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

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](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

Collaboration with NASA/JPL for future Mars missions

Read the details on this Swissinfo article
Startup: “Zurich-Eye” – Today: Facebook-Oculus Zurich

• Vision-based Localization and Mapping systems for mobile robots
Startup: “Zurich-Eye” – Today: Facebook-Oculus Zurich

• Vision-based Localization and Mapping systems for mobile robots
• In 2018, Zurich-Eye launched Oculus Quest (2 million units sold so far)
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](http://www.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 $220 \times 135$ 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.”

Why is vision hard?

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

What we see

What a computer sees
Origins of computer vision


- He is the inventor of ARPANET, the current Internet
Origins of computer vision


- 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
Computer Vision vs Computer Graphics

Images \[\rightarrow\] Computer Vision \[\rightarrow\] Model

Computer Graphics \[\leftarrow\]

Inverse problems: analysis and synthesis.
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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

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

Skydio and DJI Drones

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

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/Ncl6fJOzBsU](https://youtu.be/Ncl6fJOzBsU)
Perseverance Descent via Vision-based Terrain Relative Navigation

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

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[http://rpg.ifi.uzh.ch/people.html](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
• Room: SOC-F-106, Rämistrasse 69, 8001 Zurich.

Exercises:
• **12:15 to 13:45**: Starting from Sep. 30 (2nd 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](http://rpg.ifi.uzh.ch/teaching.html)

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

- **Schedule, lecture slides, exercise download, mini projects, course info** on the official course website: [http://rpg.ifi.uzh.ch/teaching.html](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](https://lms.uzh.ch/auth/RepositoryEntry/17073865591)

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


• **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:**
  • *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
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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.
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**
More about history and tutorials


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


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)

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](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

$R, T = ?$
VO Flow Chart

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

1. Image sequence
2. Feature detection
3. Feature matching (tracking)
4. Motion estimation
5. 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
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

Query image | Most similar places from a database of millions of images
Course Topics

• Visual-inertial fusion
Course Topics

• Event cameras
Application of event cameras: high-speed VO

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?