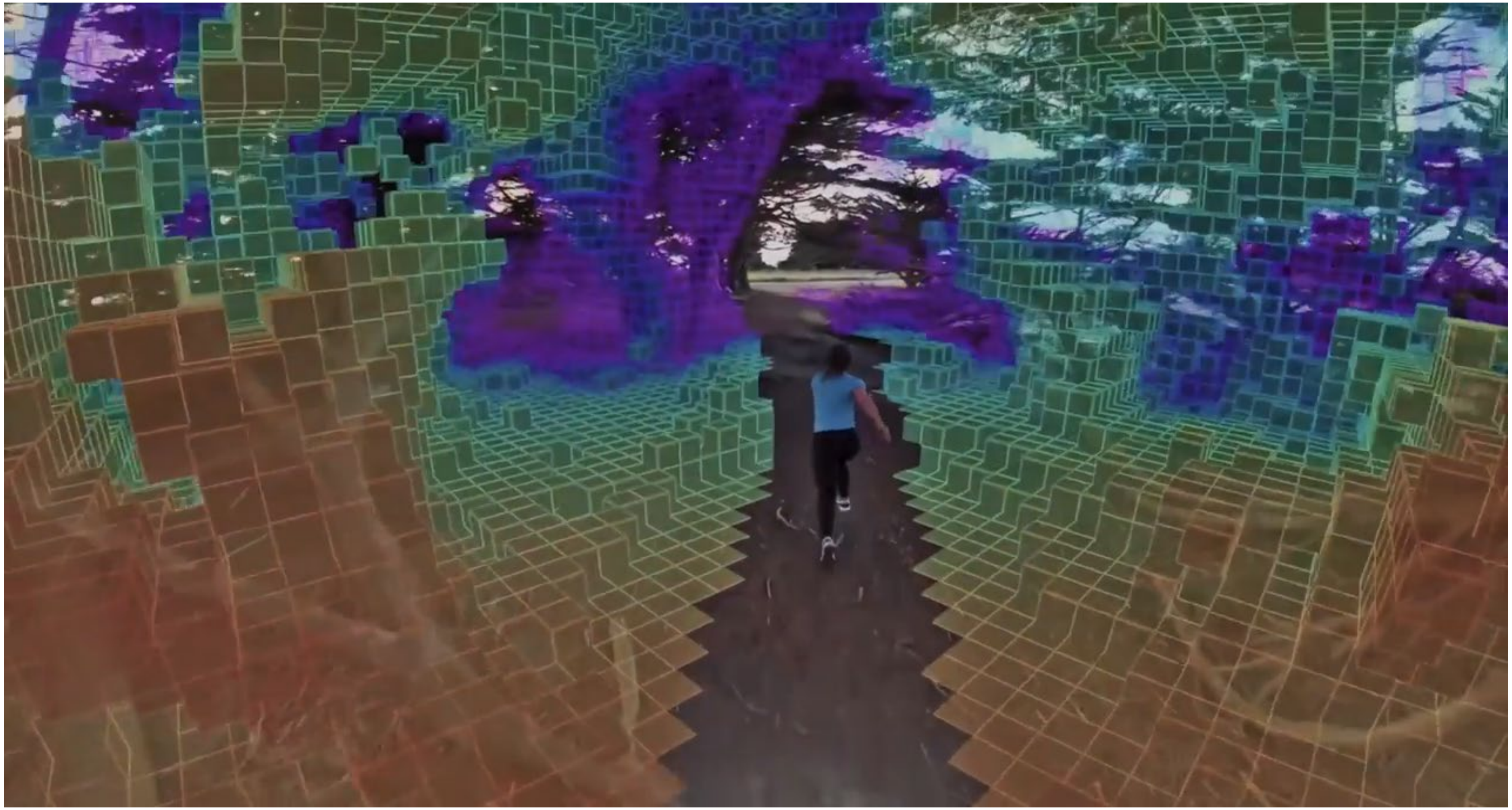
https://blog.bostondynamics.com/flipping-the-script-with-atlas

Skydio and DJI Drones

The Skydio R2 drone features 7 cameras for obstacle avoidance, visual odometry, and person following

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

Skydio and DJI Drones



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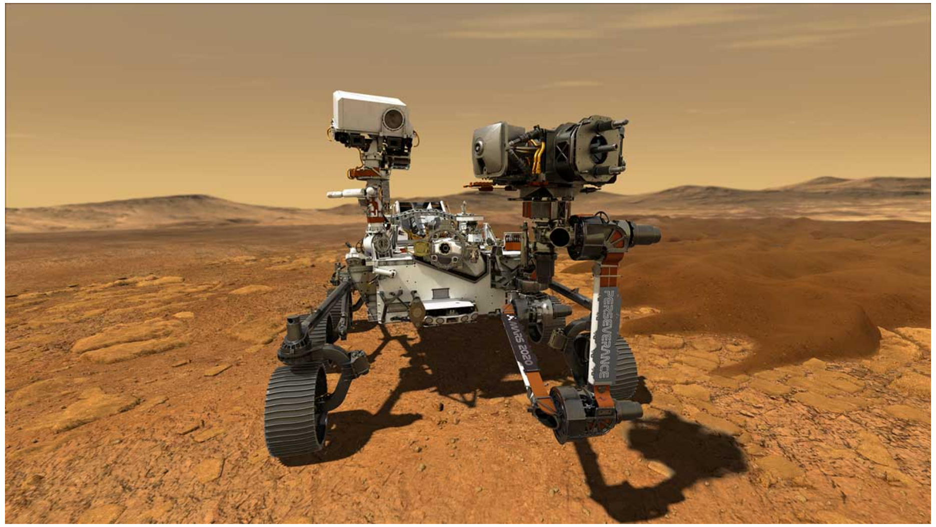
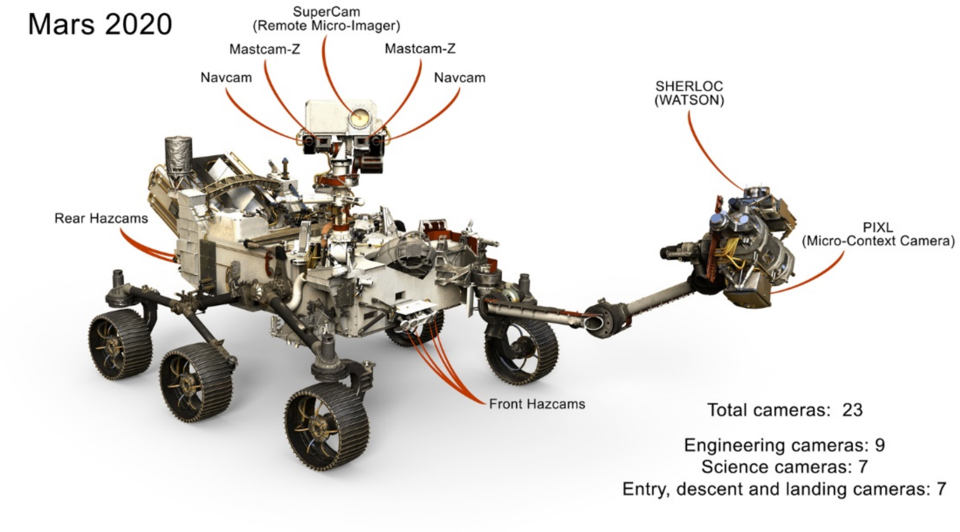
NASA Mars Rovers



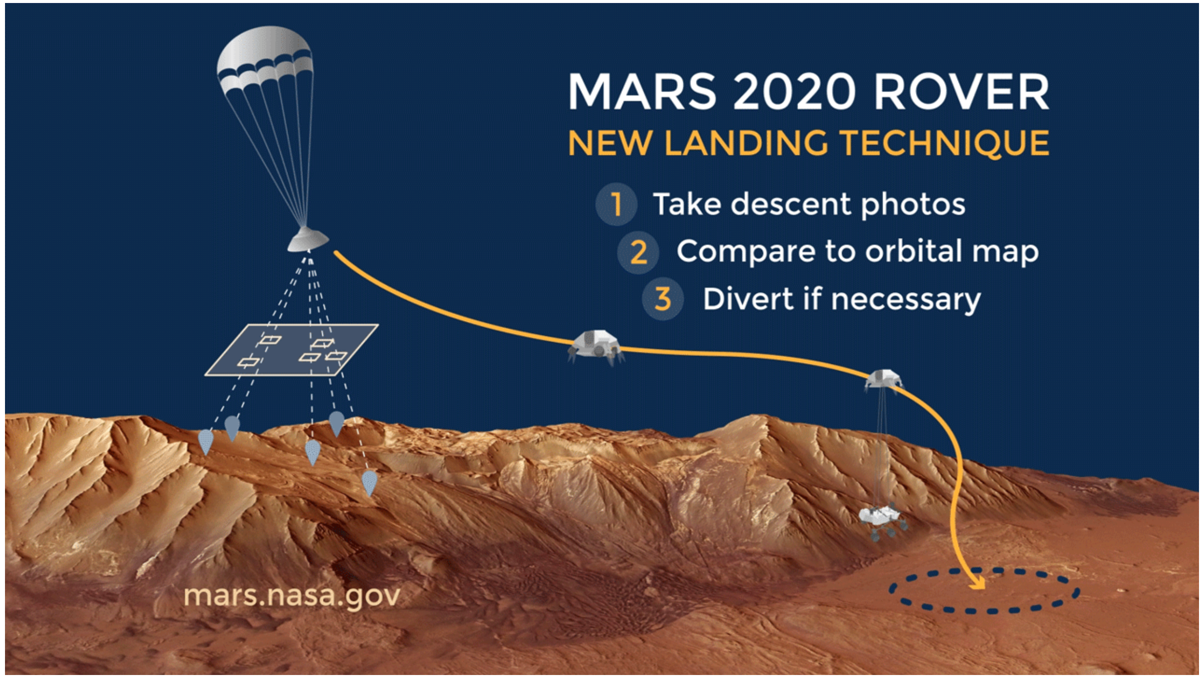


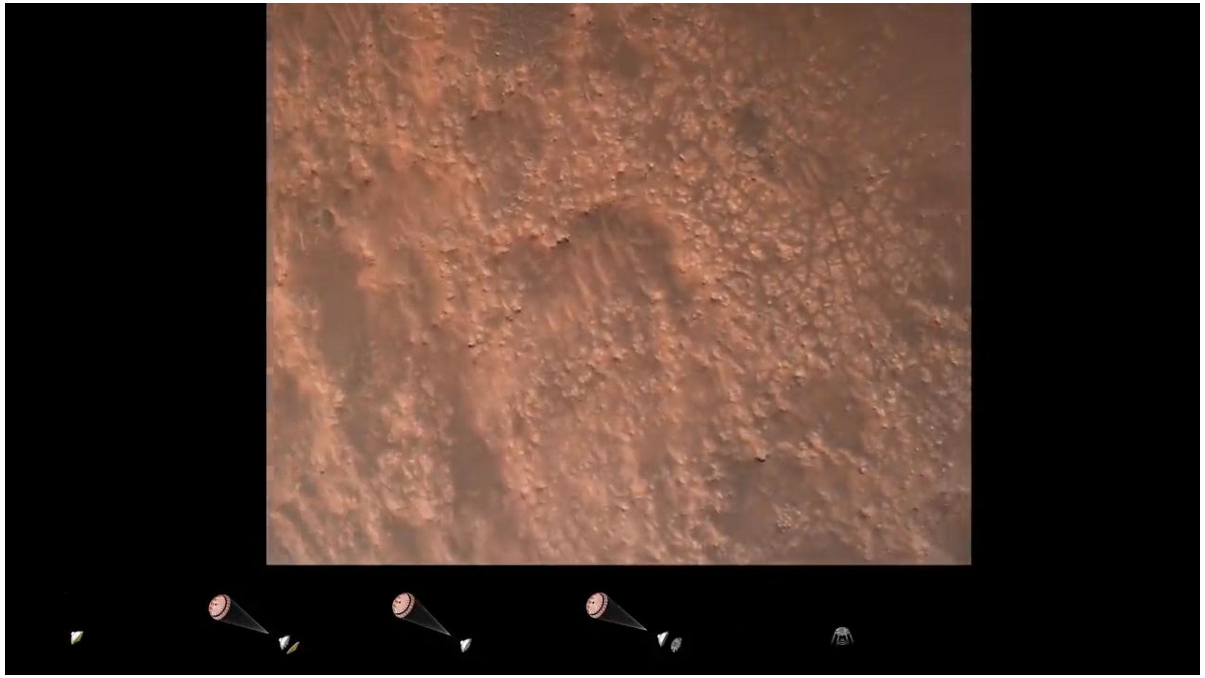
NASA'S Perseverance Rover landed in 2021 features 23 cameras used for:

- 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





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/#

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

Before the Break

Please fill this quick survey: https://forms.gle/CeHX6y64MWWaC6gF8

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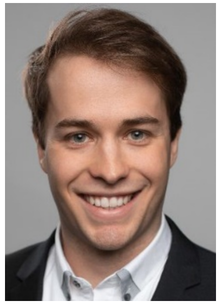
Instructors

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**: Manasi Muglikar and Nico Messikommer

Manasi Muglikar
muglikar (at) ifi (dot) uzh (dot) ch



Nico Messikommer
nmessi (at) ifi (dot) uzh (dot) ch

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

Lectures and Exercises

Lectures:

- **<u>08:00</u> to 09:45** every week. **After class**, **I usually stay for 10 more minutes** for questions
- Room: SOC-F-106, Rämistrasse 69, 8001 Zurich.

Exercises:

- **<u>12:15</u> to 13:45**: Starting from Sep. 30 (2^{nd} week). Then roughly every week.
- Room: same as above

Tentative Course Schedule

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

23.09.2021	Lecture 01 - Introduction to Computer Vision and Visual Odometry No Exercise today.
30.09.2021	Lecture 02 - Image Formation: perspective projection and camera models Exercise 01- Augmented reality wireframe cube
07.10.2021	Lecture 03 - Camera Calibration Exercise 02 - PnP problem
14.10.2021	Lecture 04 - Filtering & Edge detection No Exercise today.
21.10.2021	Lecture 05 - Point Feature Detectors, Part 1 Exercise 03 - Harris detector + descriptor + matching
28.10.2021	Lecture 06 - Point Feature Detectors, Part 2 Exercise 04 - SIFT detector + descriptor + matching
04.11.2021	Lecture 07 - Multiple-view geometry 1 Exercise 05 - Stereo vision: rectification, epipolar matching, disparity, triangulation
11.11.2021	Lecture 08 - Multiple-view geometry 2 Exercise 06 - Eight-Point Algorithm
18.11.2021	Lecture 09 - Multiple-view geometry 3 Exercise 07 - P3P algorithm and RANSAC
25.11.2021	Lecture 10 - Multiple-view geometry 4 Exercise session: Intermediate VO Integration
02.12.2021	Lecture 11 Optical Flow and KLT Tracking Exercise 08 - Lucas-Kanade tracker
09.12.2021	Lecture 12a (1st hour) - Place recognition Lecture 12b (2nd hour) - Dense 3D Reconstruction and Place recognition Lecture 12c (3rd and 4th hour, replaces exercise) - Deep Learning Tutorial Optional Exercise on Place Recogntion
16.12.2021	Lecture 13 - Visual inertial fusion Exercise 09 - Bundle Adjustment
23.12.2021	Lecture 14 - Event based vision Exercise session: Final VO Integration

Study Material

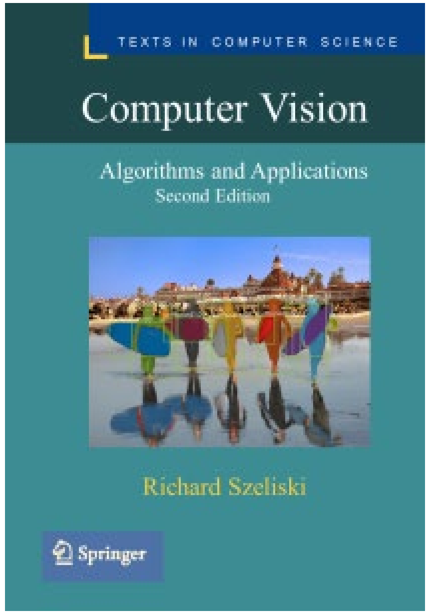
- **Schedule**, **lecture slides, exercise download, mini projects, course info** on the official course website**:** http://rpg.ifi.uzh.ch/teaching.html

- **Video Recordings** of lectures and exercises will be uploaded to OLAT: https://lms.uzh.ch/auth/RepositoryEntry/17073865591

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

Reference Textbooks

- **Computer Vision: Algorithms and Applications**, 2nd edition, by Richard Szeliski. PDF published on **28th August, 2021**, **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



- Alternative books:
  - *Robotics, Vision and Control: Fundamental Algorithms*, 2nd edition, by Peter Corke, 2017.
  - *An Invitation to 3D Vision*: Y. Ma, S. Soatto, J. Kosecka, S.S. Sastry
  - *Multiple view Geometry*: R. Hartley and A. Zisserman

Prerequisites

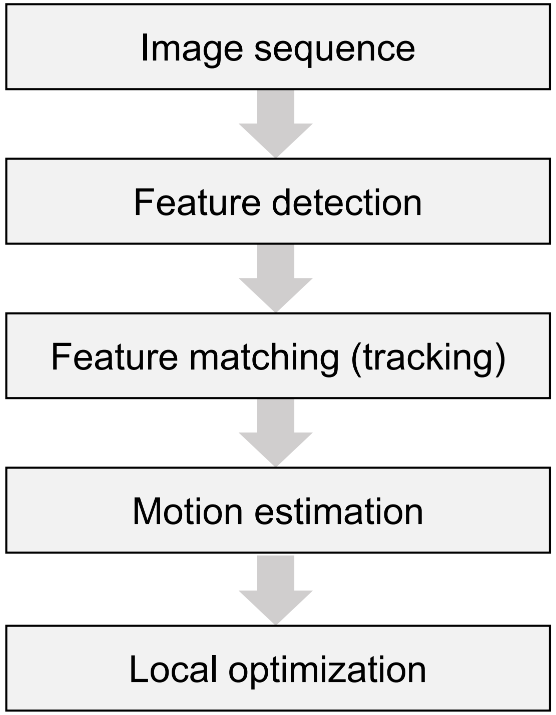
- **Linear algebra**
- **Matrix calculus**: matrix multiplication, inversion, singular value decomposition
  - Check out this Linear Algebra Primer from Stanford University
  - Check out this Immersive Linear Algebra interactive tool by Ström, Åström, and Akenine-Möller
- **No prior knowledge** of **computer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

Learning Objectives

- **High-level goal:** learn to implement the visual-inertial odometry algorithms used in current mobile robots (drones, cars, planetary robots), AR/VR products (Oculus 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** (similar to that 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 might be asked at the exam.**

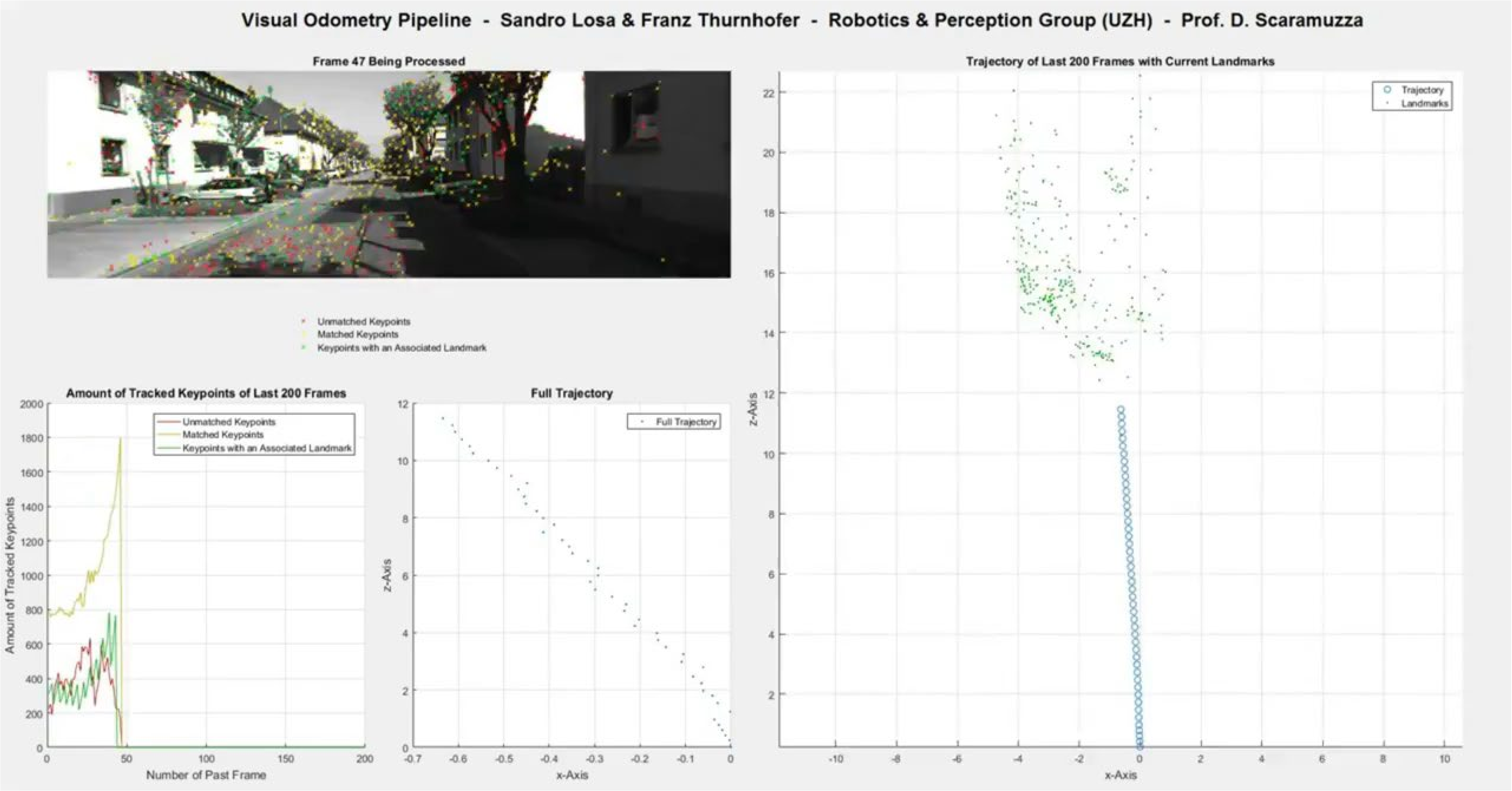


Building blocks of visual odometry along with information flow

Exercises

- **Bring your own laptop**
- Have **Matlab** pre-installed!
  - **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/2021/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). Example exam questions will be posted during the course.
  - Exam date: **January 13, 2022 from 08:00 to 10:00 in person** unless changed by UZH
  - **Closed-book exam**
  - **Details about the exam will be provided during the course**

- **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** (C++ or Python 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 09.01.2022.
  - **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

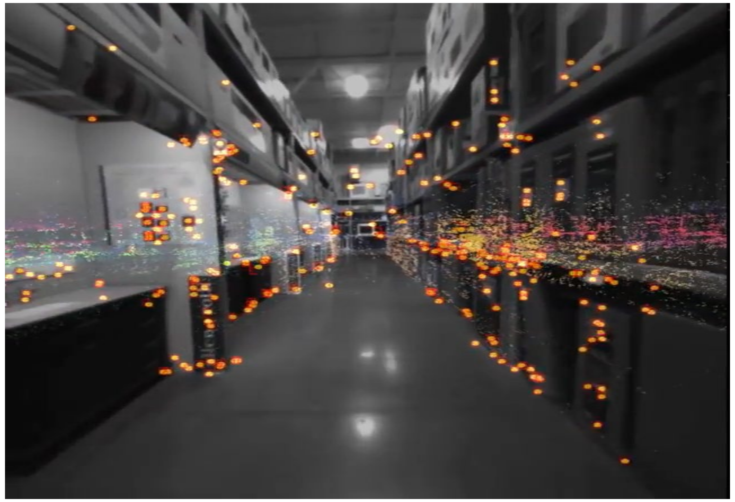
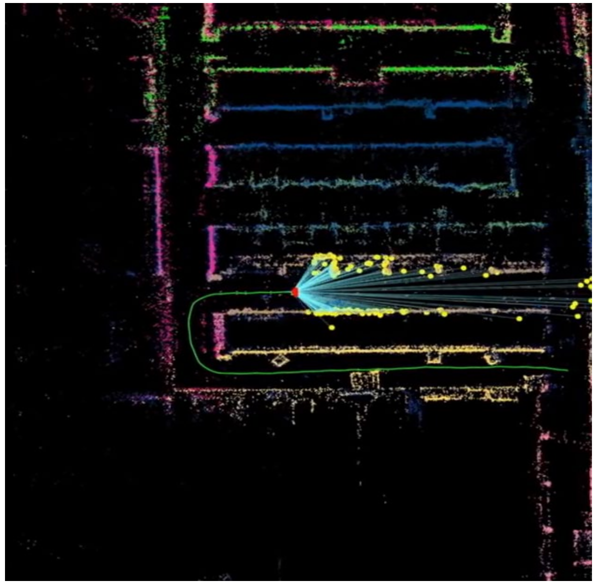


Image sequence (or video stream)
from one or more cameras attached to a moving vehicle

output



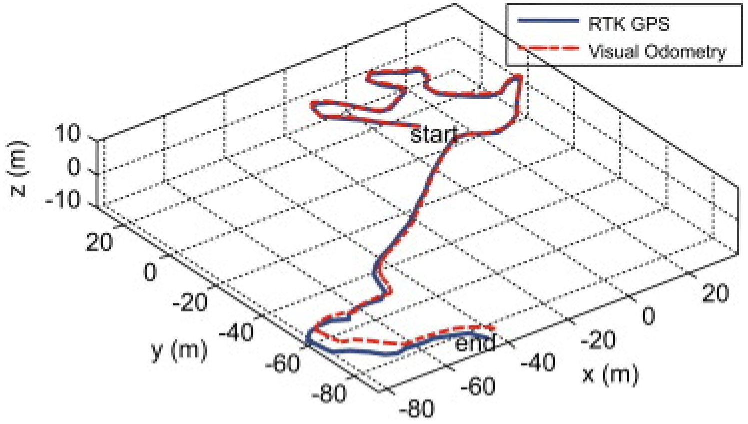
$R_0, R_1, \dots, R_i$

$t_0, t_1, \dots, t_i$

Camera trajectory (3D structure is a plus)

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

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- **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**

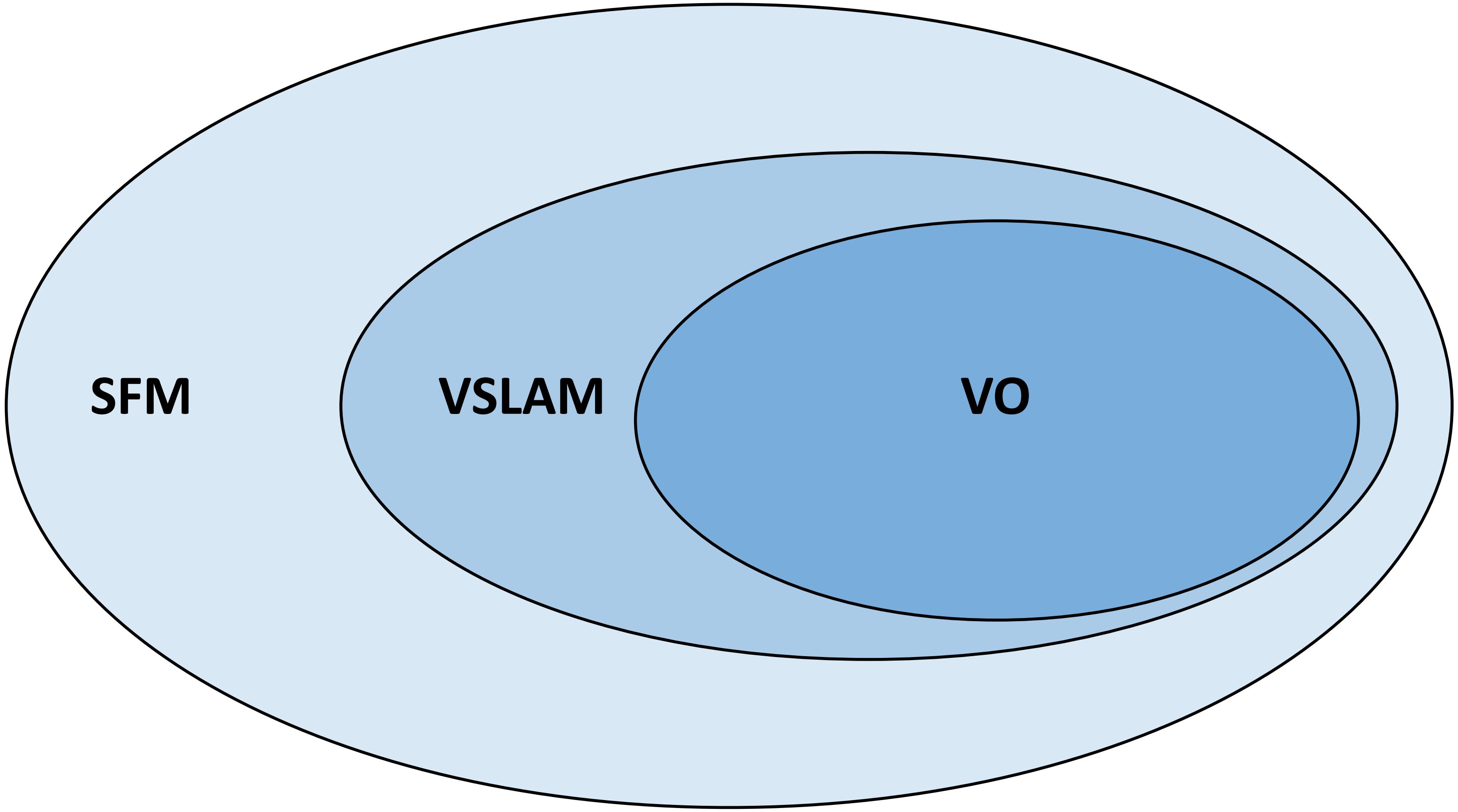
More about history and tutorials

- 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

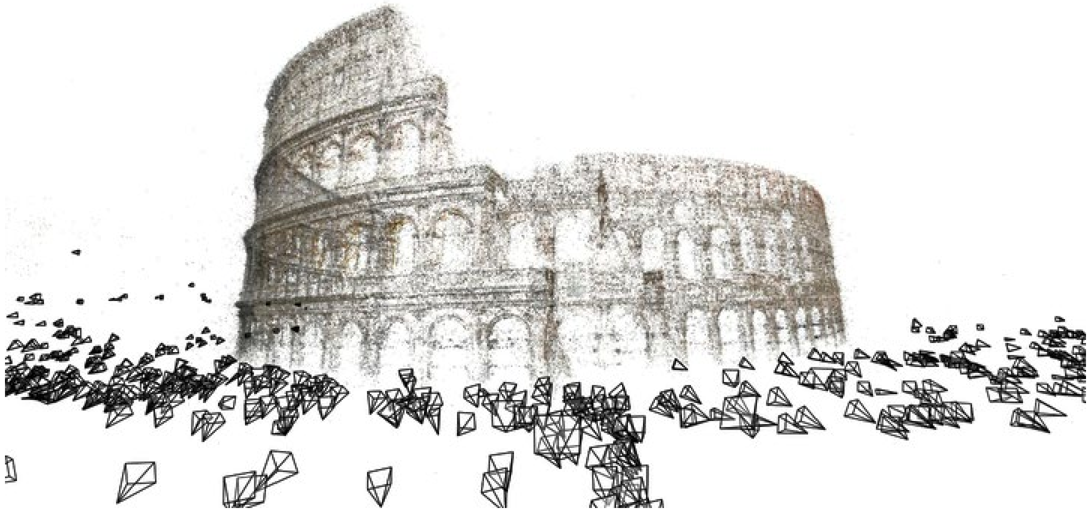
- C. Cadena, L. Carlone, H. Carrillo, Y. Latif, D. Scaramuzza, J. Neira, I.D. Reid, J.J. Leonard, **Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age**, *IEEE Transactions on Robotics*, Vol. 32, Issue 6, 2016. PDF

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

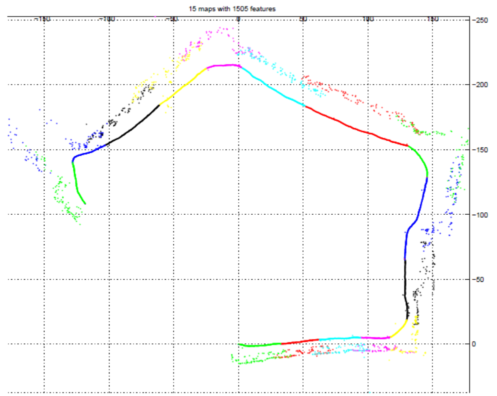
VO vs SFM

- 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**

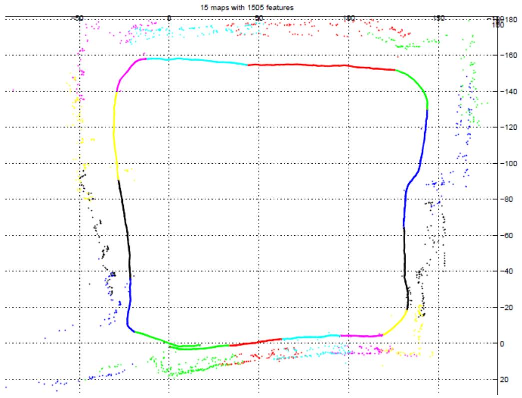
VO vs. Visual SLAM

- **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

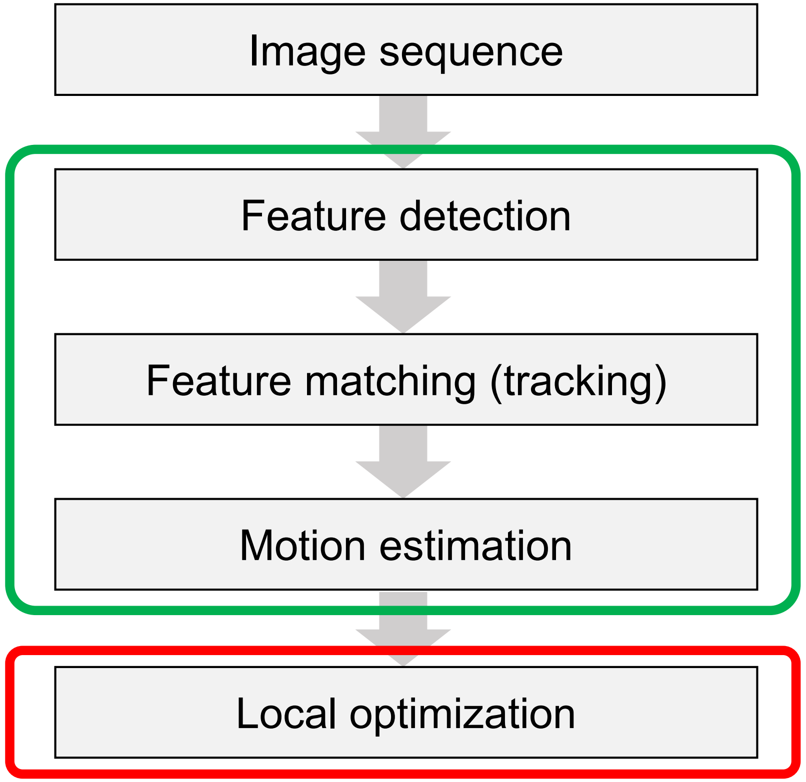


Visual SLAM

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

VO Flow Chart

- VO computes the camera path incrementally (pose after pose)



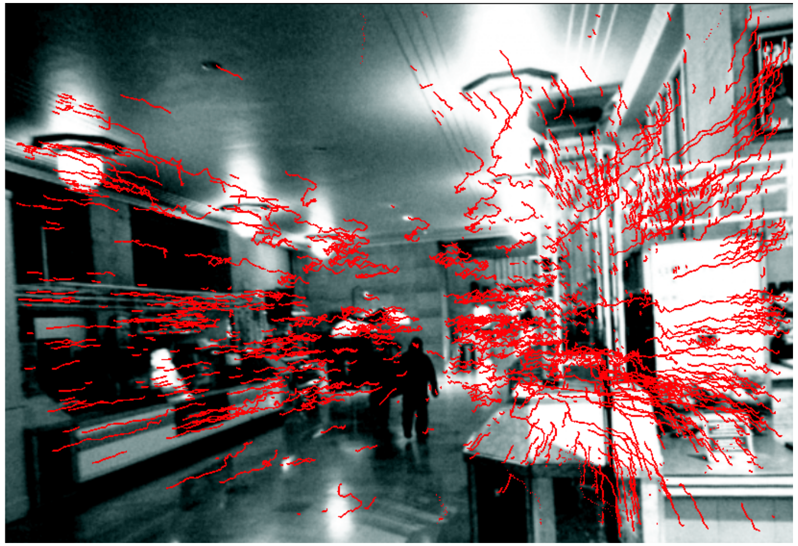
Front-end: outputs the *relative pose* between the *last two frames*

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 (tracking)
↓
Motion estimation
↓
Local optimization

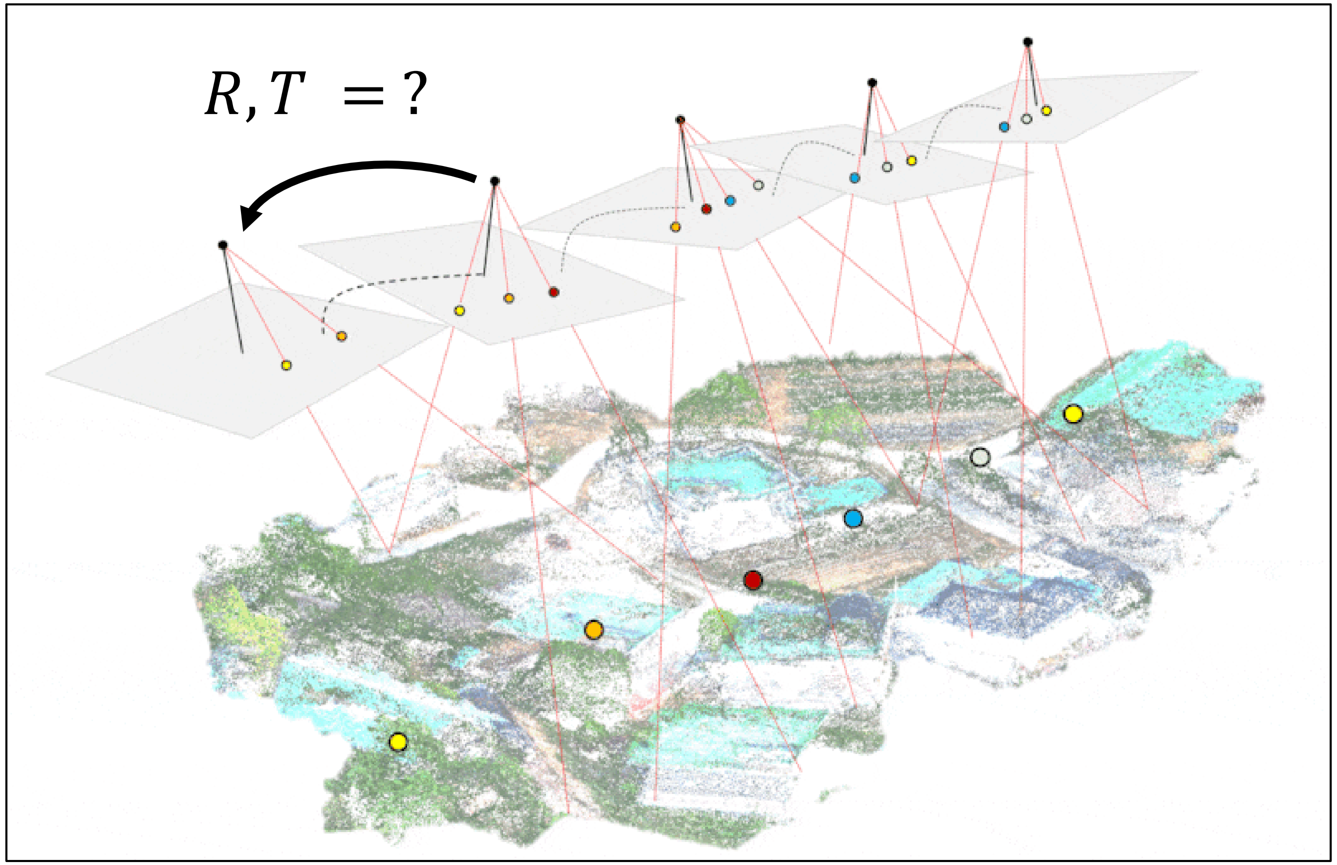


Features tracked over multiple recent frames overlaid on the last frame

VO Flow Chart

- VO computes the camera path incrementally (pose after pose)

Image sequence
↓
Feature detection
↓
Feature matching (tracking)
↓
Motion estimation
↓
Local optimization



VO Flow Chart

- VO computes the camera path incrementally (pose after pose)

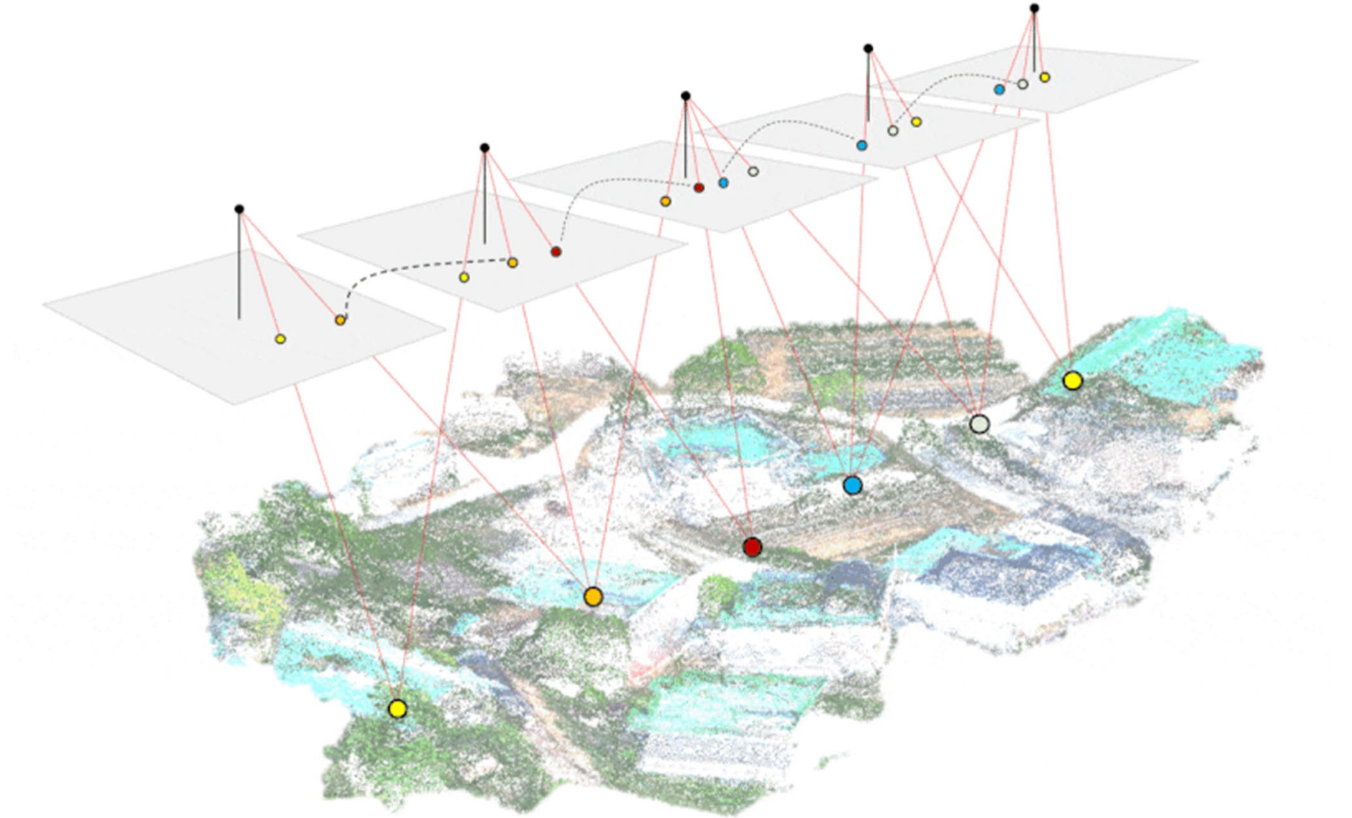
Image sequence

Feature detection

Feature matching (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
- Visual inertial fusion
- Event-based Vision

Course Topics

- Principles of image formation
  - Perspective projection
  - Camera calibration

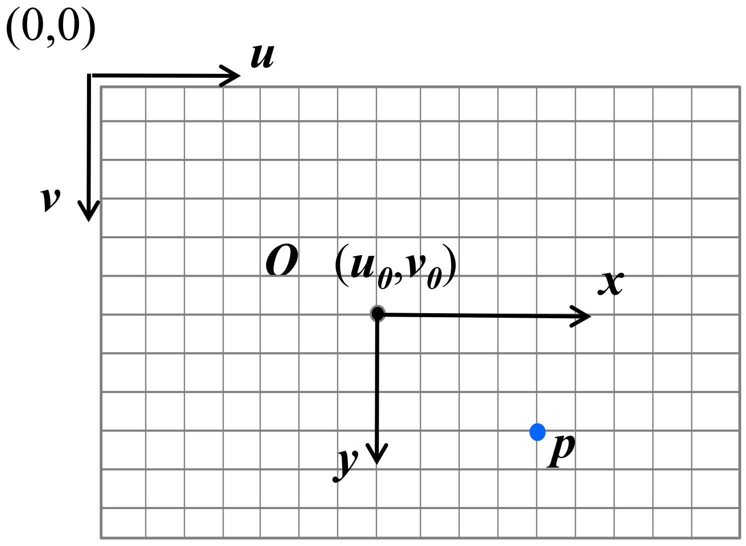


Image plane

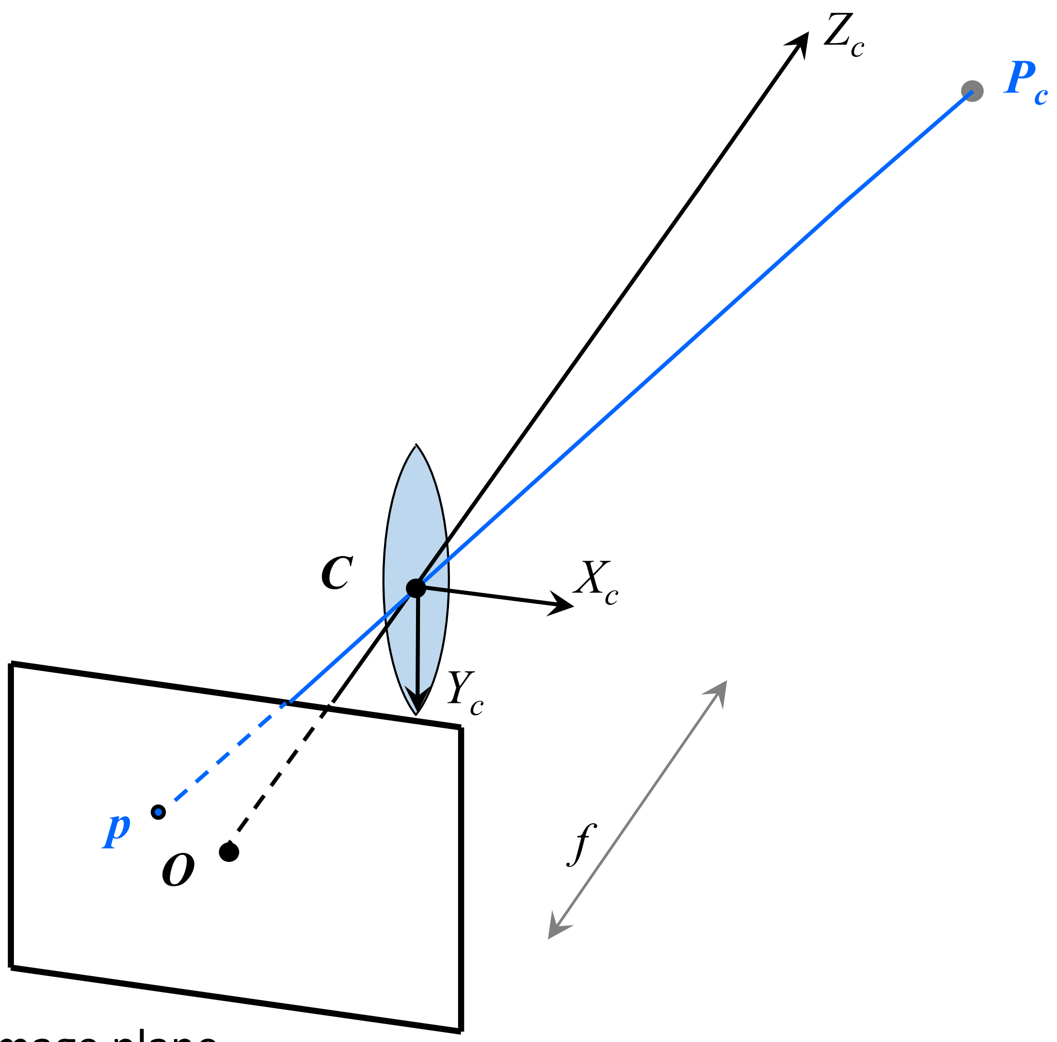
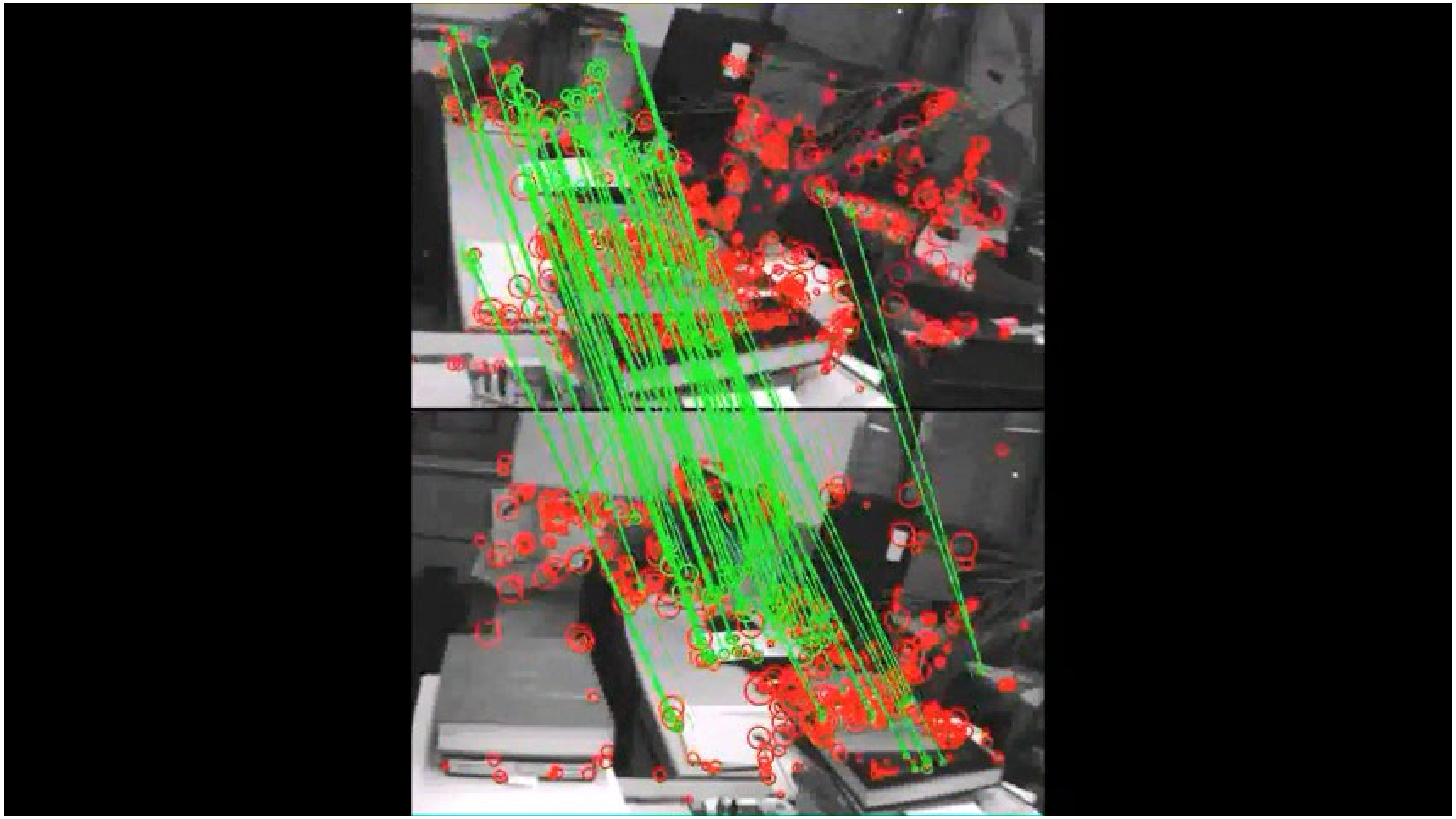


Image plane

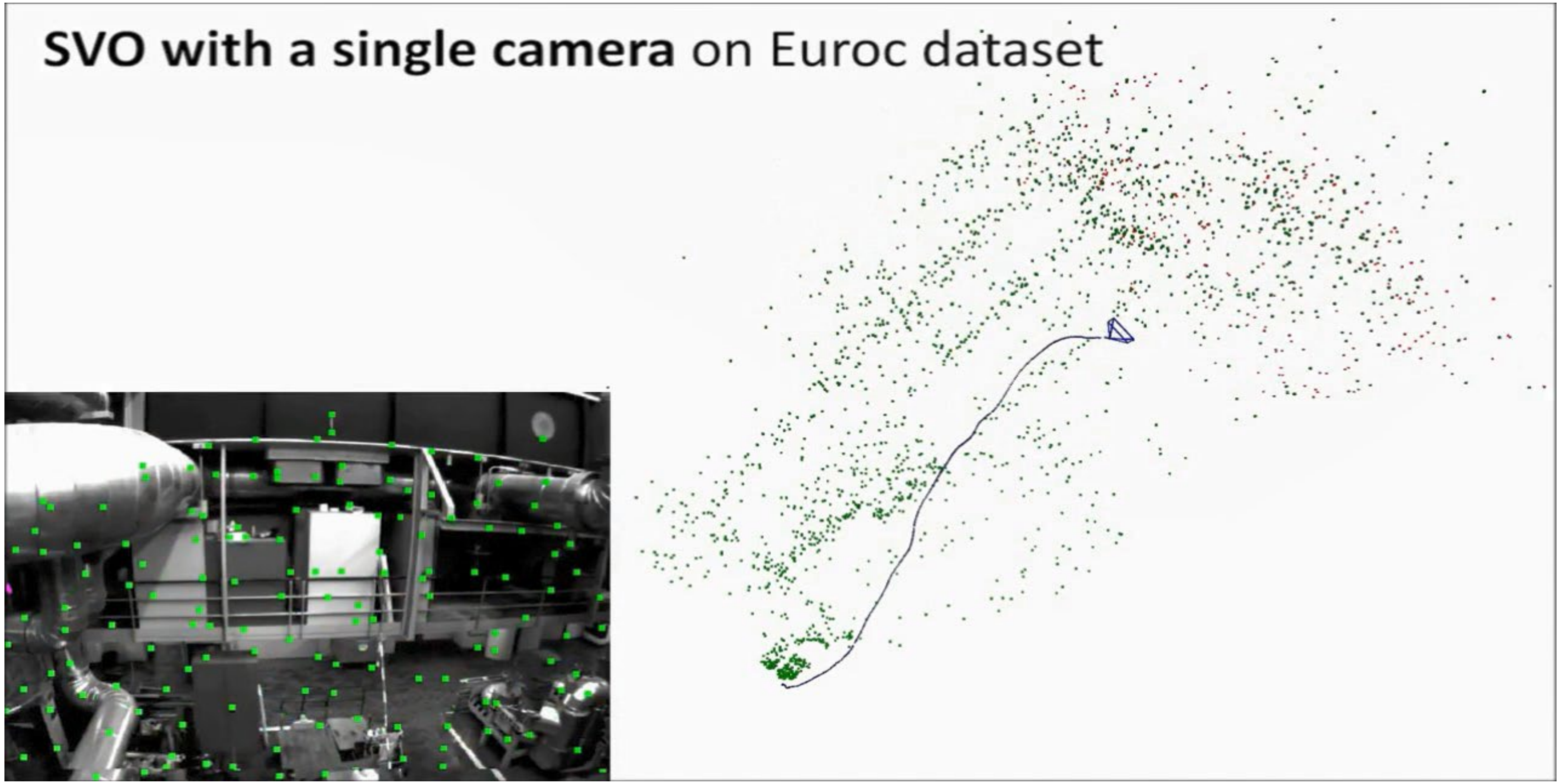
Course Topics

- Feature detection and matching



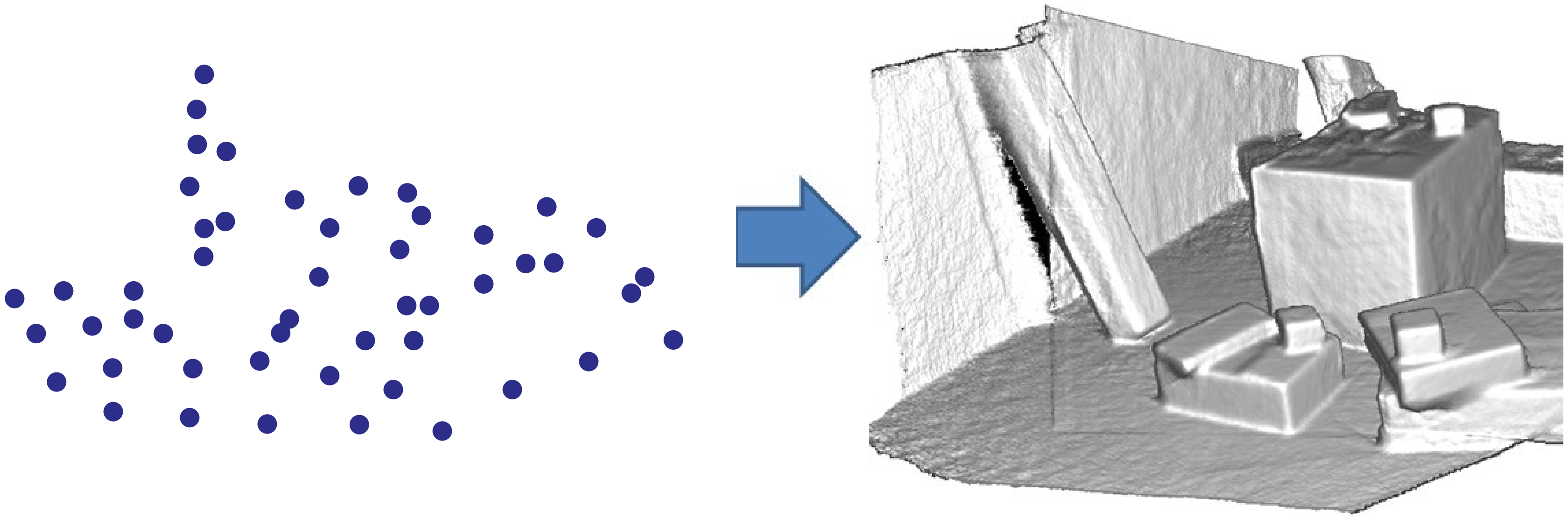
Course Topics

- Multi-view geometry and sparse 3D reconstruction



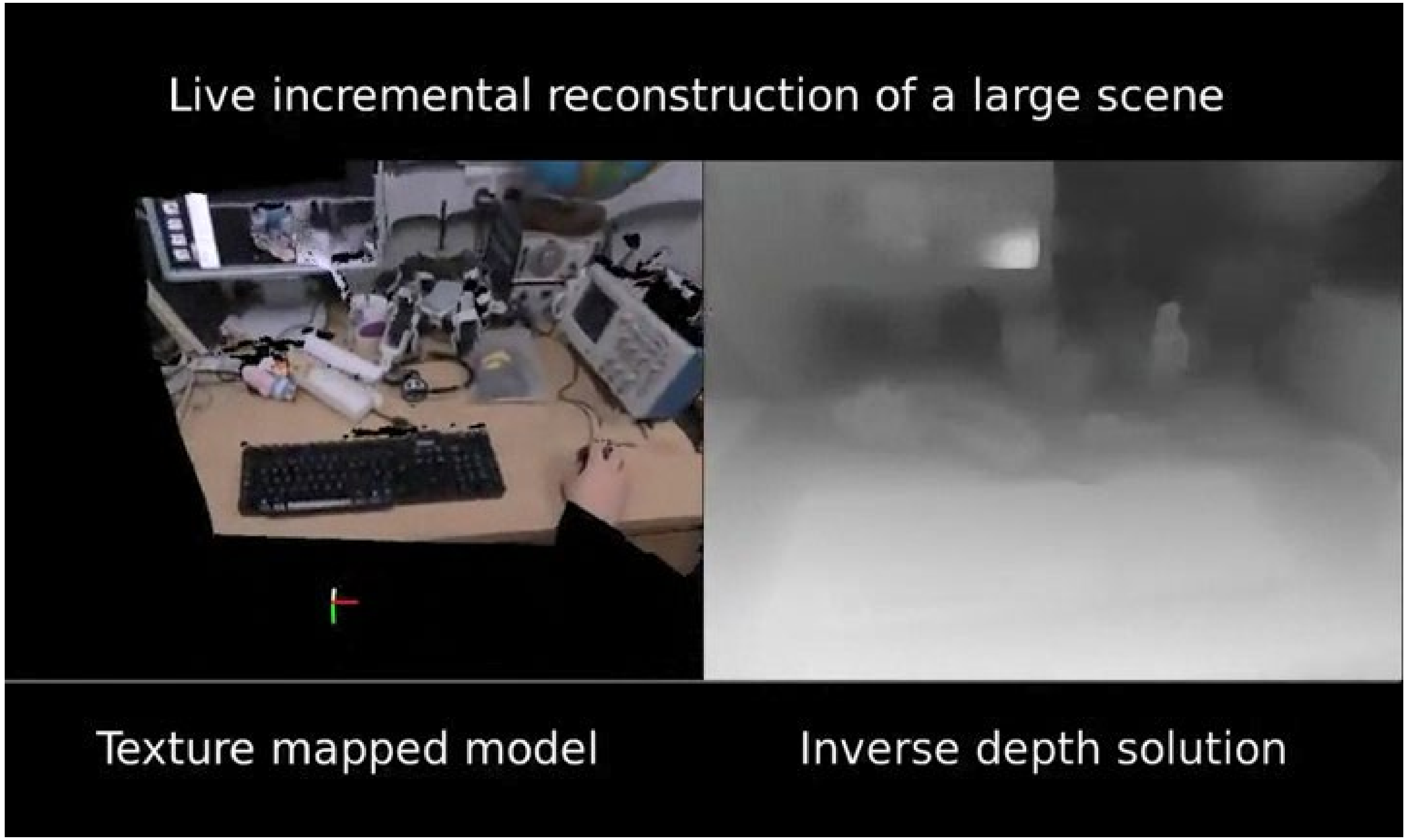
Course Topics

- Dense 3D reconstruction



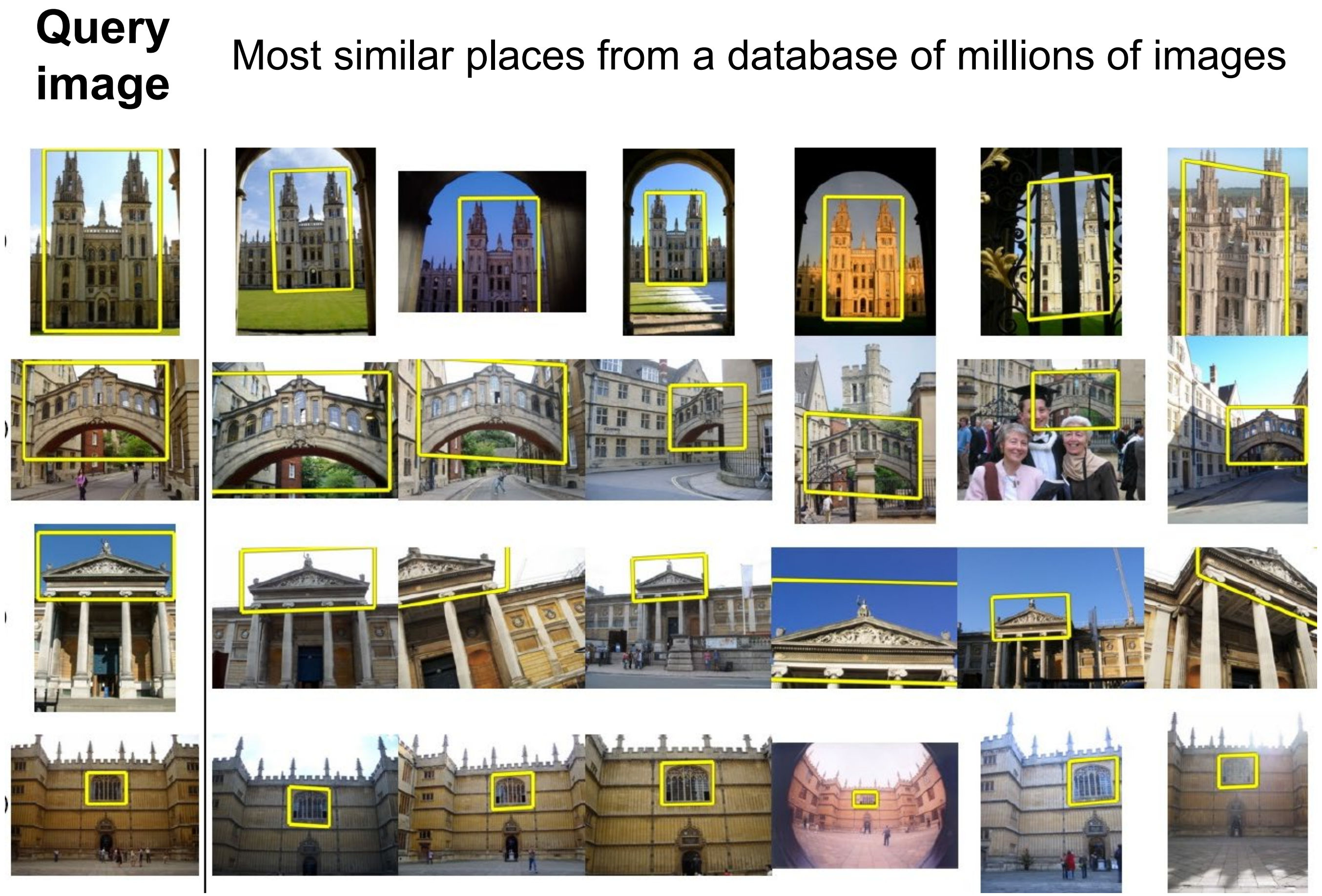
Course Topics

- Dense 3D reconstruction



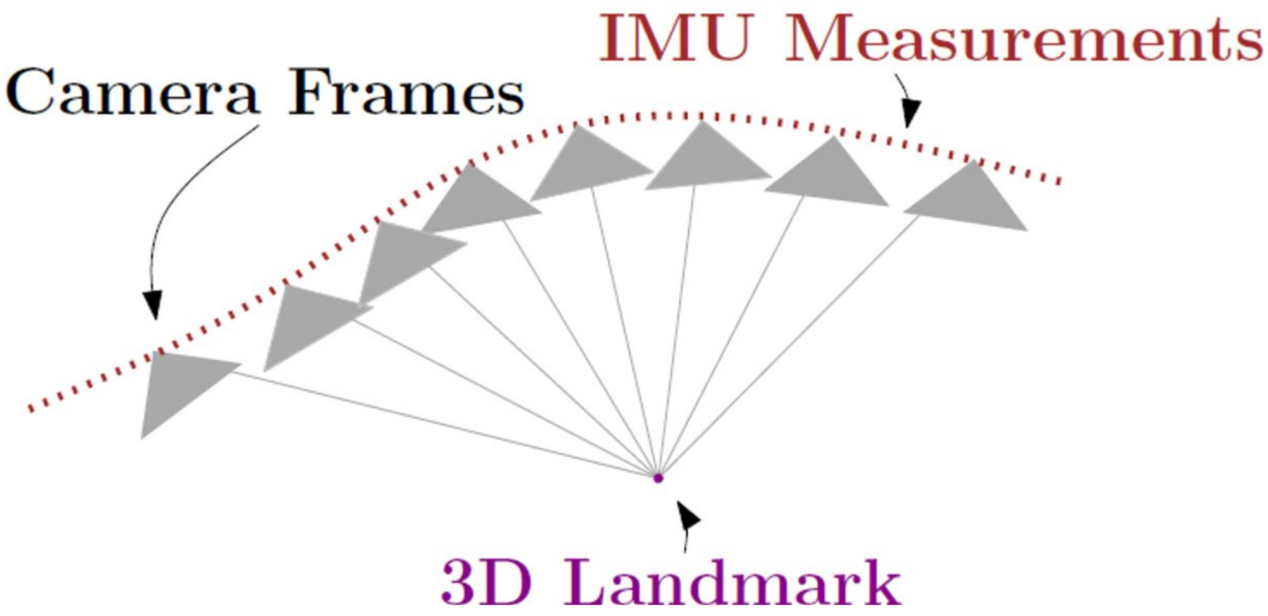
Course Topics

- Place recognition



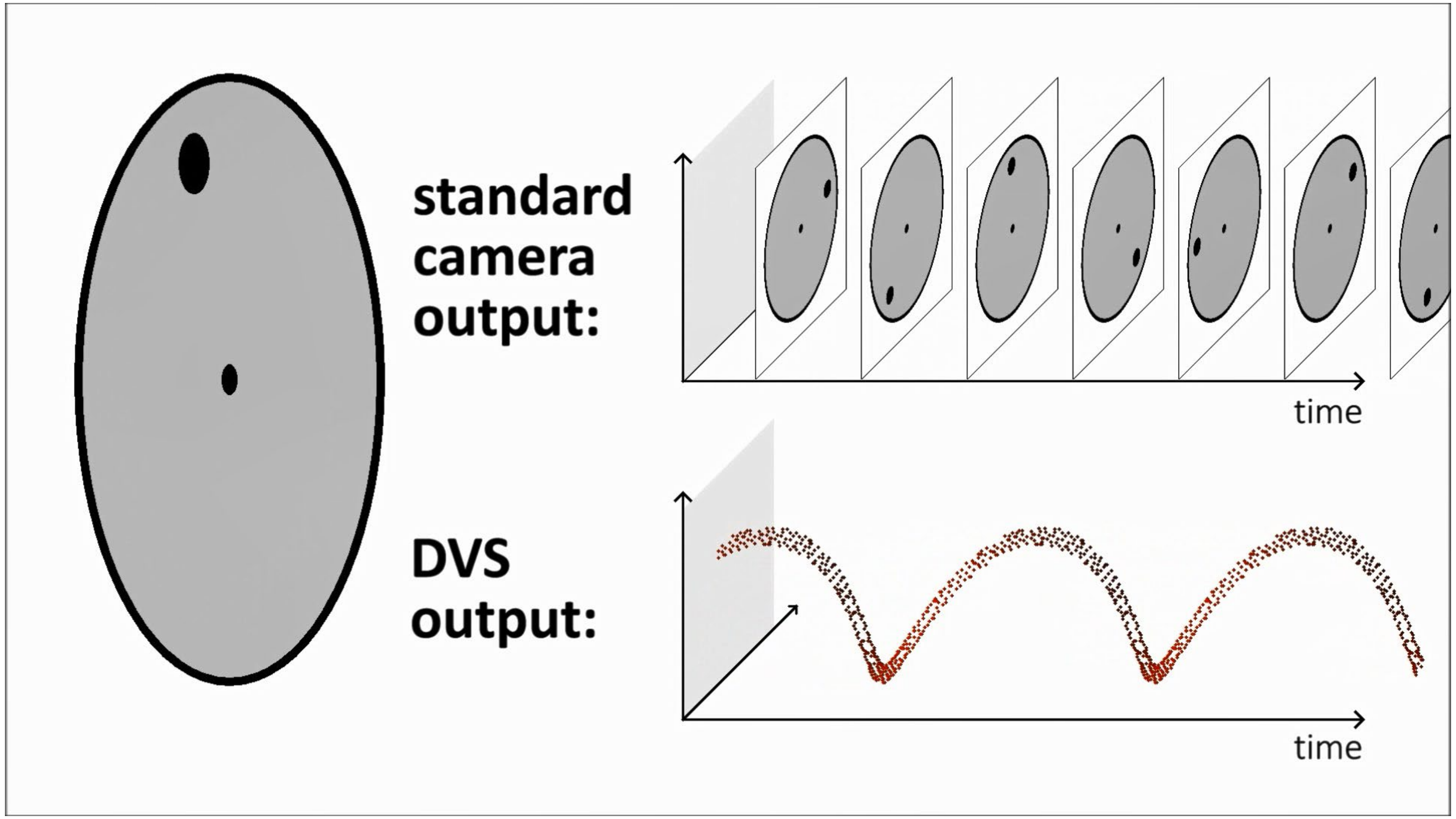
Course Topics

- Visual-inertial fusion

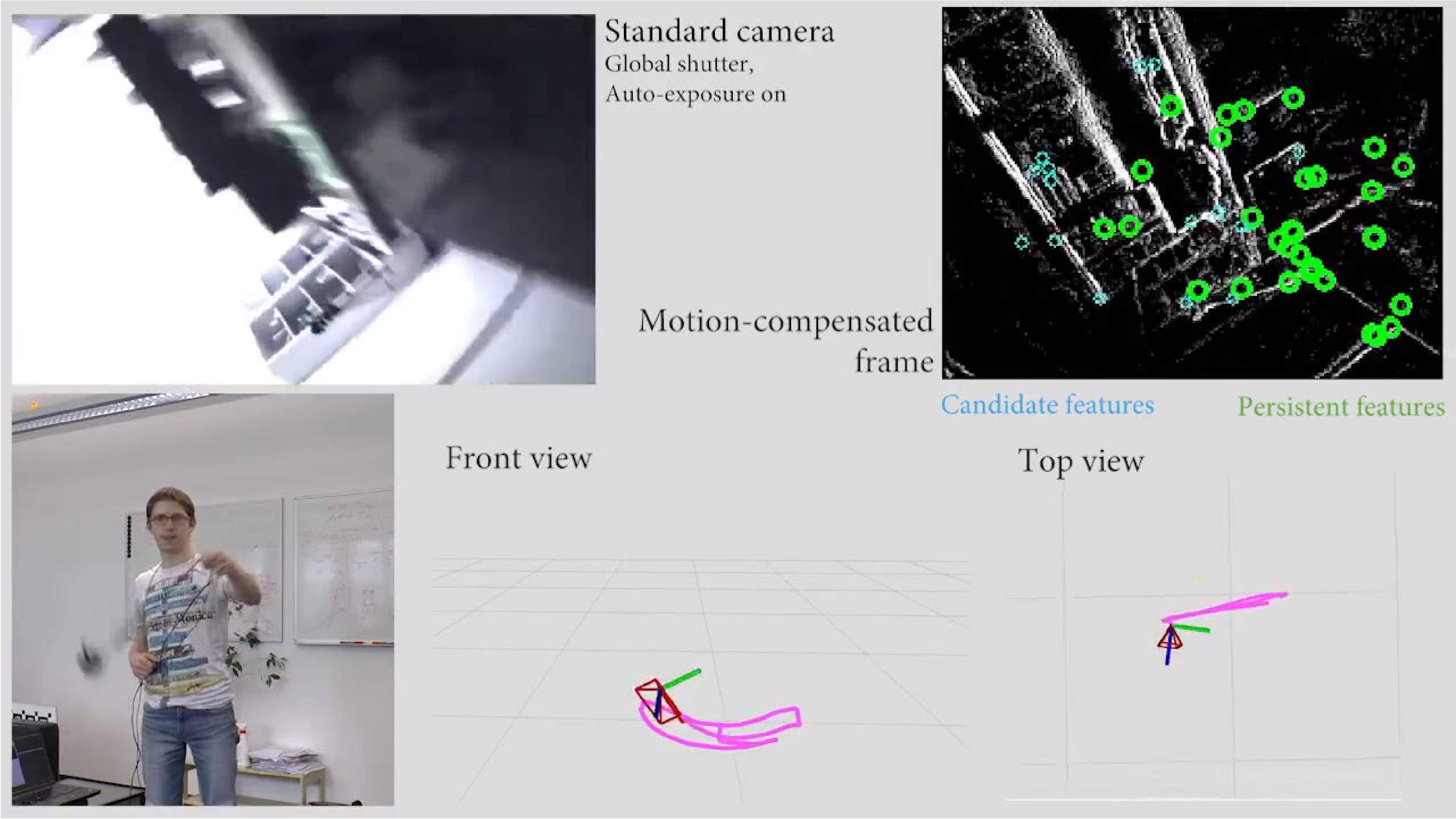


Course Topics

- 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]().

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?