Computer Vision II: Multiple View Geometry (IN2228)

Chapter 00 Introduction

Dr. Haoang Li

19 April 2023 12:00-13:30

Outline

- Course Information
- Concepts of Multiple View Geometry
- Applications of Multiple View Geometry
- Overview of Course Content

Course Information

➢ Instructors

Lecturer: Haoang Li
- Office: 02.09.057
- Email: Haoang.Li@tum.de

For an office visit, making an appointment beforehand is recommend.

Teaching Assistants:

Sergei Solonets
- Office: 02.09.059
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Daniil Sinitsyn
- Office: 02.09.059
- Email: Daniil.Sinitsyn@tum.de

Viktoria Ehm
- Office: 02.09.033
- Email: Viktoria.Ehm@tum.de

Course Information

- ➢ Lectures

First Class (90 minutes)

- Time: every Wednesday from 12:00 to 13:30
- Room: 102, Hörsaal 2, "Interims I" (5620.01.102)
- 5-minute break

Second Class (45 minutes)

- Time: every Thursday from 11:00 to 11:45
- Room: 00.02.001, MI HS 1, Friedrich L. Bauer Hörsaal (5602.EG.001)

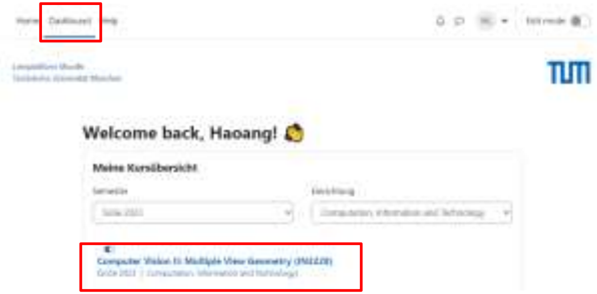
- ➢ Exercises (120 minutes)

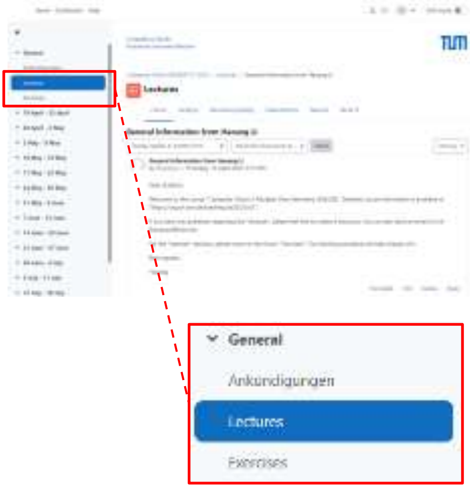
- Time: Wednesday from 16:00 to 18:00 (not every week)
- Room: 102, Hörsaal 2, "Interims I" (5620.01.102)
- Detailed schedule will be provided later

Course Information

- ➢ Lecture (90+45 minutes)

Ask questions or provide suggestions via Moodle
https://www.moodle.tum.de/mod/forum/





Course Information

➢ Tentative Lecture Schedule

For updates, slides, and additional materials:
https://cvg.cit.tum.de/teaching/ss2023/cv2

90-minute course; 45-minute course

Foundation

Wed 19.04.2023 Chapter 00: Introduction
Thu 20.04.2023 Chapter 01: Mathematical Background

Wed 26.04.2023 Chapter 02: Motion and Scene Representation (Part 1)
Thu 27.04.2023 Chapter 02: Motion and Scene Representation (Part 2)

Wed 03.05.2023 Chapter 03: Image Formation (Part 1)
Thu 04.05.2023 Chapter 03: Image Formation (Part 2)

Wed 10.05.2023 Chapter 04: Camera Calibration
Thu 11.05.2023 Chapter 05: Correspondence Estimation (Part 1)

Wed 17.05.2023 Chapter 05: Correspondence Estimation (Part 2)
Thu 18.05.2023 No lecture

Core part

Wed 24.05.2023 Chapter 06: 2D-2D Geometry (Part 1)
Thu 25.05.2023 Chapter 06: 2D-2D Geometry (Part 2)

Wed 31.05.2023 Chapter 06: 2D-2D Geometry (Part 3)
Thu 01.06.2023 Chapter 07: 3D-2D Geometry (Part 1)

Wed 07.06.2023 Chapter 07: 3D-2D Geometry (Part 2)
Thu 08.06.2023 No lecture

Wed 14.06.2023 Chapter 08: 3D-3D Geometry (Part 1)
Thu 15.06.2023 Chapter 08: 3D-3D Geometry (Part 2)

Wed 21.06.2023 Chapter 09: Single-view Geometry (Part 1)
Thu 22.06.2023 Chapter 09: Single-view Geometry (Part 2)

Wed 28.06.2023 Chapter 10: Bundle Adjustment and Optimization (Part 1)
Thu 29.06.2023 Chapter 10: Bundle Adjustment and Optimization (Part 2)

Advanced topics and high-level task

Wed 05.07.2023 Chapter 11: Robot Estimation
Thu 06.07.2023 Chapter 12: Photometric Error

Wed 12.07.2023 Chapter 13: SLAM and SFM (Part 1)
Thu 13.07.2023 Chapter 13: SLAM and SFM (Part 2)

Wed 19.07.2023 Chapter 14: Advanced Topics (Part 1)
Thu 20.07.2023 Chapter 14: Advanced Topics (Part 2)

Course Information

➢ Tentative Exercise Schedule

- ✓ Please note that exercise sessions may be re-scheduled depending on the course progress.
- ✓ Details of content will be provided by our teaching assistants.

Wed 26.04.2023 Exercise 1: Mathematical Background

Wed 03.05.2023 Exercise 2: Mathematical Background

Wed 10.05.2023 Exercise 3: Representing a Moving Scene

Wed 24.05.2023 Exercise 4: Perspective Projection

Wed 31.05.2023 Exercise 5: Lucas-Kanade Method

Wed 14.06.2023 Exercise 6: Reconstruction from two views

Wed 21.06.2023 Exercise 7: Reconstruction from multiple views

Wed 05.07.2023 Exercise 8: Direct Image Alignment

Wed 12.07.2023 Exercise 9: Direct Image Alignment

Teaching assistants will design 5-6 coding assignments on C++ or Python.

Course Information

➢ References

Course

- "Computer Vision II" provided by Prof. Daniel Cremers

Materials: https://cvg.cit.tum.de/teaching/ss2022/mvg2022
Video: https://www.youtube.com/playlist?list=PLTBdjV_4f-EJn6udZ34tht9EVIW7lbeo4

Prof. **Daniel Cremers**
(on sabbatical at
Oxford University)

	Knowledge	Formal Mathematical Definitions	Intuitive Illustrations
Prof. Cremers	✓	✓	
This year	✓✓		✓

- "Vision Algorithms for Mobile Robotics" provided by Prof. Davide Scaramuzza

Materials: https://rpg.ifi.uzh.ch/teaching.html

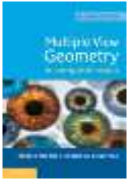
Course Information

➢ References

Book

- “Multiple View Geometry in Computer Vision”: R. Hartley and A. Zisserman

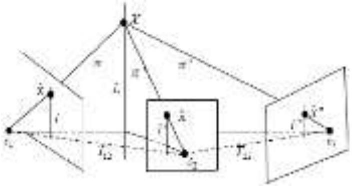
Link: https://www.robots.ox.ac.uk/~vgg/hzbook/



- “An Invitation to 3D Vision”: Y. Ma, S. Soatto, J. Kosecka, S.S. Sastry

Link: https://www.eecis.udel.edu/~cer/arv/readings/old_mkss.pdf

Treat them as further reading for
- Formal definition and rigorous derivation
- Additional knowledge



Trifocal tensor

Course Information

➢ Acknowledgement

Source of figures, tables, and videos

✓ Internet, e.g., Youtube

✓ Academic papers

✓ This course partly refers to the slides of the following courses:

- University of Zurich “Vision Algorithms for Mobile Robotics”
- University of Washington “Computer Vision”

…

Course Information

➢ Prerequisite Course and Knowledge

There is not a mandatory requirement that you should take a certain prerequisite course.

Some recommendations

✓ TUM course “Computer Vision I: Variational Methods”

- Desirable but not essential

Link: https://cvg.cit.tum.de/teaching/online/cvvm

✓ Any “Advanced Mathematics” and “Linear Algebra” courses

Course Information

➢ Prerequisites Knowledge

✓ **Linear Algebra** and **Matrix Calculus**

- Necessary (will be reviewed)
- Reference: “Linear Algebra Primer” from Stanford University

Link: http://vision.stanford.edu/teaching/cs131_fall1617/lectures/lecture2_linalg_review_cs131_2016.pdf

✓ **Image Processing**

- Desirable but not essential
- Reference: “Digital Image Processing”: R. C. Gonzalez and R. E. Woods

Link: http://sdeuoc.ac.in/sites/default/files/sde_videos/Digital%20Image%20Processing%203rd%20ed.%20-%20R.%20Gonzalez%2C%20R.%20Woods-ilovepdf-compressed.pdf

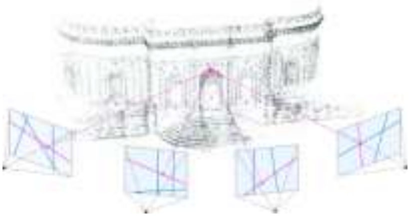
Course Information

➢ Learning Objectives

✓ To understand the concepts and knowledge for recovering 3D shape from images

✓ Explore classical and state-of-the-art approaches in multiple view geometry

✓ Implement fundamental multiple view geometry algorithms in person



Our ultimate goal

Course Information

➢ Grading

The final grade is based on **a final exam** and **assignment bonus**.

- For example, for a student whose grade on the final exam is 1.3. If he/she obtained the bonus, his/her final grade is 1.0.

Exam

- Written and closed-book exam
- Details about the exam and example exam questions will be provided during the course

Assignment bonus (optional)

- There will be 5-6 coding assignments.
- If **all** the assignment codes submitted by a student 1) pass the automatic checking system, and also 2) meet the evaluation standard, the student will obtain a bonus of 0.3. There is not a partial bonus, e.g. 0.1.
- Evaluation standard is defined by our teaching assistants.

Concepts of Multi-view Geometry

- Computer Vision

Automatic extraction of “meaningful” information from images and videos

Semantic information

Geometric information

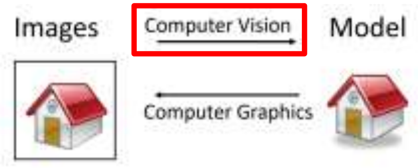
This course

Course “Computer Vision III: Detection, Segmentation and Tracking” provided by Dr. Nikita Araslanov

Concepts of Multi-view Geometry

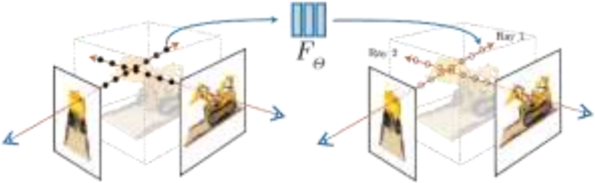
➢ Computer Vision vs Computer Graphics

Previous:



Inverse problems

Now:



A representative of combination: NeRF [1]

[1] Ben Mildenhall*, Pratul P. Srinivasan*, Matthew Tancik*, Jonathan T. Barron, Ravi Ramamoorthi, and Ren Ng, “NeRF Representing Scenes as Neural Radiance Fields for View Synthesis”, In ECCV, 2020. (Best Paper Honorable Mention)

Concepts of Multi-view Geometry

➢ Journals and Conferences in Computer Vision/Robotics

What papers should you read? Why do you need to read papers?

Journals:
- International Journal of Computer Vision (IJCV)
- IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI)
- International Journal of Robotics Research (IJRR)
- IEEE Transactions on Robotics (TRO)

…

Conferences:
- IEEE International Conference on Computer Vision (ICCV)
- IEEE Computer Vision and Pattern Recognition Conference (CVPR)
- European Conference on Computer Vision (ECCV)
- IEEE International Conference on Robotics and Automation (ICRA)
- IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)

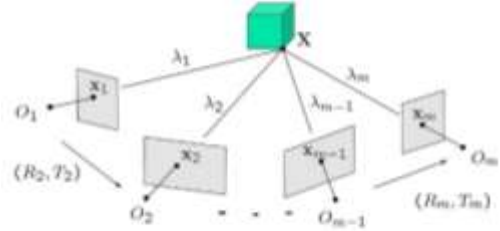
…

Relatively high quality in general

Concepts of Multi-view Geometry

➢ Multi-view Geometry

✓ A field studying the relationship between cameras, 3D structure, and image features when there are feature correspondences between images taken from varying viewpoints.
✓ The image features are usually feature points or lines.



Point case

Line case

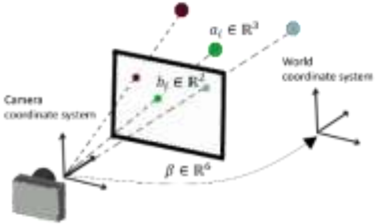
Concepts of Multi-view Geometry

➢ Multi-view Geometry

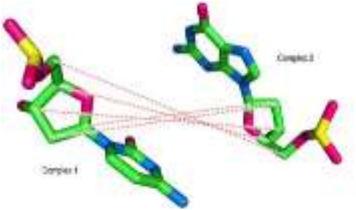
Terminology Definition or Differentiation

✓ 2D-2D, 3D-2D, and 3D-3D correspondences

2D-2D correspondences



3D-2D correspondences



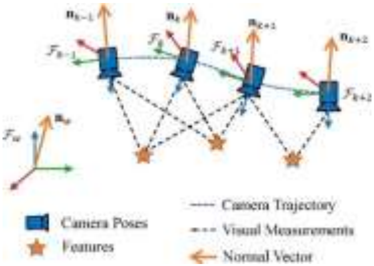
3D-3D correspondences

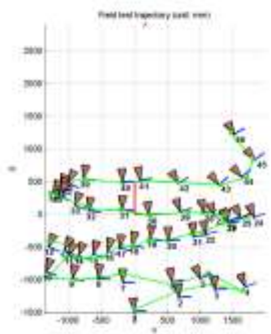
Concepts of Multi-view Geometry

➢ Multi-view Geometry

Terminology Definition or Differentiation

✓ Camera position, camera pose, and camera trajectory





Applications of Multi-view Geometry

- Virtual Reality (VR)/Augmented Reality (AR)

Estimate the pose of the head/glasses

Tracked 2D-2D correspondences

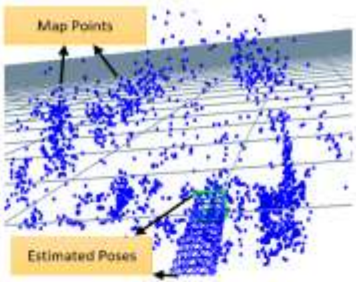
Applications of Multi-view Geometry

- Virtual Reality (VR)/Augmented Reality (AR)

A demo video

Applications of Multi-view Geometry

- Autonomous Driving



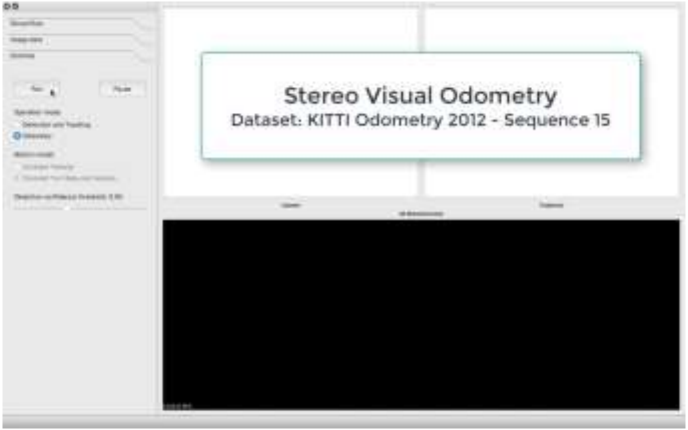
3D map and camera trajectory

Tracked 3D-2D correspondences

Localize cars: 1) car collision warning, 2) lane departure warning, and 3) safety distance monitoring and warning

Applications of Multi-view Geometry

- Autonomous Driving

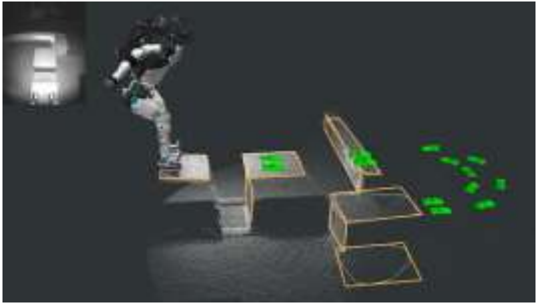


A demo video

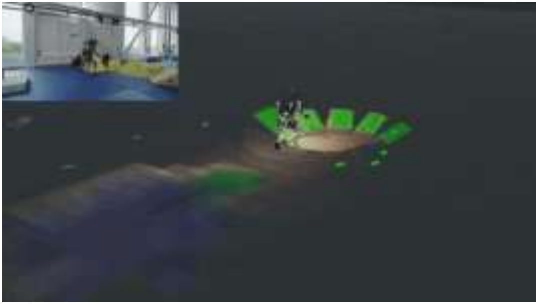
KITTI dataset (Karlsruhe Institute of Technology and Toyota Technological Institute)

Applications of Multi-view Geometry

- Humanoid Robot



Dense 3D map



Object-level completion

Localize the robot and reconstruct the 3D scene

Applications of Multi-view Geometry

- Humanoid Robot

A demo video of robot dog

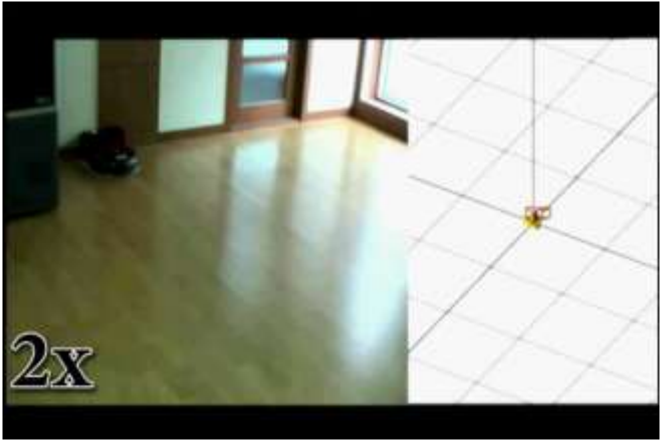
Applications of Multi-view Geometry

- Vacuum Cleaner

Navigate vacuum cleaner for path planning and obstacle avoidance

Applications of Multi-view Geometry

- Vacuum Cleaner

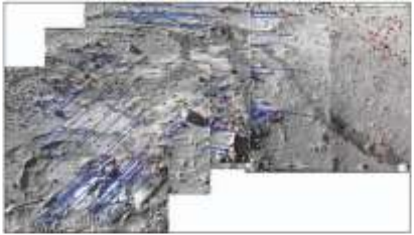


A demo video

Applications of Multi-view Geometry

- Mars Rovers

Landing



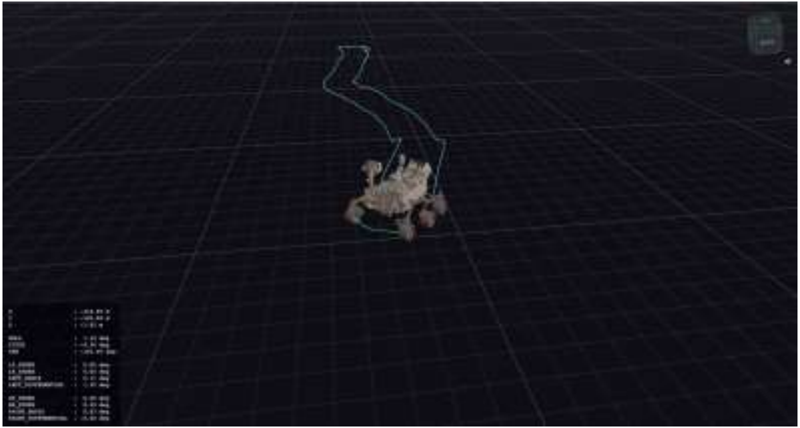
2D-2D correspondence

navigation

Improve the reliability of autonomous landing on Mars and autonomously navigate the robot.

Applications of Multi-view Geometry

- Mars Rovers

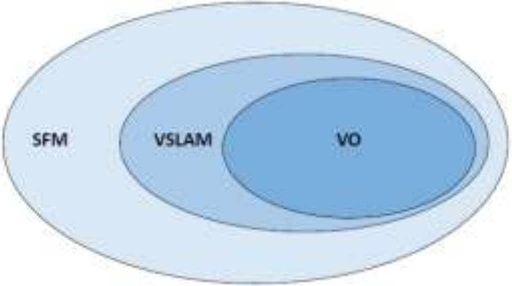


A demo video for navigation

Overview of Course Content

- From High Level

We will provide necessary knowledge used in Visual Odometry (VO), Visual Simultaneous Localization and Mapping (VSLAM), and Structure from Motion (SFM).



Relationship between VO, VSLAM, and SFM

Overview of Course Content

- From High Level

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

Sequential images from one or more cameras attached to a moving vehicle

Matched/tracked features

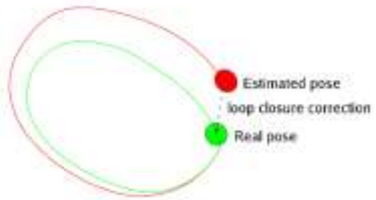
Camera trajectory (red) and 3D map (green)

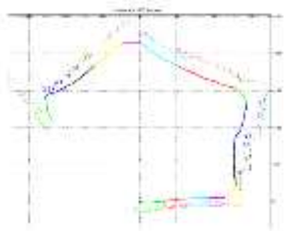
Overview of Course Content

- From High Level

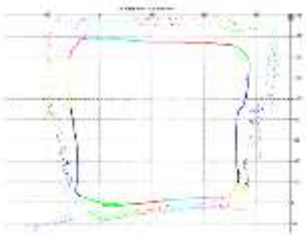
VSLAM = VO + **loop detection & closure**

- VO is affected by noise
- SLAM guarantees global consistency





Visual odometry



Visual SLAM

An example of loop detection and correction

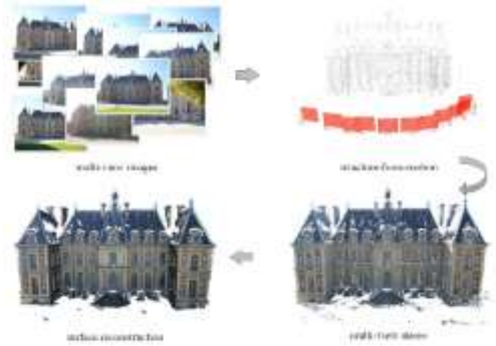
What if the loop does not exist?

Overview of Course Content

➢ From High Level

SFM is more general than SLAM and tackles the problem **from unordered image sets**.

Sparse reconstruction



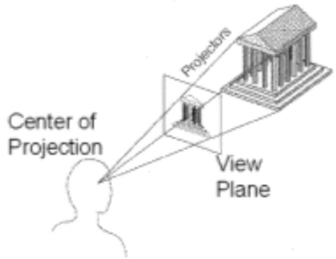
From sparse to dense reconstruction

Overview of Course Content

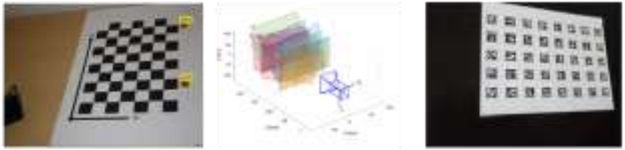
- From High Level

Image pair
↓
Feature detection
↓
Feature matching/tracking
↓
Camera pose estimation
↓
3D reconstruction
↓
Local optimization

Flow Chart of VO/VSLAM/SFM



Perspective projection



Camera calibration

Overview of Course Content

➢ From High Level

Image pair

↓

Feature detection

↓

Feature matching/tracking

↓

Camera pose estimation

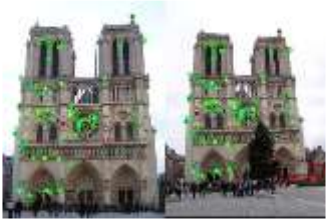
↓

3D reconstruction

↓

Local optimization

Flow Chart of VO/VSLAM/SFM



Feature detection

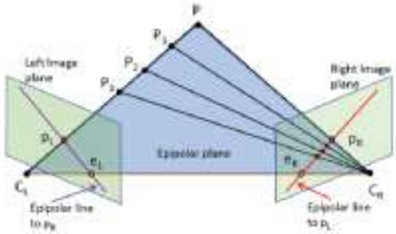
Feature matching

Overview of Course Content

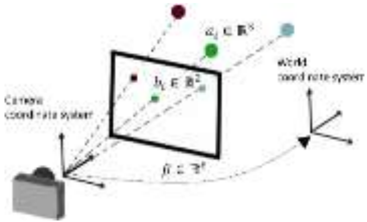
- From High Level

Image pair
↓
Feature detection
↓
Feature matching/tracking
↓
Camera pose estimation
↓
3D reconstruction
↓
Local optimization

Flow Chart of VO/VSLAM/SFM



Relative camera pose



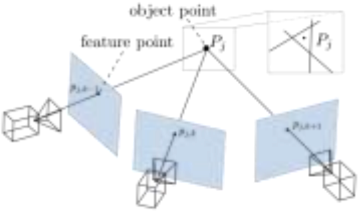
Absolute camera pose

Overview of Course Content

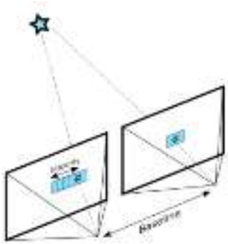
- From High Level

Image pair
↓
Feature detection
↓
Feature matching/tracking
↓
Camera pose estimation
↓
3D reconstruction
↓
Local optimization

Flow Chart of VO/VSLAM/SFM



Triangulation



Depth from Disparity

Overview of Course Content

- From High Level

Image pair

↓

Feature detection

↓

Feature matching/tracking

↓

Camera pose estimation

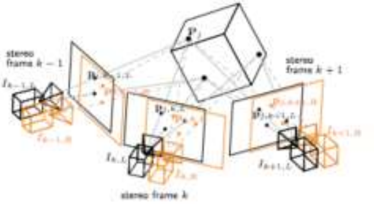
↓

3D reconstruction

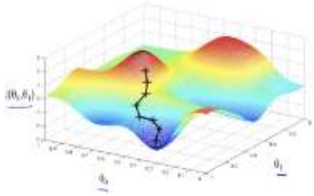
↓

Local optimization

Flow Chart of VO/VSLAM/SFM



Bundle Adjustment



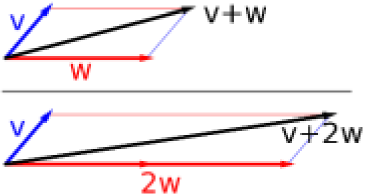
Optimization

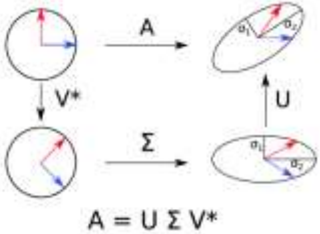
Overview of Course Content

➢ Knowledge to Learn

Chapter 01: Mathematical Backgrounds

- Vector operations, e.g., cross product and dot product
- Vector space, e.g., linear independence
- Matrix property, e.g., rank, trace, eigenvalue and eigenvectors
- Matrix decomposition, e.g.,., SVD



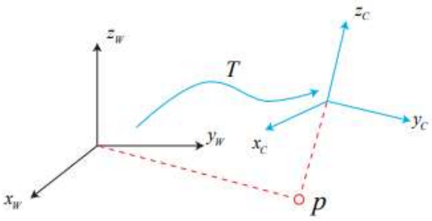


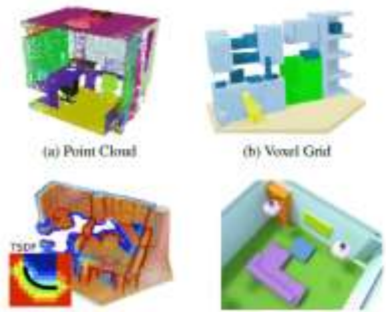
Overview of Course Content

➢ Knowledge to Learn

Chapter 02: Motion and Scene Representation

- Motion representation, e.g., rotation matrix
- Motion computation/operation, i.e., Lie group and Lie algebra
- 3D scene representation





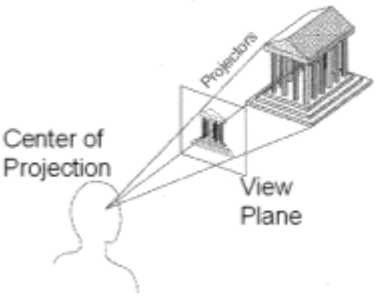
(a) Point Cloud (b) Voxel Grid (c) Implicit Surface (d) Mesh

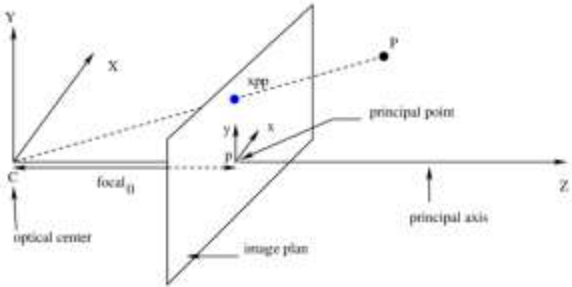
Overview of Course Content

➢ Knowledge to Learn

Chapter 03: Image Formation

- Pinhole camera model and perspective projection
- Image coordinates and homogenous coordinates



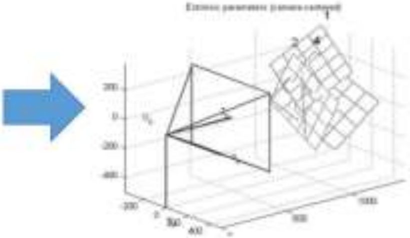


Overview of Course Content

➢ Knowledge to Learn

Chapter 04: Camera Calibration

- From 3D objects
- From planar grids

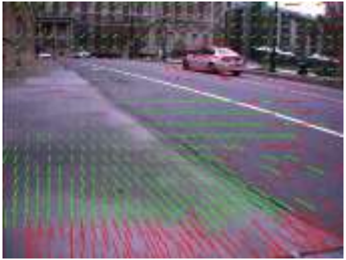


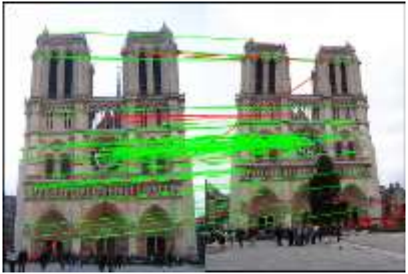
Overview of Course Content

➢ Knowledge to Learn

Chapter 05: Correspondence Estimation

- Small motion: Optical flow, e.g., Lucas-Kanade Method
- Wide baseline: Descriptor computation and matching, e.g., SIFT and ORB



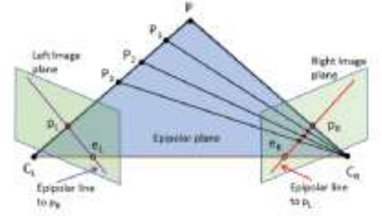


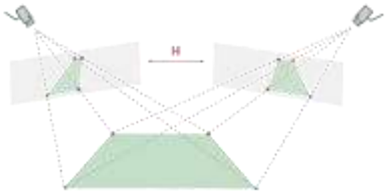
Overview of Course Content

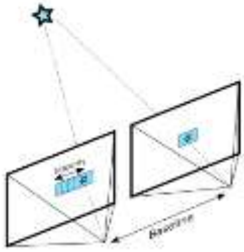
➢ Knowledge to Learn

Chapter 06: 2D-2D Geometry

- Epipolar geometry, e.g., 5-point method, 8-point method
- Stereo vision, e.g., stereo matching, relationship between disparity and depth





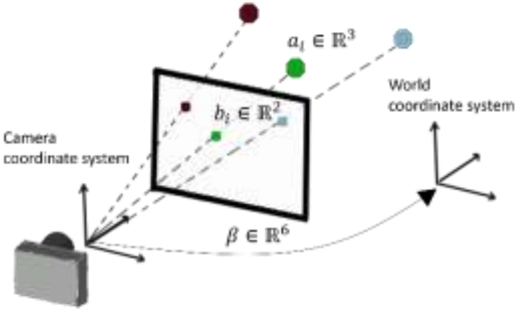


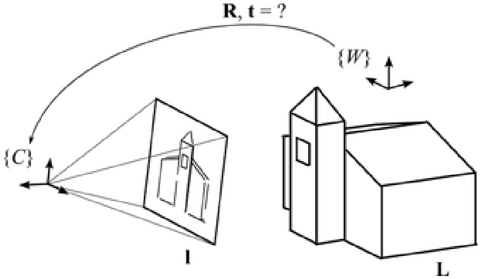
Overview of Course Content

➢ Knowledge to Learn

Chapter 07: 2D-3D Geometry

- Perspective-n-Points
- Perspective-n-Lines (not presented in most multi-view geometry courses)



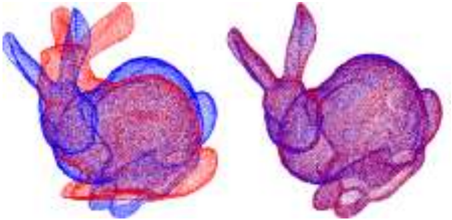


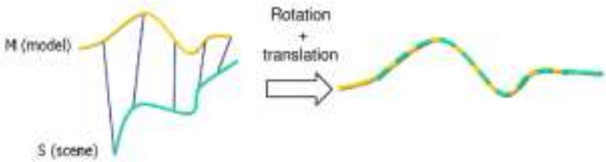
Overview of Course Content

➢ Knowledge to Learn

Chapter 08: 3D-3D Geometry

- Iterative closest point (ICP) algoritm
- Closed-form algorithms, e.g., Horn’s method and Umeyama algorithm





Overview of Course Content

- Knowledge to Learn

Chapter 09: Single-view Geometry

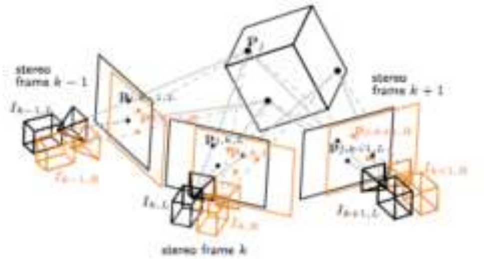
- Vanishing point
- Single-view reconstruction

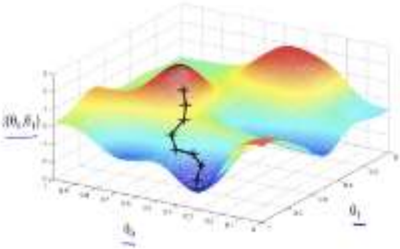
Overview of Course Content

➢ Knowledge to Learn

Chapter 10: Bundle Adjustment and Optimization

- Re-projection error
- Gradient descent algorithms



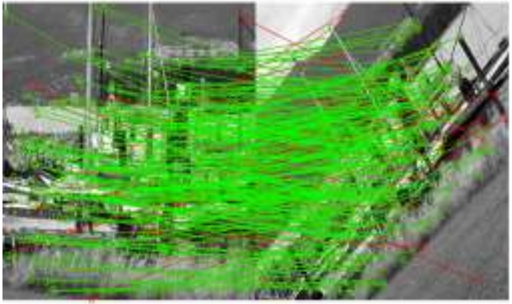


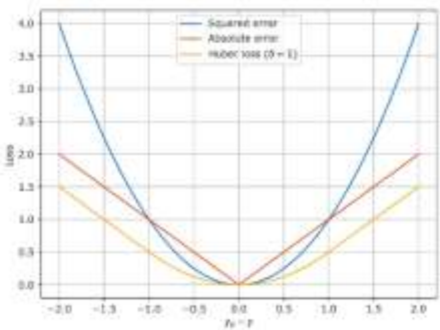
Overview of Course Content

➢ Knowledge to Learn

Chapter 11: Robot Estimation

- RANSAC
- M-Estimator



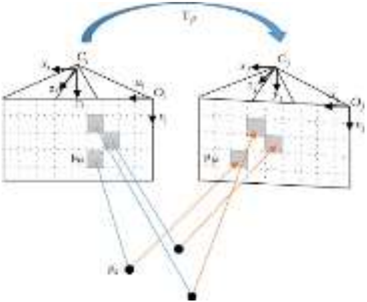


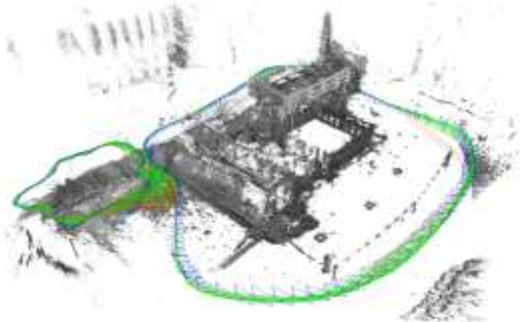
Overview of Course Content

➢ Knowledge to Learn

Chapter 12: Photometric Loss

- Definition
- Applications

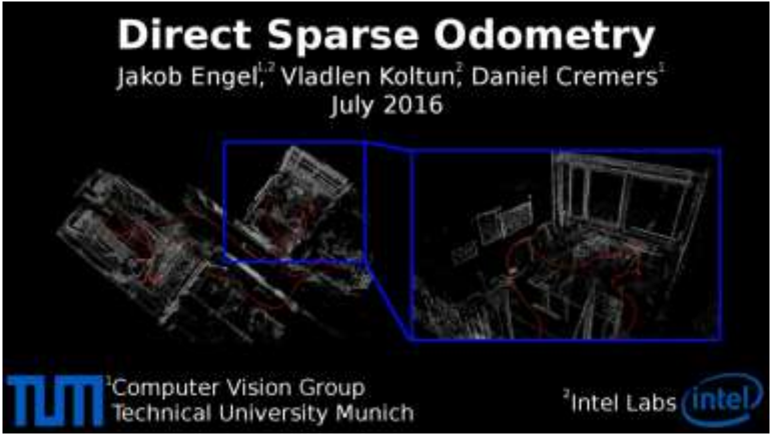




Overview of Course Content

- Knowledge to Learn

Chapter 13: SLAM and SFM



Demo video of VO from our Computer Vision Group, TUM

This method uses the photometirc loss

Overview of Course Content

- Knowledge to Learn

Chapter 13: SLAM and SFM

Demo video of VIO from
Hong Kong University
of Science and Technology

This system relies on the inertial
measurement unit (IMU)

Overview of Course Content

- ➢ Knowledge to Learn

Chapter 13: SLAM and SFM

Demo video of SLAM from University of Zaragoza

This method relies on the point features

Overview of Course Content

- Knowledge to Learn

Chapter 13: SLAM and SFM

Demo video of SLAM from Shanghai Jiao Tong University

This method relies on the line features

Overview of Course Content

➢ Knowledge to Learn

Chapter 13: SLAM and SFM

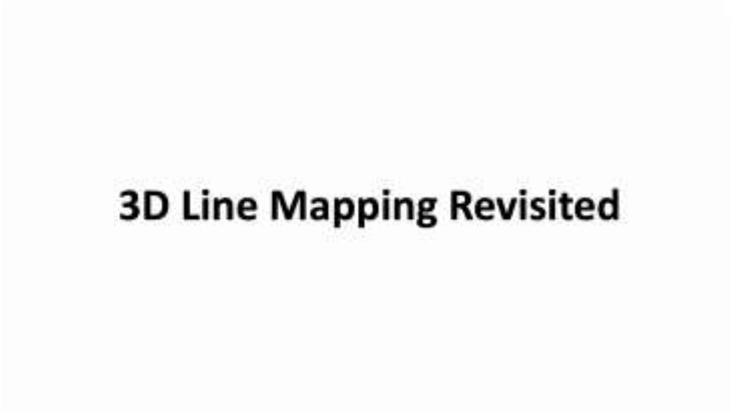
Demo video of SFM from Cornell University
"Building Rome in a Day"

This method relies on the point features

Overview of Course Content

➢ Knowledge to Learn

Chapter 13: SLAM and SFM



Demo video of SFM from ETH Zurich

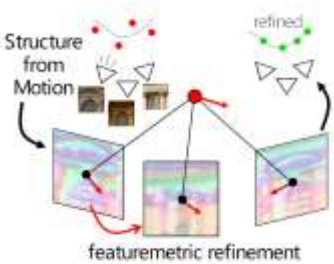
This method relies on the line features

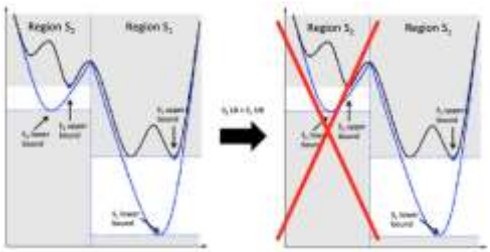
Overview of Course Content

➢ Knowledge to Learn

Chapter 14: Advanced Topics

- Deep learning for geometric problems, e.g., deep feature-based matching featuremetric Loss
- Additional robust estimation algorithms, e.g., branch and bound
- Additional optimization problems, e.g., quadratically constrained quadratic program (QCQP)





Summary

- Course Information
- Concepts of Multiple View Geometry
- Applications of Multiple View Geometry
- Overview of Course Content

Thank you for your listening!
If you have any questions, please come to me :-)