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
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Viktoria Ehm
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- 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/
## Tentative Lecture Schedule

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<th>Date</th>
<th>Chapter/Part</th>
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<td>Chapter 00: Introduction</td>
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<td>Thu 20.04.23</td>
<td>Chapter 01: Mathematical Backgrounds</td>
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<tr>
<td>Wed 26.04.23</td>
<td>Chapter 02: Motion and Scene Representation (Part 1)</td>
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<td>Thu 27.04.23</td>
<td>Chapter 02: Motion and Scene Representation (Part 2)</td>
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<td>Wed 03.05.23</td>
<td>Chapter 03: Image Formation (Part 1)</td>
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<td>Wed 10.05.23</td>
<td>Chapter 04: Camera Calibration</td>
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<td>Thu 11.05.23</td>
<td>Chapter 05: Correspondence Estimation (Part 1)</td>
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<td>Wed 17.05.23</td>
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<tr>
<td>Thu 18.05.23</td>
<td>No lecture</td>
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<tr>
<td>Wed 24.05.23</td>
<td>Chapter 06: 2D-2D Geometry (Part 1)</td>
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<td>Thu 25.05.23</td>
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<td>Wed 31.05.23</td>
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<td>Thu 01.06.23</td>
<td>Chapter 07: 3D-2D Geometry (Part 1)</td>
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<td>Wed 07.06.23</td>
<td>Chapter 07: 3D-2D Geometry (Part 2)</td>
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<td>Thu 08.06.23</td>
<td>No lecture</td>
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<td>Wed 14.06.23</td>
<td>Chapter 08: 3D-3D Geometry (Part 1)</td>
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<td>Thu 15.06.23</td>
<td>Chapter 08: 3D-3D Geometry (Part 2)</td>
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<td>Wed 21.06.23</td>
<td>Chapter 09: Single-view Geometry (Part 1)</td>
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<td>Wed 28.06.23</td>
<td>Chapter 10: Bundle Adjustment and Optimization (Part 1)</td>
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<td>Thu 29.06.23</td>
<td>Chapter 10: Bundle Adjustment and Optimization (Part 2)</td>
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<td>Wed 05.07.23</td>
<td>Chapter 11: Robot Estimation</td>
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<td>Thu 06.07.23</td>
<td>Chapter 12: Photometric Error</td>
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<td>Chapter 13: SLAM and SFM (Part 1)</td>
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<td>Chapter 14: Advanced Topics (Part 1)</td>
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<td>Chapter 14: Advanced Topics (Part 2)</td>
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### Course Information

- **90-minute course; 45-minute course**
- **Foundation**
  - Wed 19.04.23: Chapter 00: Introduction
  - Thu 20.04.23: Chapter 01: Mathematical Backgrounds
  - Wed 26.04.23: Chapter 02: Motion and Scene Representation (Part 1)
  - Thu 27.04.23: Chapter 02: Motion and Scene Representation (Part 2)
  - Wed 03.05.23: Chapter 03: Image Formation (Part 1)
  - Thu 04.05.23: Chapter 03: Image Formation (Part 2)
  - Wed 10.05.23: Chapter 04: Camera Calibration
  - Thu 11.05.23: Chapter 05: Correspondence Estimation (Part 1)
  - Wed 17.05.23: Chapter 05: Correspondence Estimation (Part 2)
  - Thu 18.05.23: No lecture
  - Wed 24.05.23: Chapter 06: 2D-2D Geometry (Part 1)
  - Thu 25.05.23: Chapter 06: 2D-2D Geometry (Part 2)

- **Core part**
  - Wed 31.05.23: Chapter 06: 2D-2D Geometry (Part 3)
  - Thu 01.06.23: Chapter 07: 3D-2D Geometry (Part 1)
  - Wed 07.06.23: Chapter 07: 3D-2D Geometry (Part 2)
  - Thu 08.06.23: No lecture
  - Wed 14.06.23: Chapter 08: 3D-3D Geometry (Part 1)
  - Thu 15.06.23: Chapter 08: 3D-3D Geometry (Part 2)
  - Wed 21.06.23: Chapter 09: Single-view Geometry (Part 1)
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  - Wed 28.06.23: Chapter 10: Bundle Adjustment and Optimization (Part 1)
  - Thu 29.06.23: Chapter 10: Bundle Adjustment and Optimization (Part 2)

- **Advanced topics and high-level task**
  - Wed 05.07.23: Chapter 11: Robot Estimation
  - Thu 06.07.23: Chapter 12: Photometric Error
  - Wed 12.07.23: Chapter 13: SLAM and SFM (Part 1)
  - Thu 13.07.23: Chapter 13: SLAM and SFM (Part 2)
  - Wed 19.07.23: Chapter 14: Advanced Topics (Part 1)
  - Thu 20.07.23: Chapter 14: Advanced Topics (Part 2)

For updates, slides, and additional materials: [https://cvg.cit.tum.de/teaching/ss2023/cv2](https://cvg.cit.tum.de/teaching/ss2023/cv2)
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-EJn6udZ34ttht9EVIW7lbeo4

- “Vision Algorithms for Mobile Robotics” provided by Prof. Davide Scaramuzza
  Materials: https://rpg.ifi.uzh.ch/teaching.html

Prof. Daniel Cremers
(on sabbatical at Oxford University)
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
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

- **Image Processing**
  - Desirable but not essential
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

Course “Computer Vision III: Detection, Segmentation and Tracking” provided by Dr. Nikita Araslanov
Concepts of Multi-view Geometry

➢ Computer Vision vs Computer Graphics

Previous: Images $\rightarrow$ Computer Vision $\rightarrow$ Model $\leftarrow$ Computer Graphics

Now: Inverse problems $\rightarrow$ A representative of combination: NeRF [1]

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.
Concepts of Multi-view Geometry

- Multi-view Geometry

Terminology Definition or Differentiation

- 2D-2D, 3D-2D, and 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
  - Estimated Poses
  - Map Points

- Tracked 3D-2D correspondences

Localization cars: 1) car collision warning, 2) lane departure warning, and 3) safety distance monitoring and warning
Applications of Multi-view Geometry

- Autonomous Driving

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

A demo video
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

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

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.**
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**

  1. Image pair
  2. Feature detection
  3. Feature matching/tracking
  4. **Camera pose estimation**
  5. 3D reconstruction
  6. 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
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
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) algorithm
- 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 photometric 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 feature metric 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 :-}