Introduction to

Simultaneous Localization and Mapping

Spring Semester Course 2019

CS284

Course Convener:

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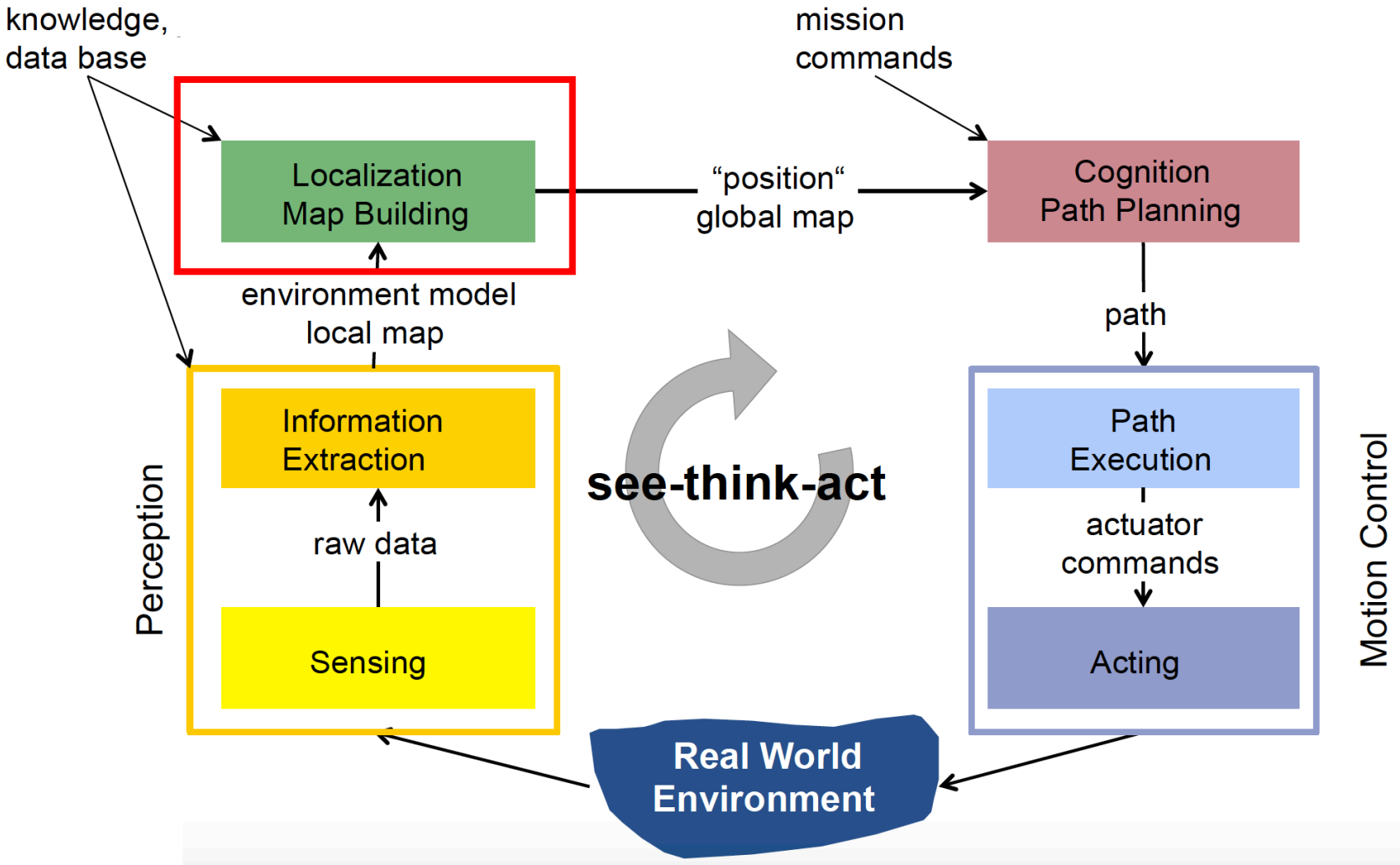
Disclaimer

- Some of the lecturing material is naturally taken from publically available online material from other groups. Sources include:
  - Autonomous Systems Lab ETH Zurich
  - Research School of Engineering, ANU
  - Informatik Department, Uni Freiburg
  - MIT
  - …
- By using the present material you confirm that
  - You use it only internally and for the purpose of education
  - You are aware that the lecture material may originate from other sources, even if explicit reference is occasionally missing

What is …

- … Simultaneous Localization and Mapping?

Mobile Robot Control Scheme



Simultaneous Localization and Mapping

- The SLAM problem:
  - How can a body navigate/localize in a previously unknown environment while constantly building and updating a map of its workspace using onboard sensors (& onboard computation) only?

- When do we need SLAM?
  - When the body simply needs to know or keep track of where it is
  - When there is no prior knowledge about the environment
  - When we cannot place beacons and cannot use external positioning systems (like GPS)
  - When the body needs to have some (real or virtual) interaction with the environment

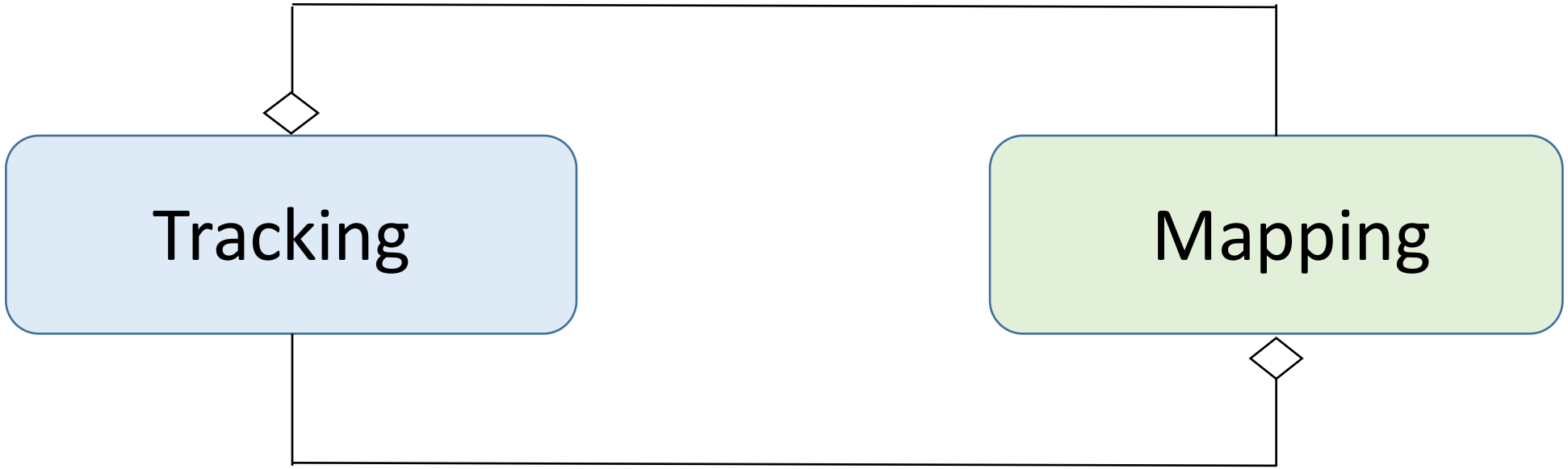
Simultaneous Localization and Mapping

- SLAM: The backbone of spatial awareness in intelligent systems
  - One of the most challenging problems in the relevant applications.
- A chicken-and-egg problem
  - An unbiased map is necessary for localizing the body.
    Pure localization with a known map.

    SLAM: no a priori knowledge of the agent's workspace.
  - An accurate pose estimate is necessary for building a map of the environment
    Mapping with known agent poses.

    SLAM: The body's poses have to be estimated along the way.

Simultaneous Localization and Mapping



Simultaneous Localization and Mapping

- Many related terms
  - State estimation
  - Localization
  - Ego-motion estimation
  - Navigation
  - Motion planning
  - Mapping
  - Structure from motion
  - Bundle adjustment
  - SLAM
  - …

Perception in Nature

- What is nature's solution to this problem?

Perception in Nature

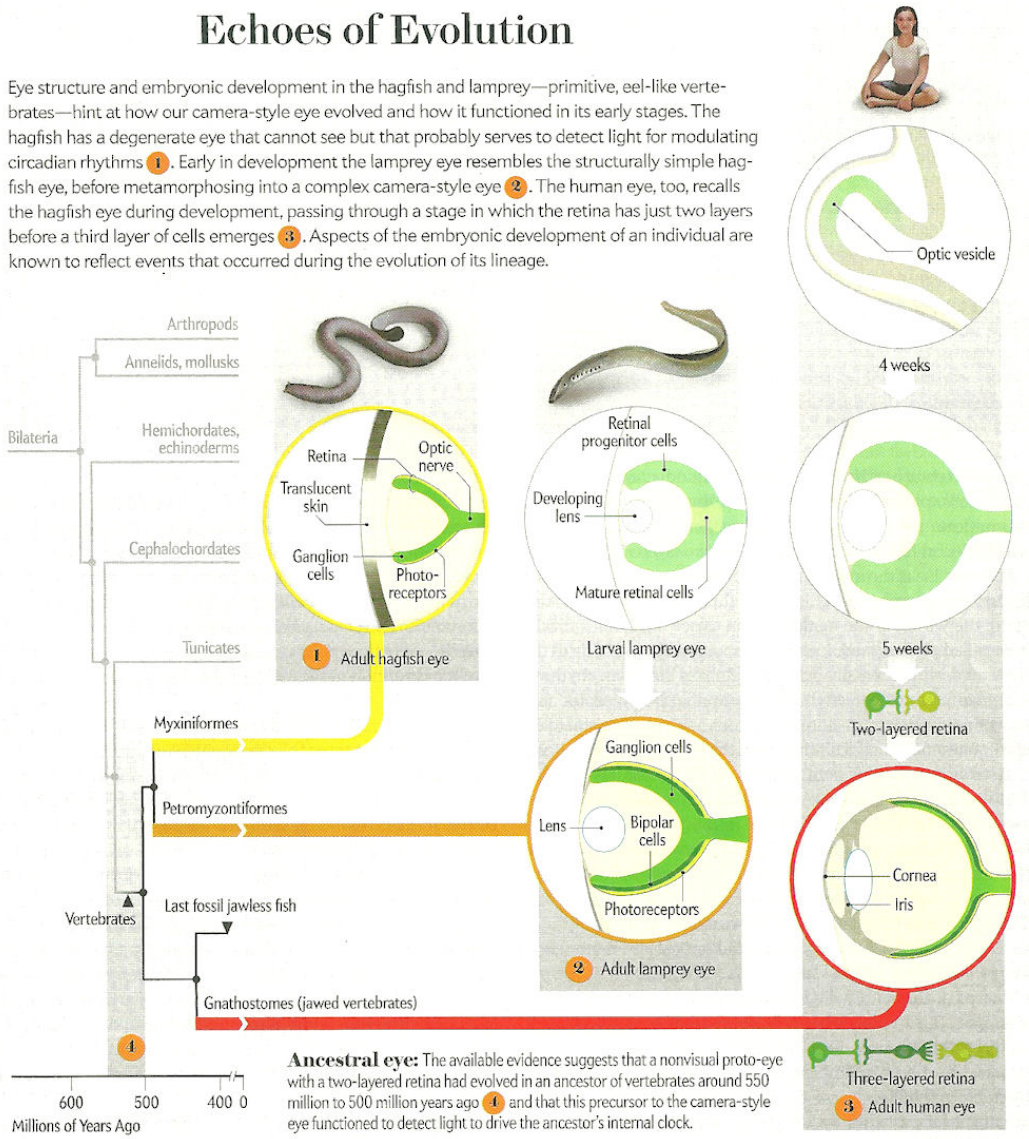
- What if we don’t see?

Perception in Nature

- Visual perception is believed to be a key-factor in the Cambrian explosion (543 million years B.C.)

Perception in Nature

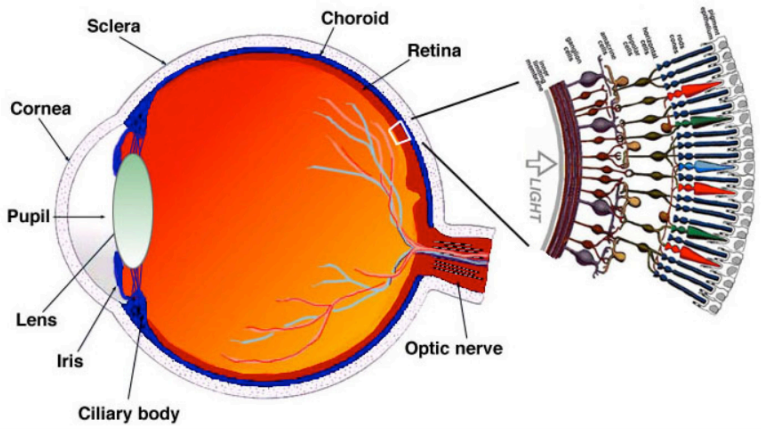
- From first vertebrates to seeing animals



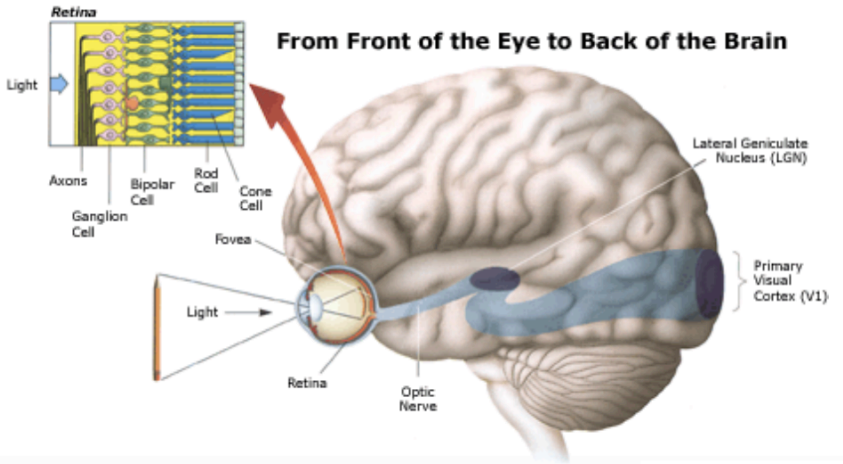
Perception in Nature

- **Vision** is our most powerful sense in aiding our perception of the 3D world around us
- Retina is ~10cm2. contains millions of **photoreceptors**
  (120 mil. rods and 7 mil. cones for colour sampling)
- Provides enormous amount of information: data-rate of ~**3GB / s**

→ A large portion of our brain is dedicated to processing the signals from our eyes



http://webvision.med.utah.edu/sretina.html

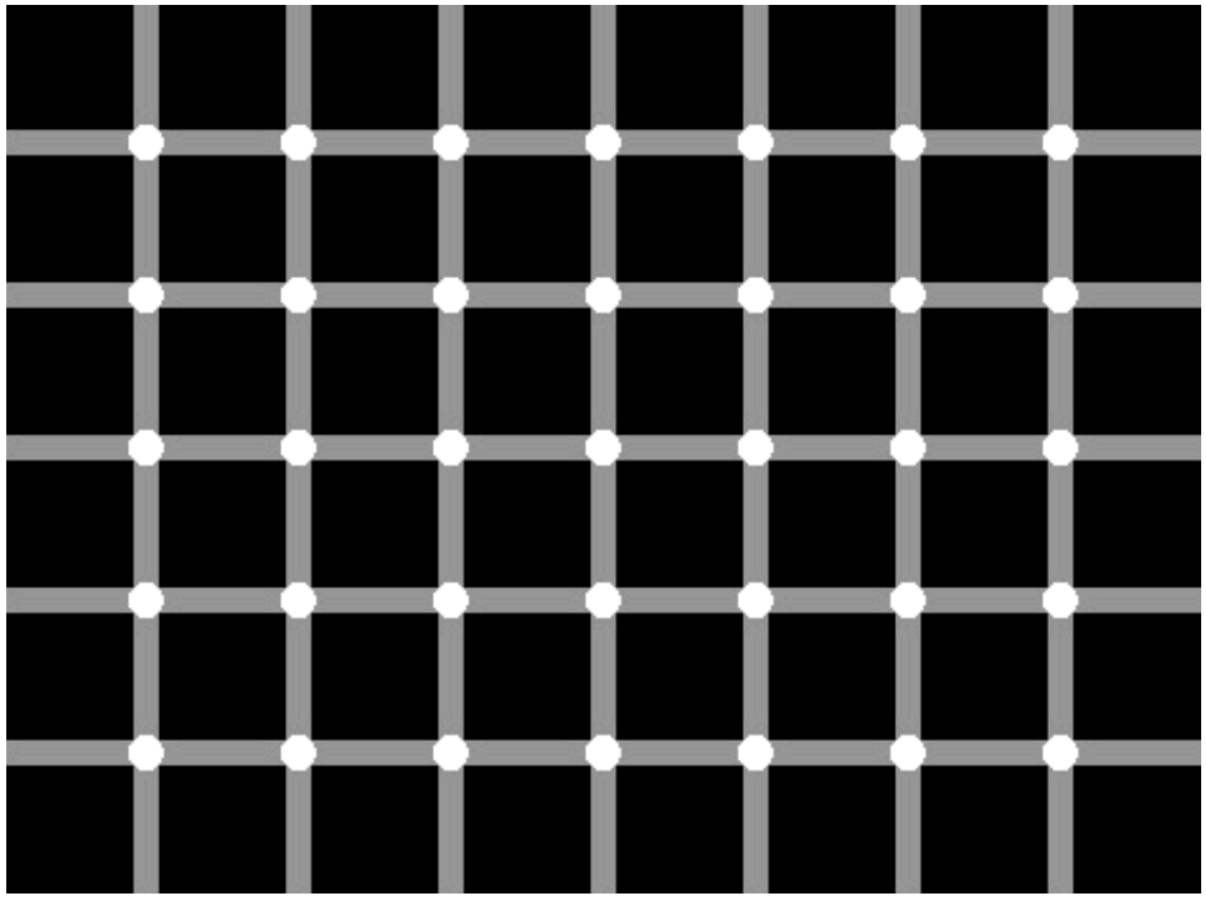


Perception in Nature

- Our vision system is very sophisticated
- Humans can interpret images successfully under a wide range of conditions – even in the presence of very limited cues

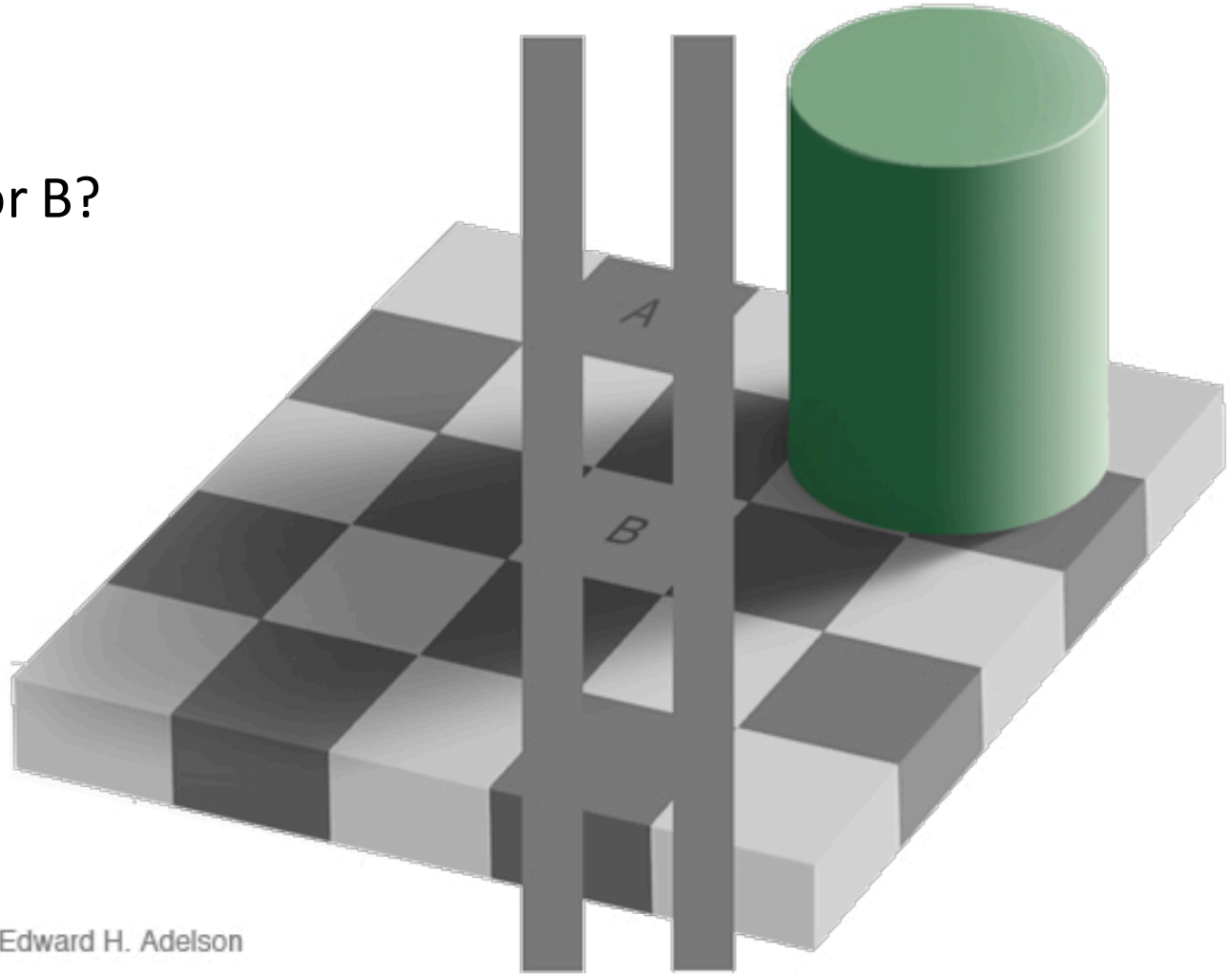
Perception in Nature

- Do we always get it right?
  - How many black spots do you see?



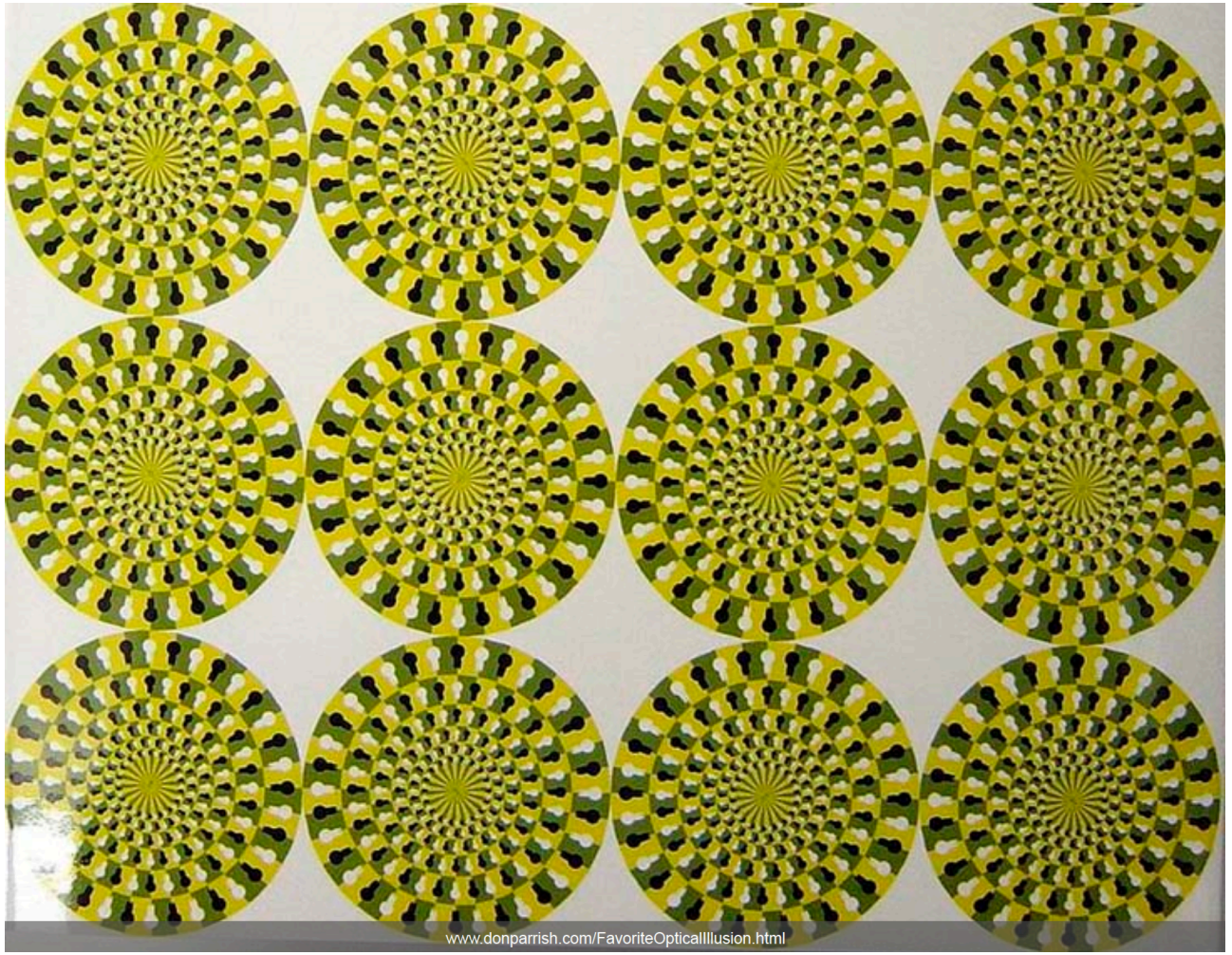
Perception in Nature

- Do we always get it right?
  - Which square is darker, A or B?



Perception in Nature

- Do we always get it right?
  - Anything moving here?



Machine Vision

- Enormous descriptability of images → a lot of data to process
  (human vision involves 60 billion neurons)
- Vision provides humans with a great deal of useful cues

- →Explore the power of vision towards intelligent systems
- →**Cameras!**
  - An increasingly popular choice as an exteroceptive sensing modality
    - Descriptive
    - Compactness, compatibility, …
    - Low cost
    - HW advances necessary to support the processing of images

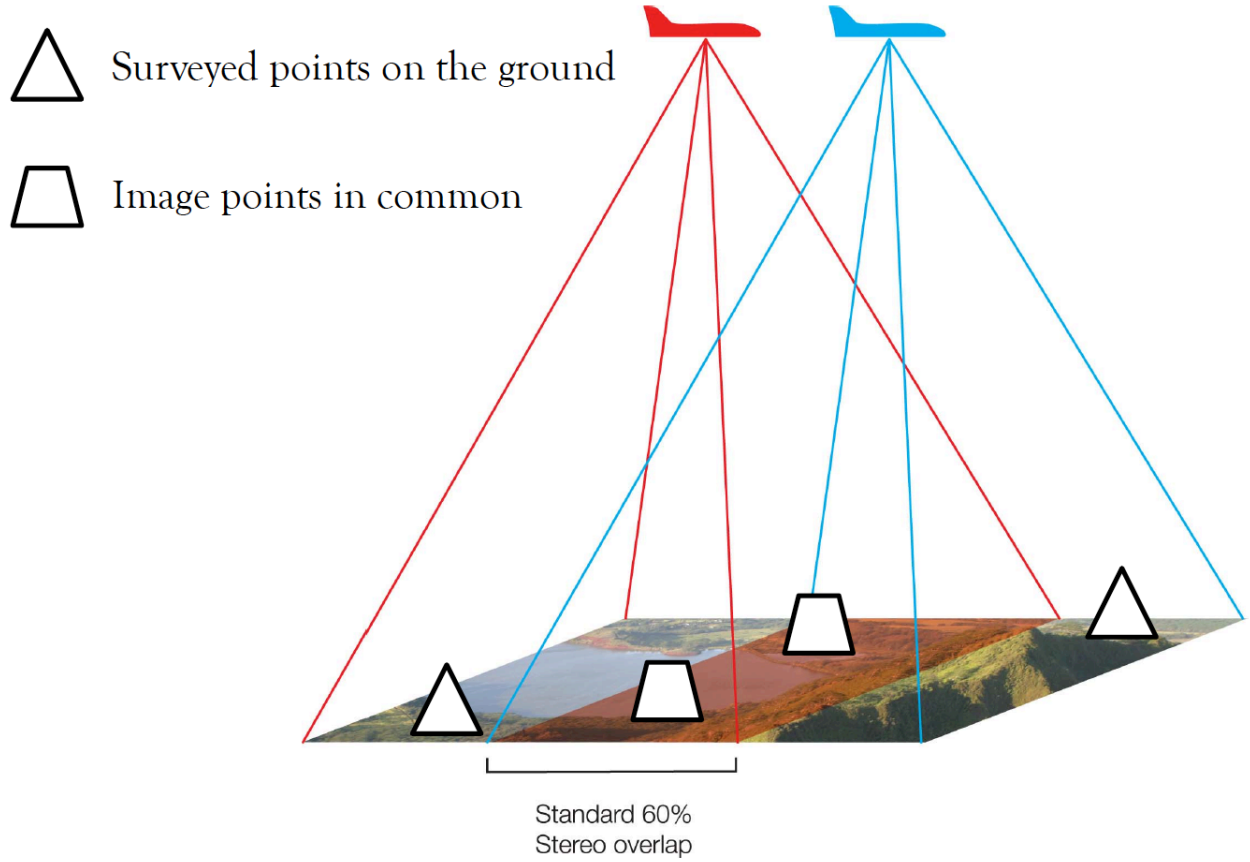
SLAM approaches

- Large variety of different SLAM approaches have been proposed
- Most robotics conferences dedicate multiple tracks to SLAM
- The majority of techniques uses probabilistic concepts
- History of SLAM dates back to the mid-eighties
- Related problems in geodesy and photogrammetry
- → **Visual SLAM** (focus of this lecture)

Visual SLAM: Origins in photogrammetry

- "Photogrammetry" – the practice of determining the geometric properties of objects from images.

- Originated from efforts to formalize production of topographic maps from aerial images



Surveying for Mapping---part 1, http://www.icsm.gov.au/mapping/surveying1.html

Visual SLAM: Origins in photogrammetry

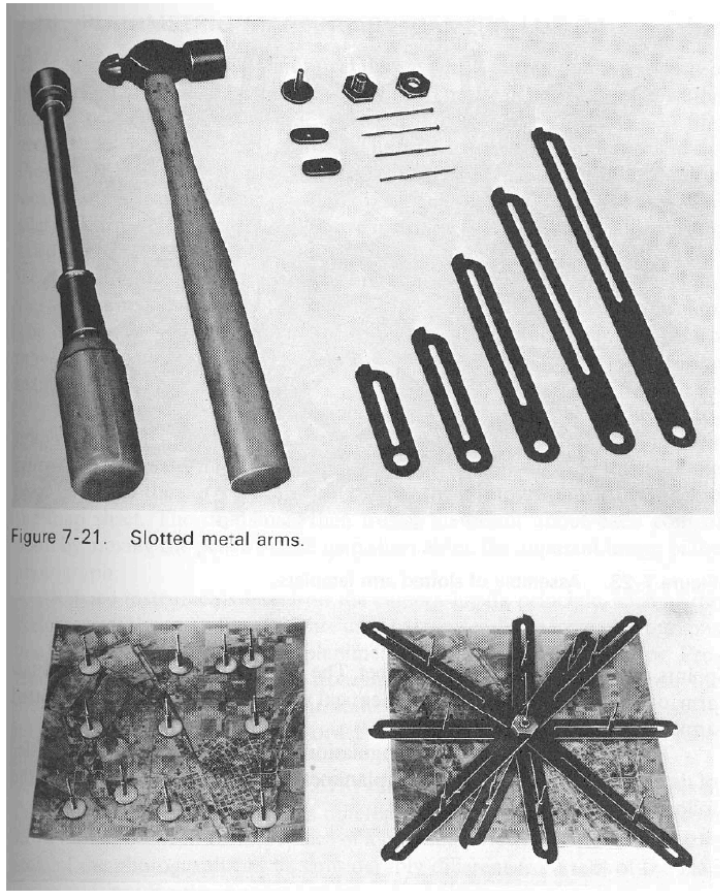
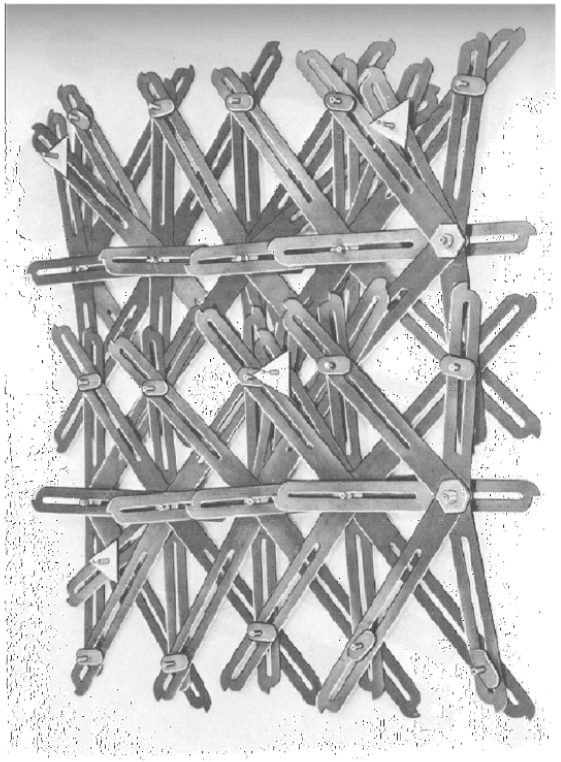


Figure 7-21. Slotted metal arms.



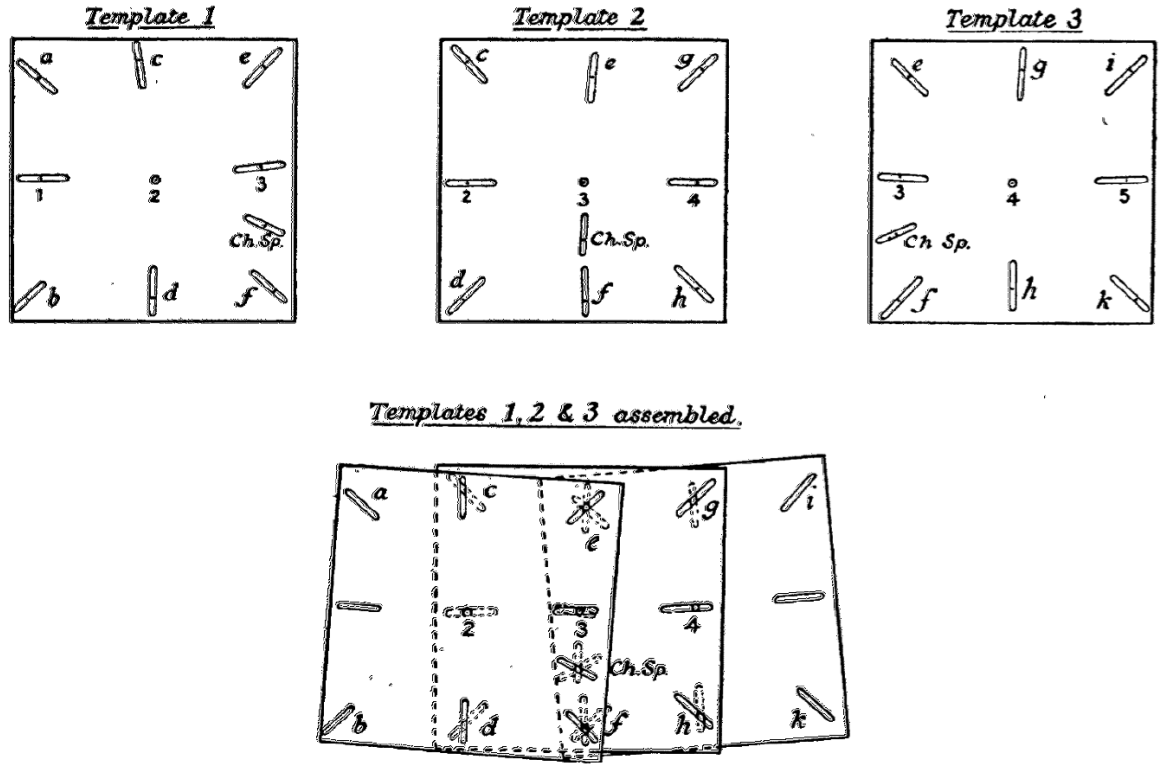
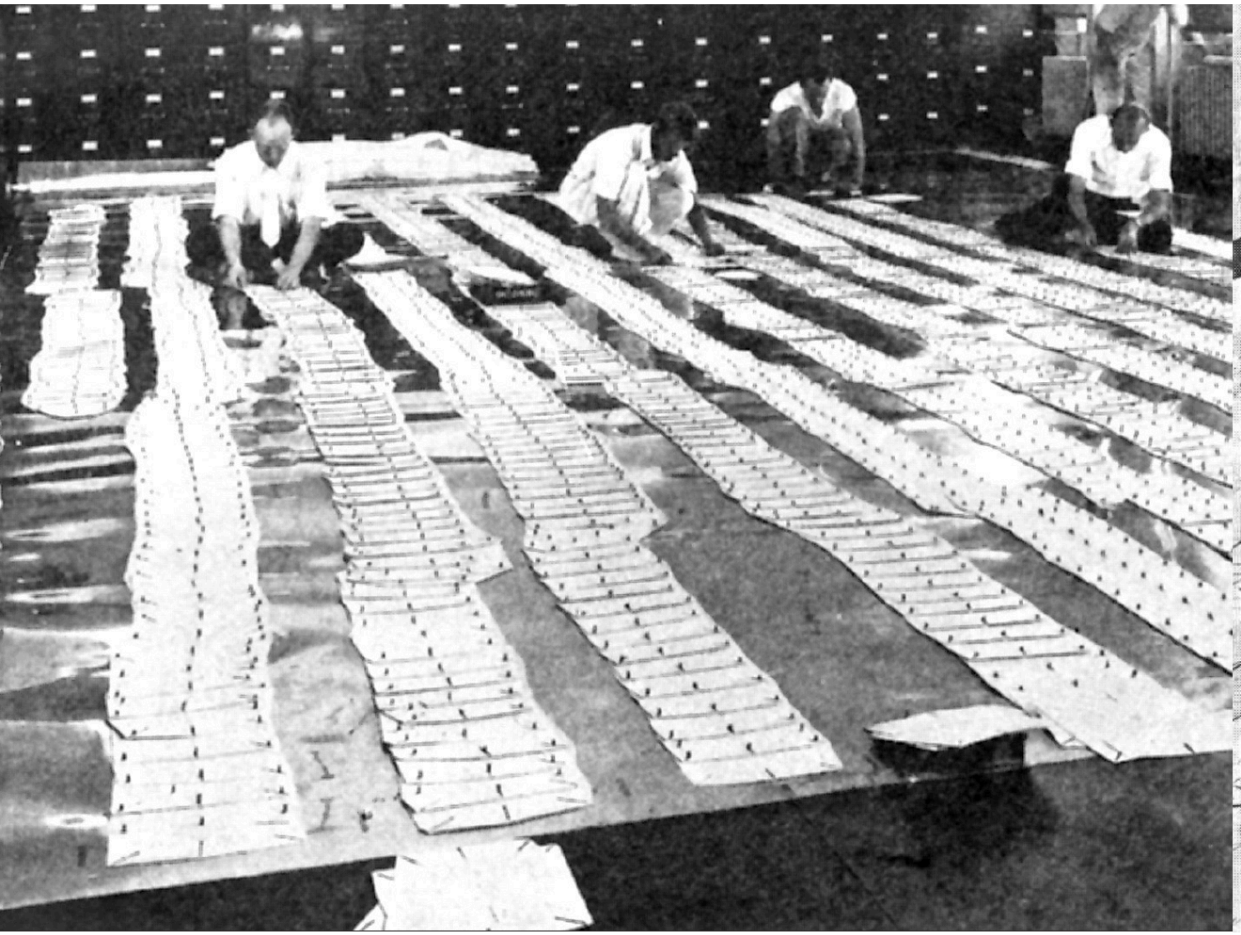


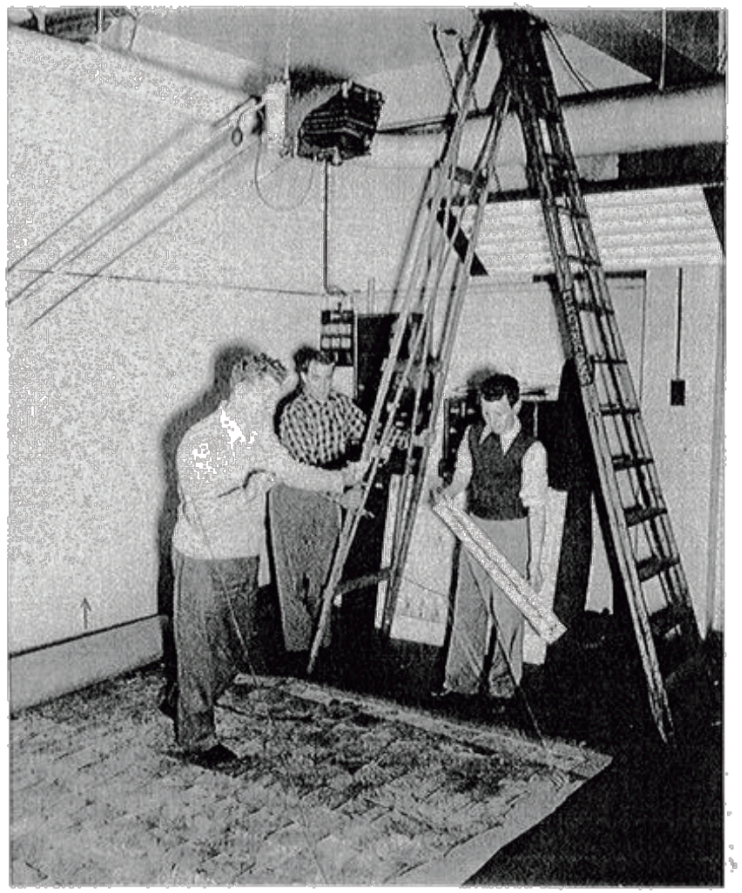
Fig. 9. Slotted template method of assembling air photographs

Visual SLAM: Origins in photogrammetry



Visual SLAM: Origins in photogrammetry

NATMAP EARLY DAYS, MAP COMPILATION FROM AERIAL PHOTOGRAPHS 1948 -1970S David R. Hocking



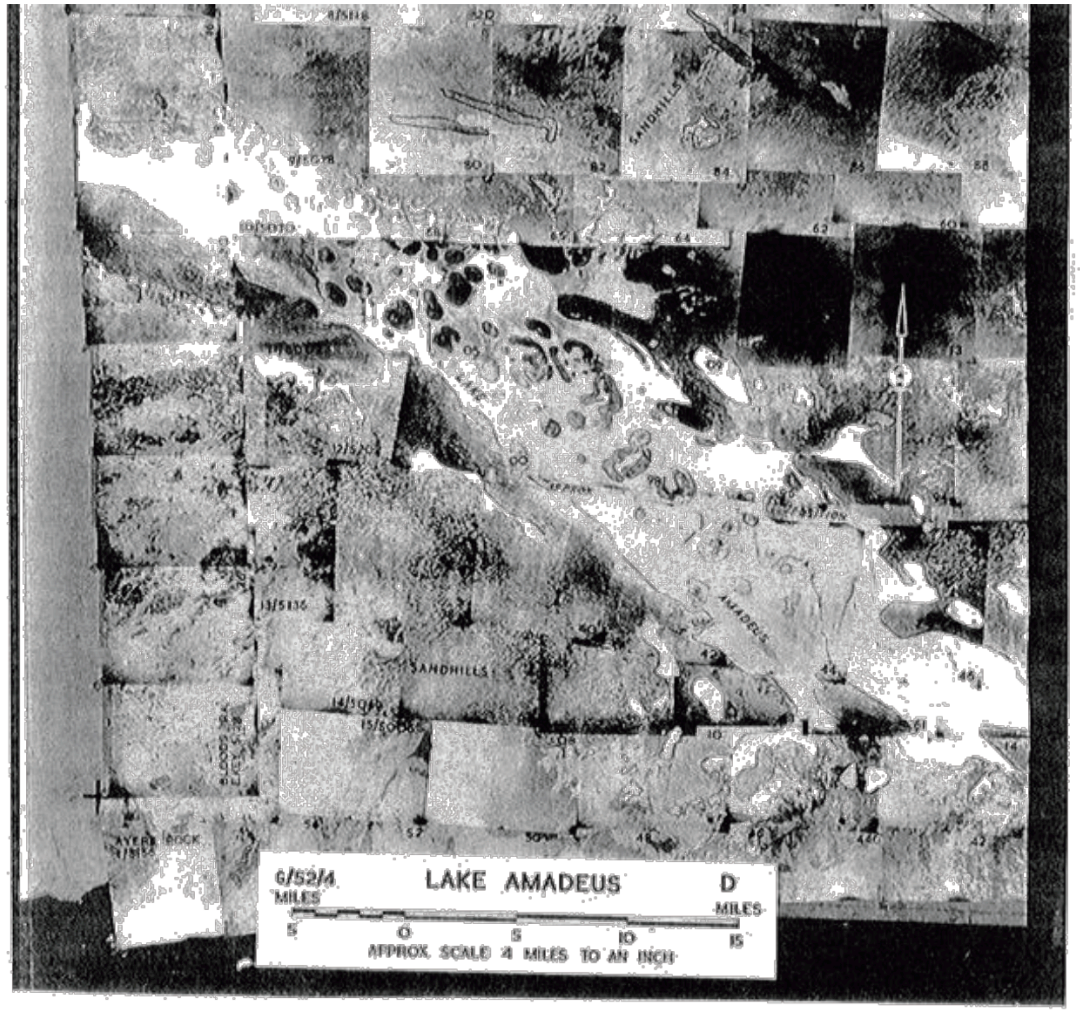
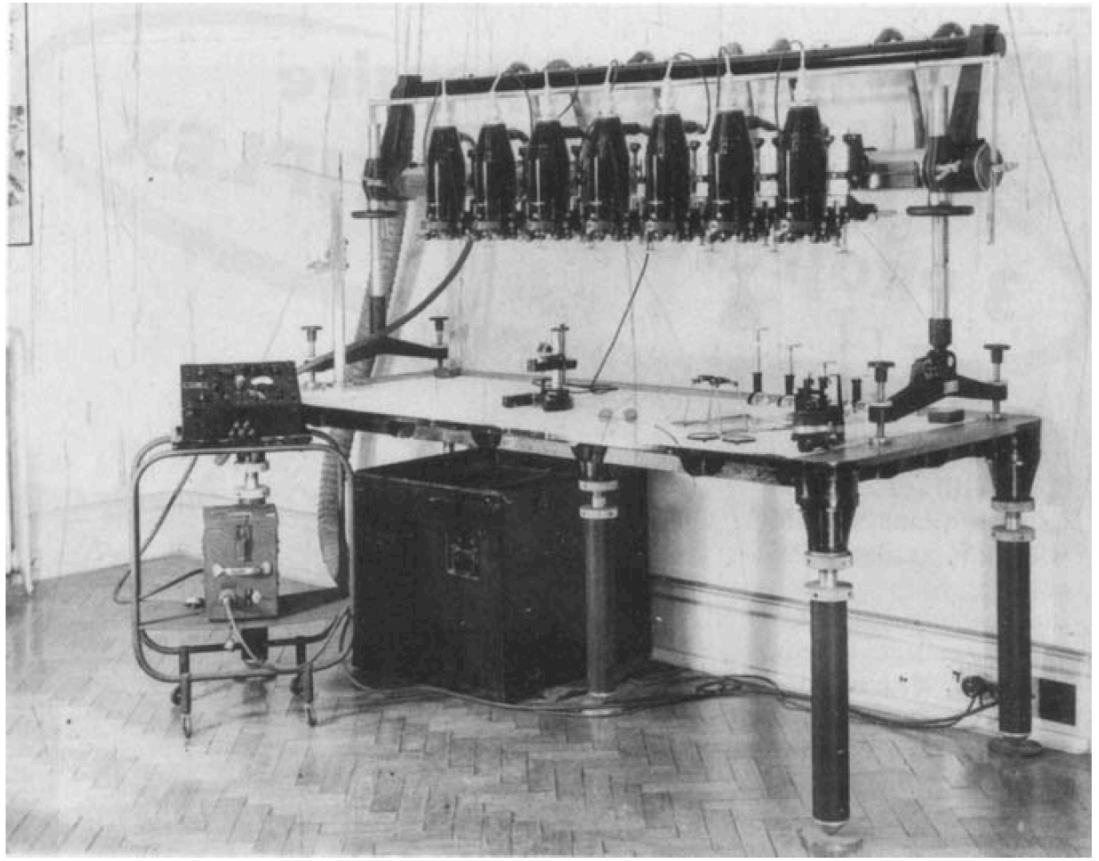
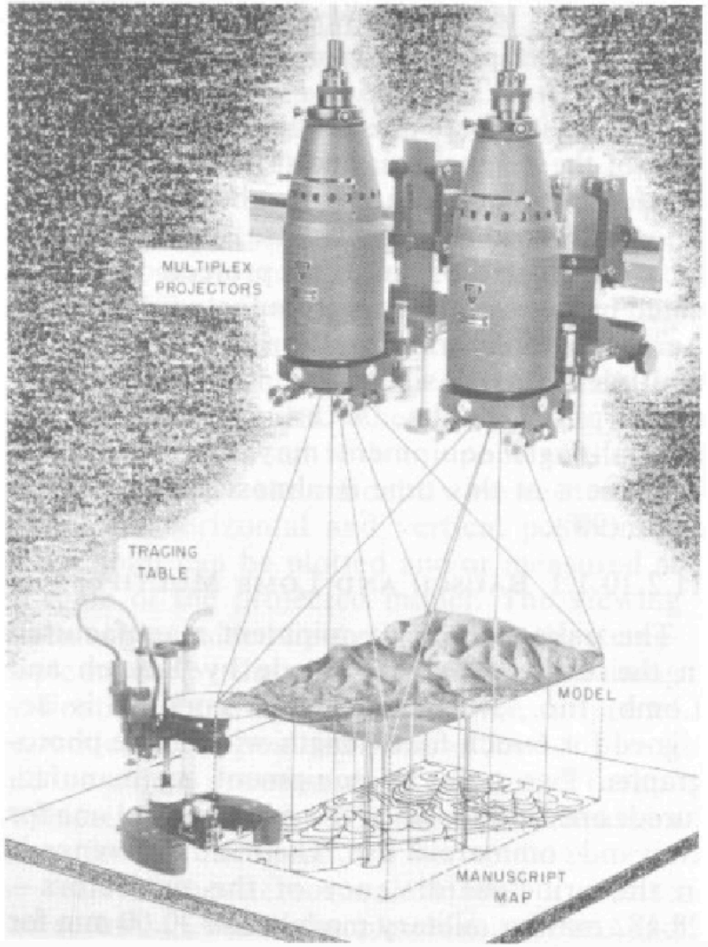


Fig. 6. Overhead camera set up to photograph a section of a 'four mile' mosaic. Fig. 7. One of six sections of SG-52-04 Lake Amadeus (Amadeus 5048).

Visual SLAM: Origins in photogrammetry

1940s: Opto-mechanical systems: aerial images set on glass plates, arranged in a series of projectors





C. Burnside. The photogrammetric society analogue instrument project: a second extract. The Photogrammetric Reco
14(83):769–782, 1994.

Visual SLAM: Origins in photogrammetry

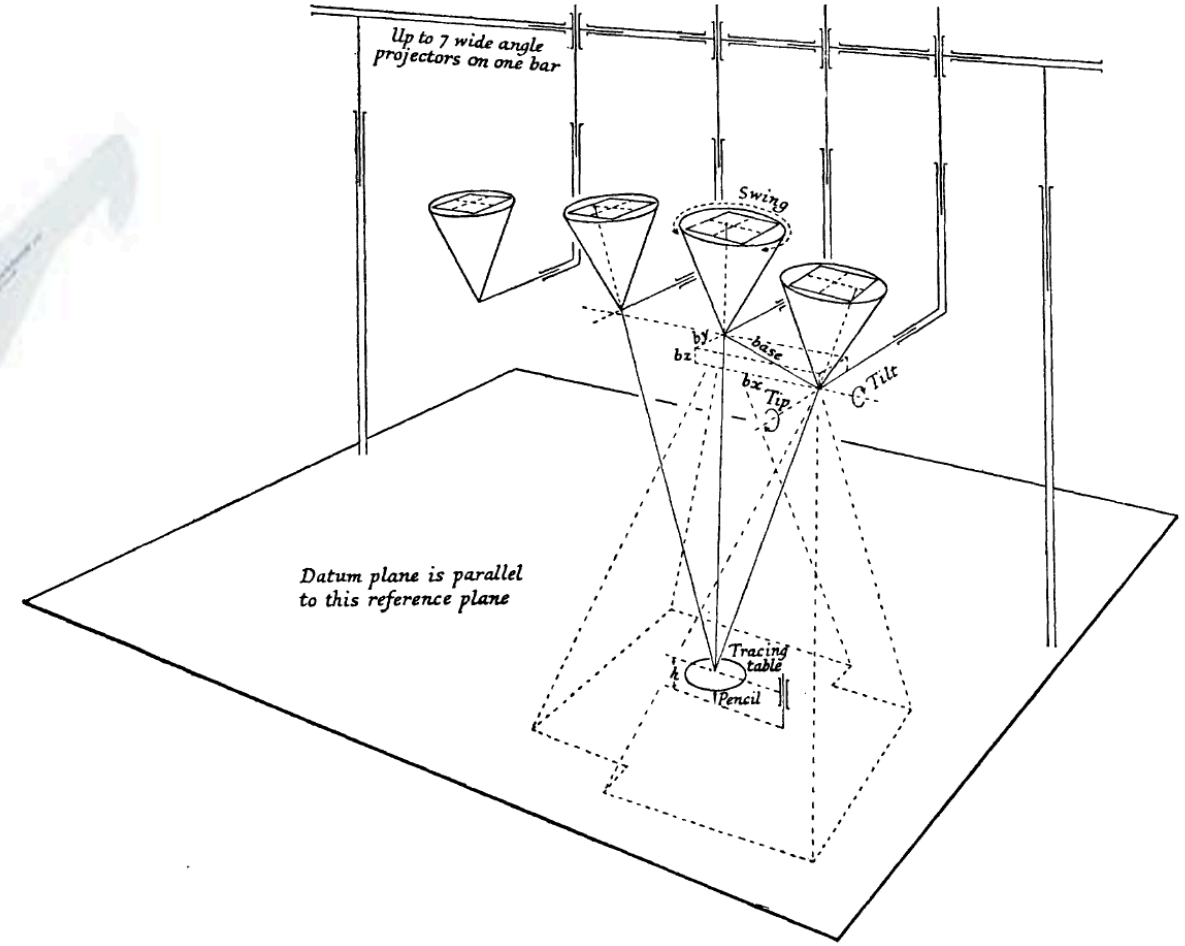
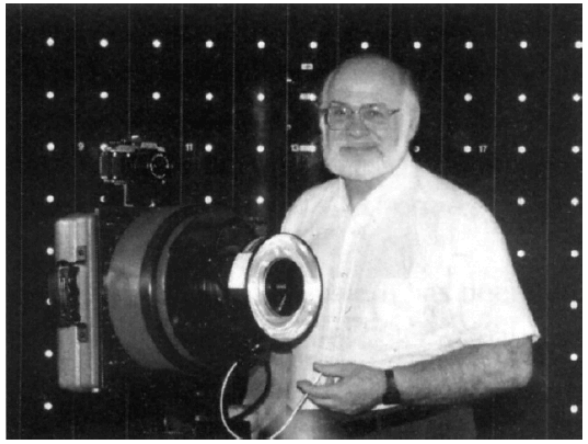


Fig. 10. Theory of Multiplex

C. Hart. Air survey: The modern aspect. The Geographical Journal, 108(4/6):179–198, 1946

Visual SLAM: Origins in photogrammetry

Bundle Adjustment



D.C. Brown

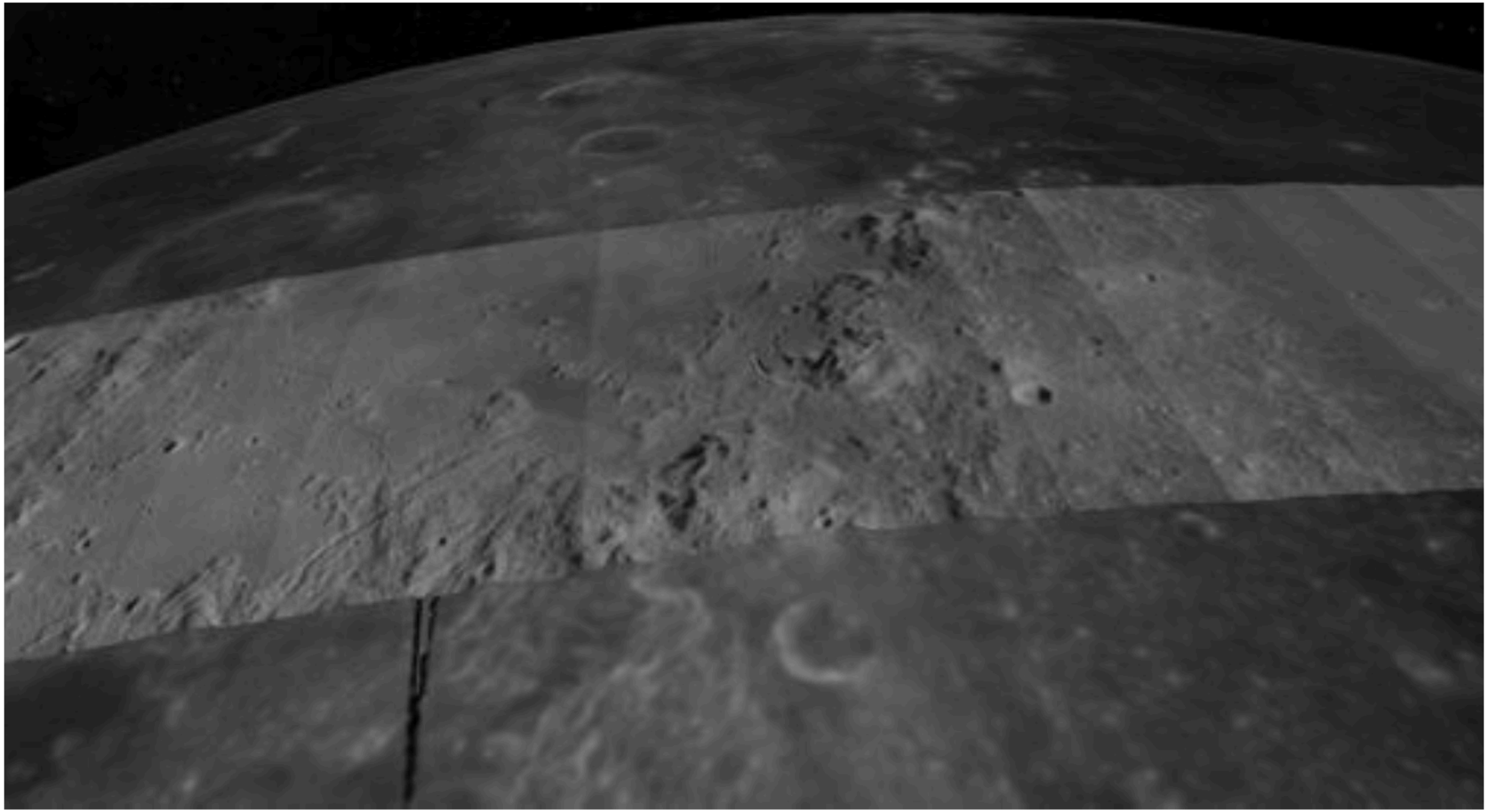
"A rigorous least squares adjustment, believed to be of unprecedented universality, is given for the simultaneous adjustment of the entire set of observations arising from a general m-station photogrammetric net.

...

A computing program for automatic electronic computers is outlined."

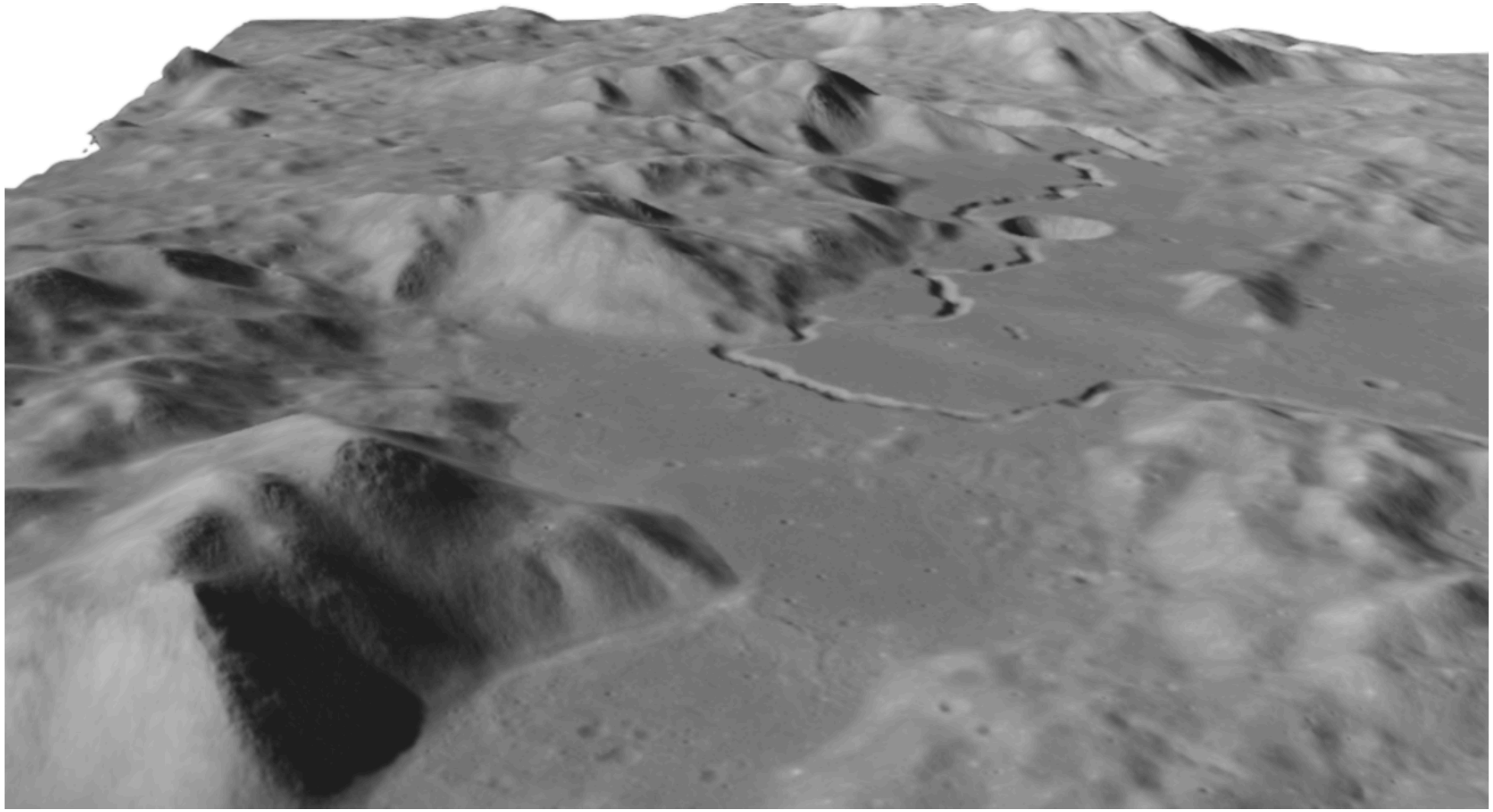
Brown, D.C., A Solution to the General Problem of Multiple Station Analytical Stereo triangulation, RCA Technical Report No. 43, February 1958

Visual SLAM: Origins in photogrammetry



Michael J. Broxton, Ara V. Nefian, Zachary Moratto, Taemin Kim, Michael Lundy, and Aleksandr V. Segal, "3D Lunar Terrain Reconstruction from Apollo Images", *International Symposium on Visual Computing 2009*

Visual SLAM: Origins in photogrammetry



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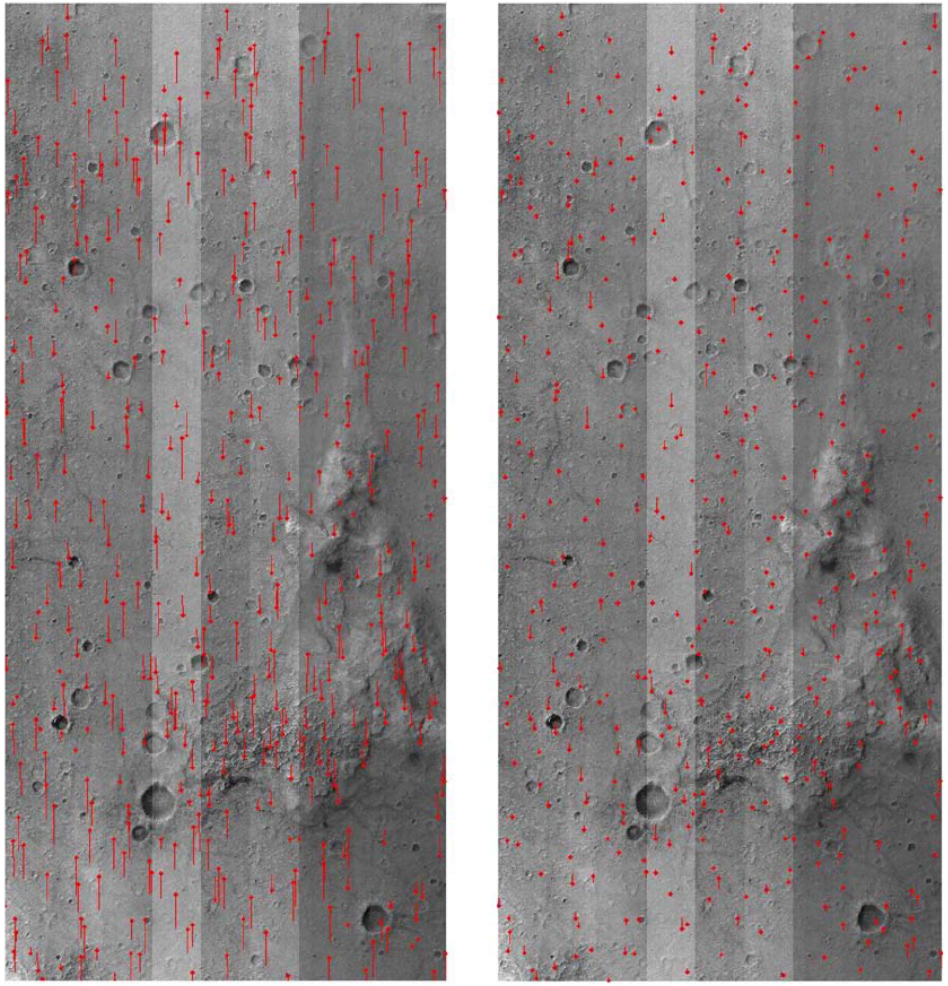

R. Li, J. Hwangbo, Y. Chen, and K. Di. Rigorous photogrammetric processing of hirise stereo imagery for mars topographic mapping. Geoscience and Remote Sensing, IEEE Transactions on, (99):1–15, 2008.

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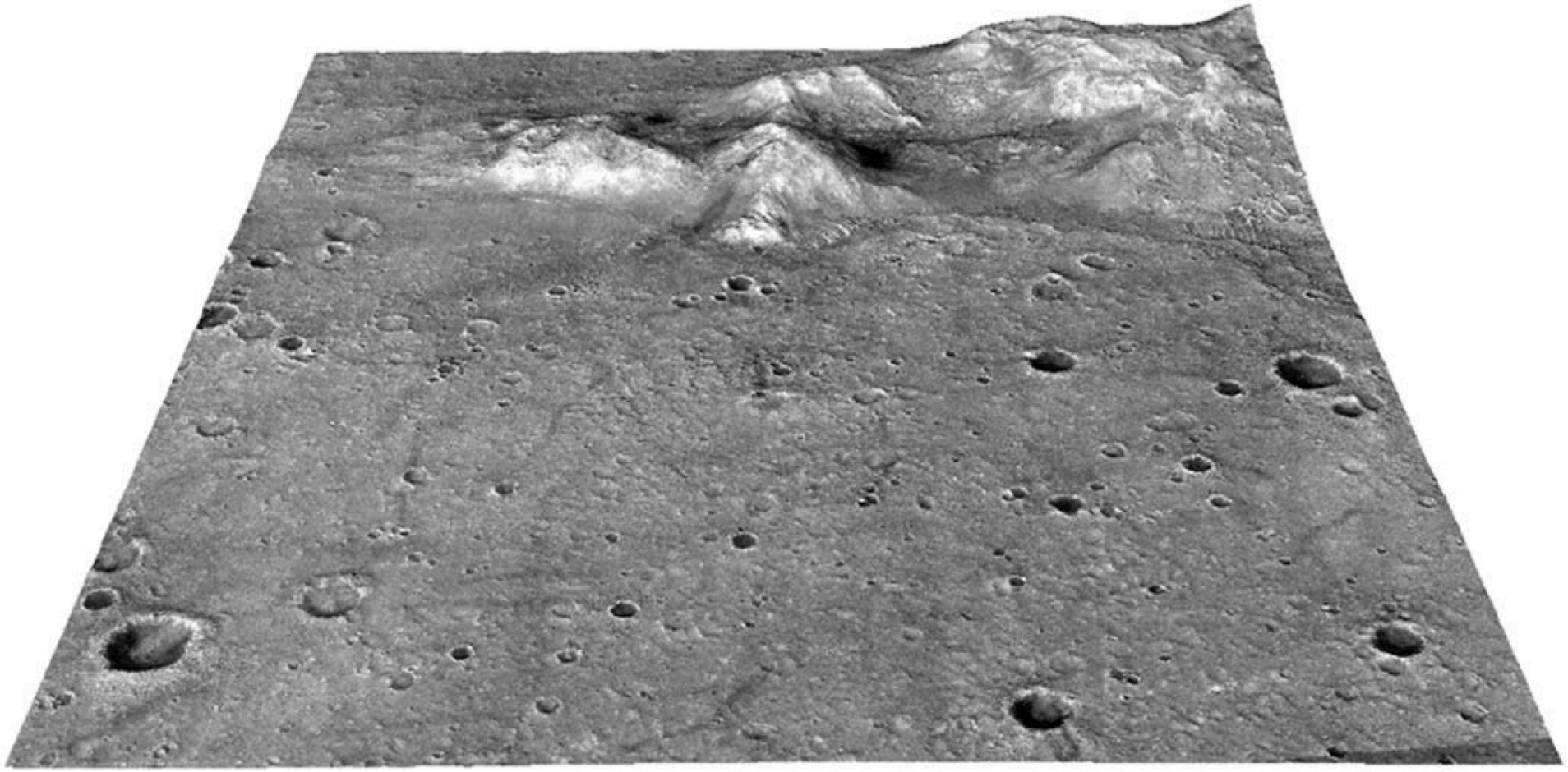

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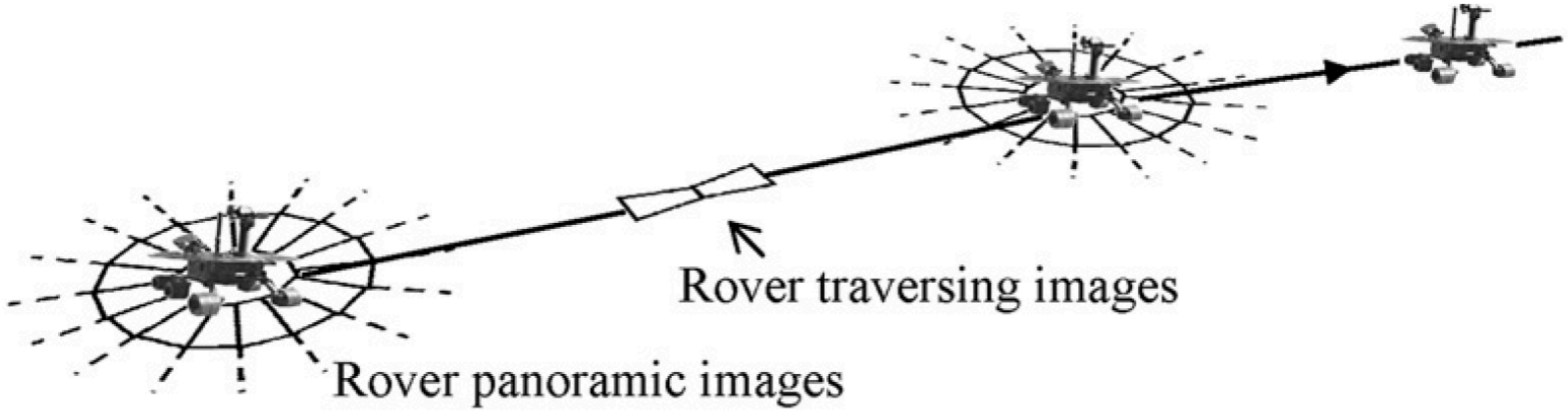
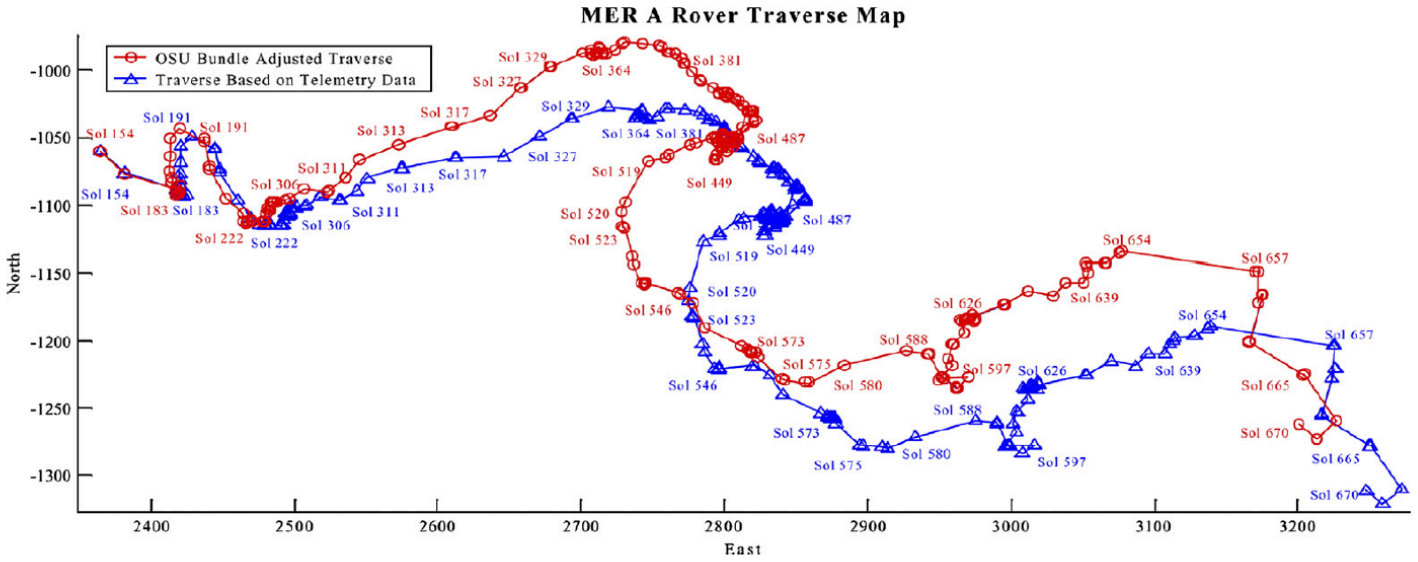
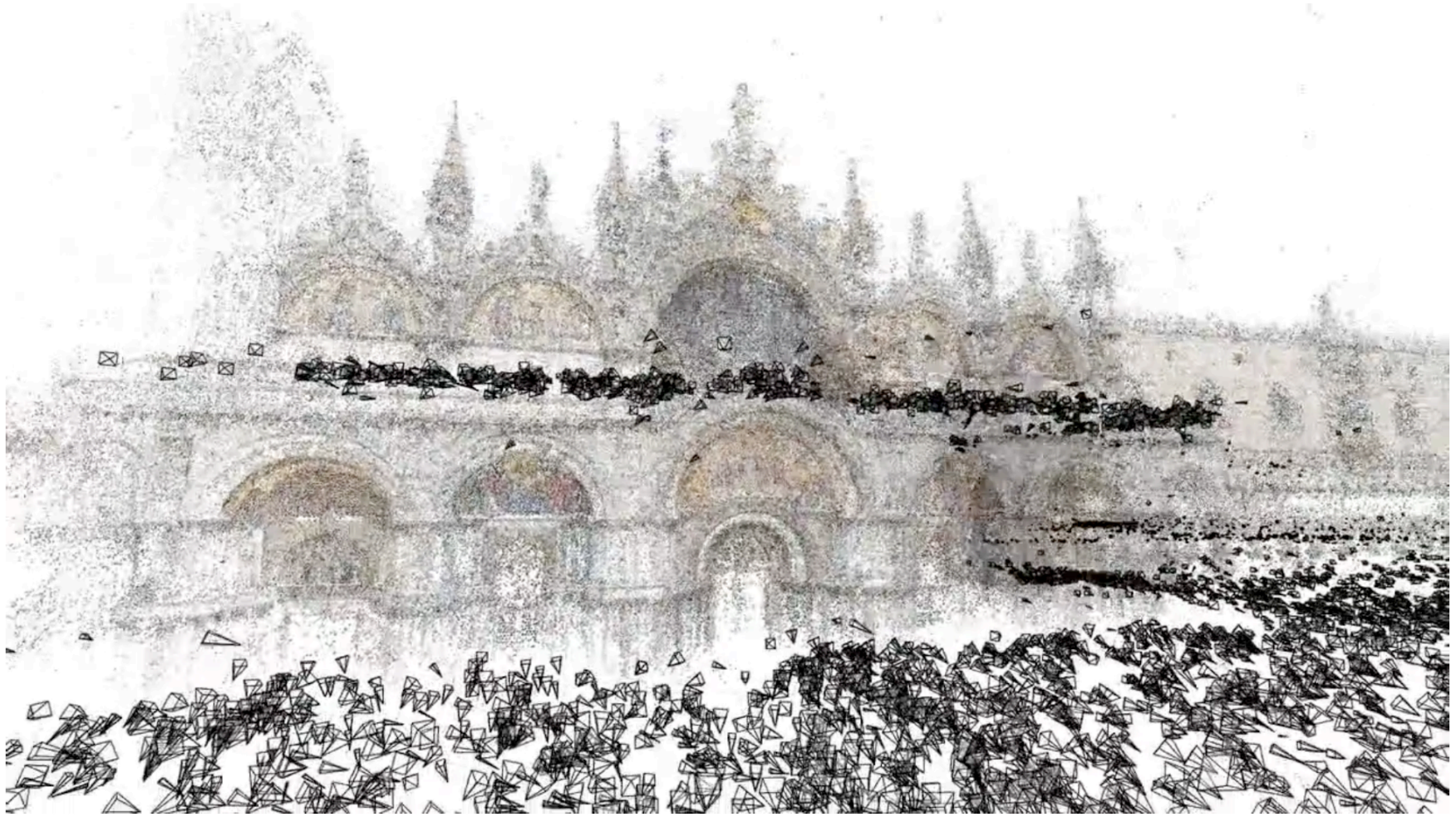




K. Di, F. Xu, J. Wang, S. Agarwal, E. Brodyagina, R. Li, and L. Matthies. Photogrammetric processing of rover imagery of the 2003 mars exploration rover mission. ISPRS Journal of Photogrammetry and Remote Sensing, 63(2):181–201, 2008.

Visual SLAM: From photogrammetry to SfM



S. Agarwal, Y. Furukawa, N. Snavely, B. Curless, S. M. Seitz and R. Szeliski,
“Reconstructing Rome”, IEEE Computer, 2010

Visual SLAM: from SfM to SLAM

https://www.youtube.com/watch?v=Qe10ExwzCqk

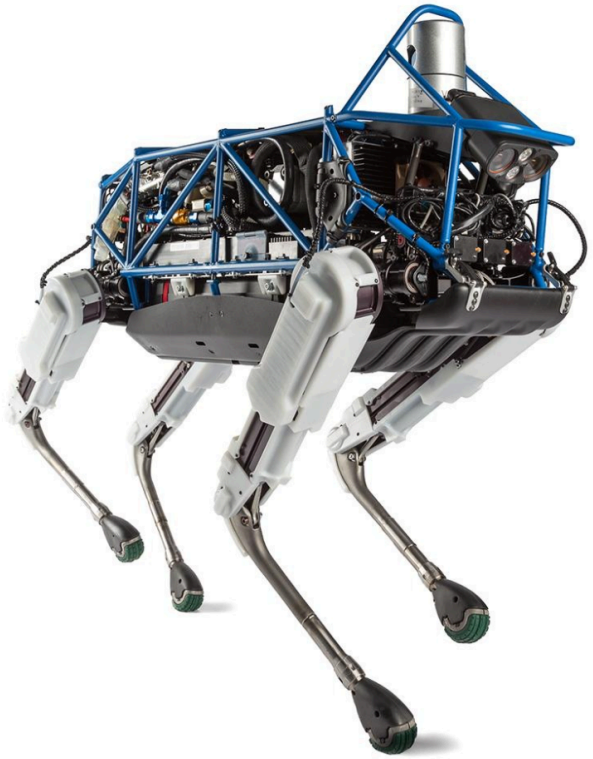
Applications

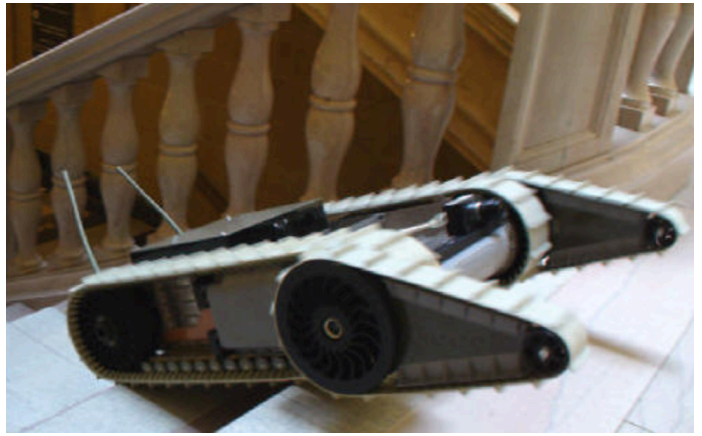
Applications of SLAM

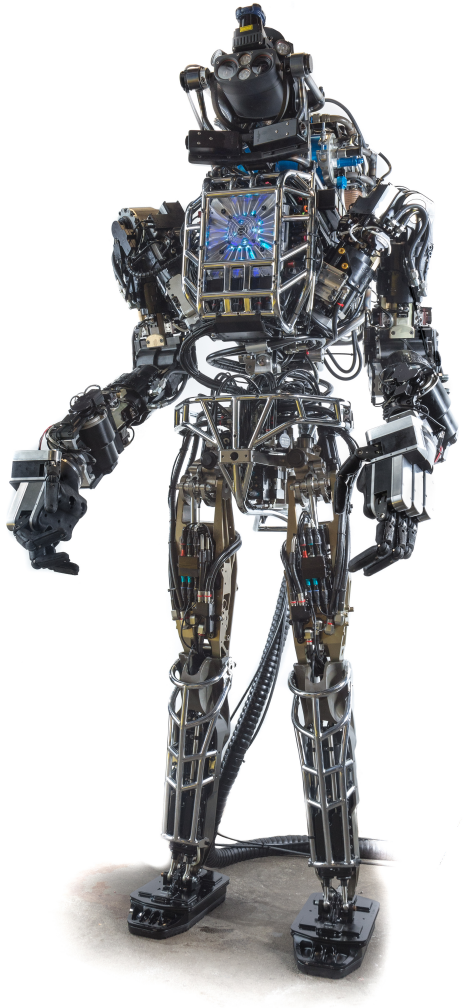
- Robotics!

Applications of SLAM

- Robotics!

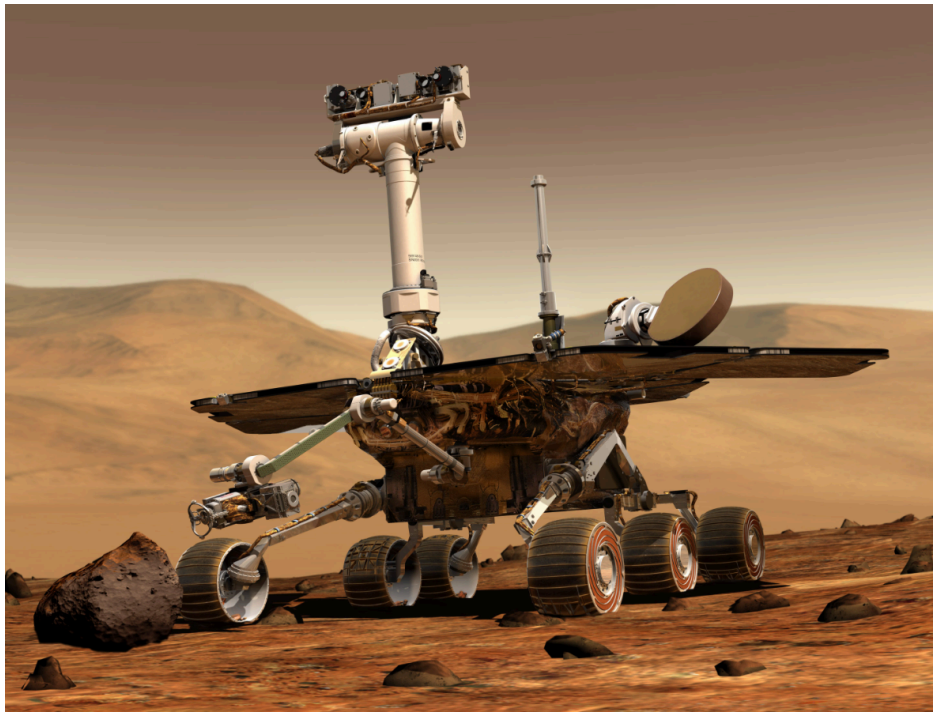






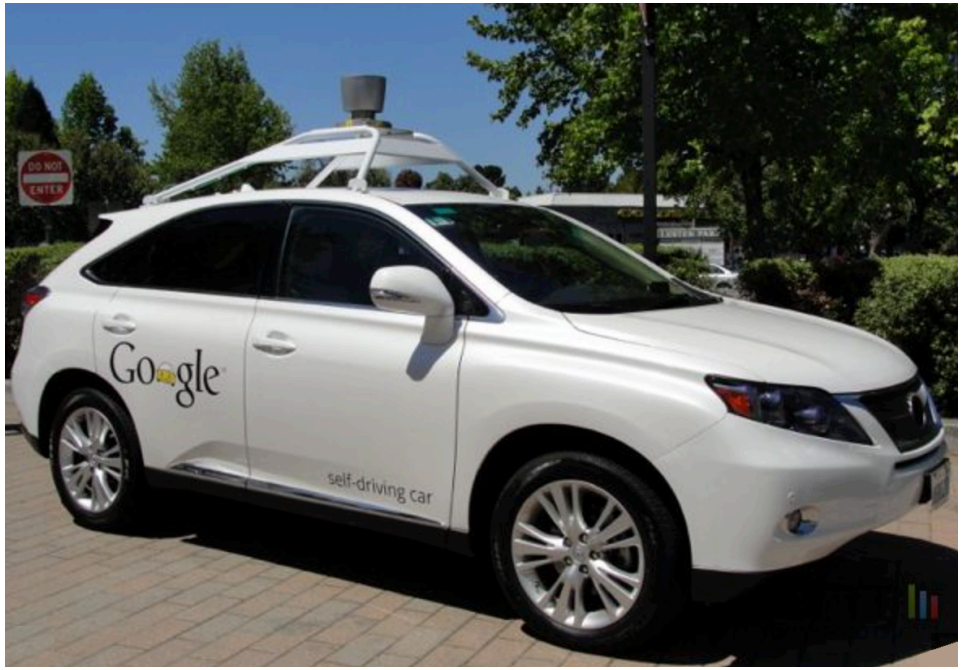
Applications of SLAM

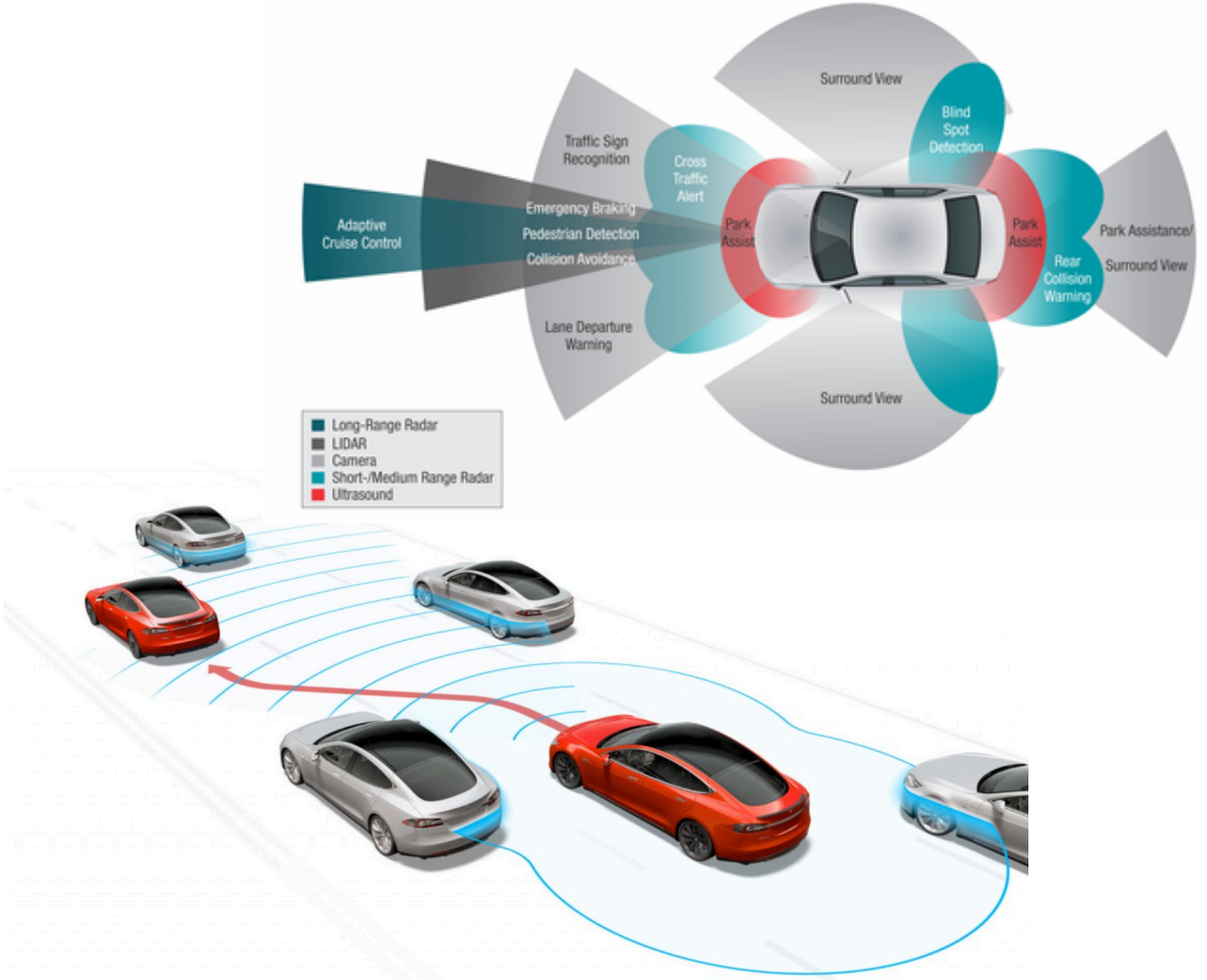
- Robotics!



Applications of SLAM

- Autonomous driving





Applications of SLAM

- Virtual reality!

Head-mounted display (Oculus):
→ Needs to infer 3D head motion!

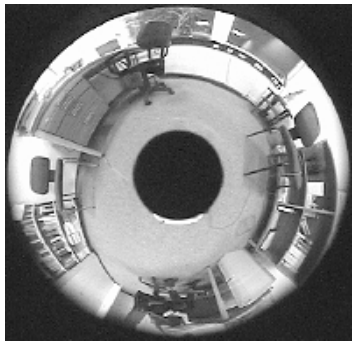
Applications of SLAM

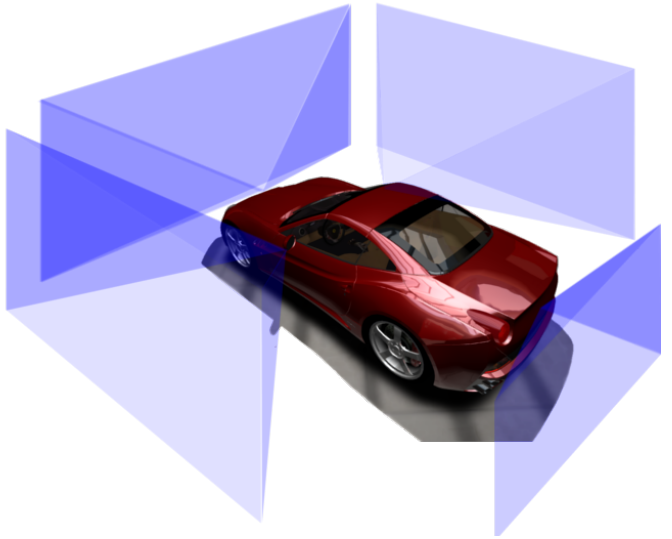
- Augmented reality!

Applications of SLAM

- Mixed reality!

SLAM: different sensors

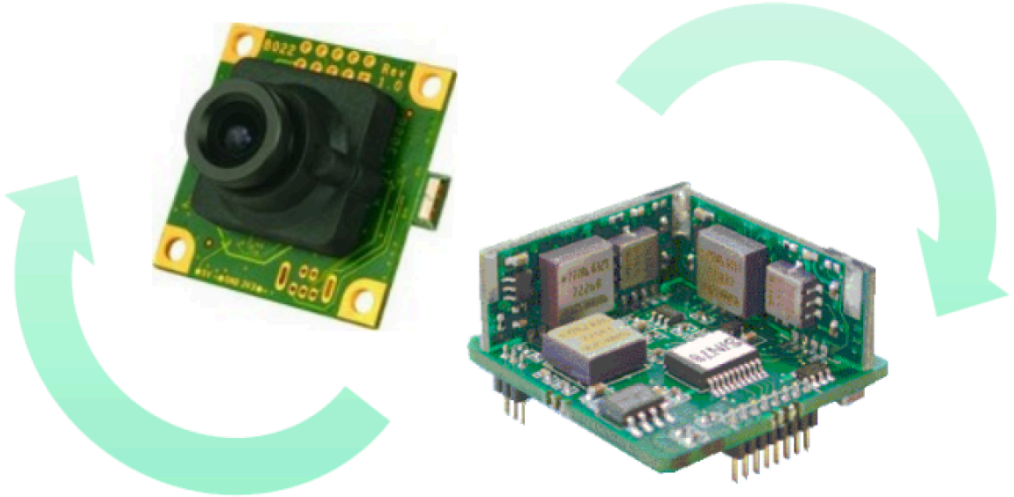


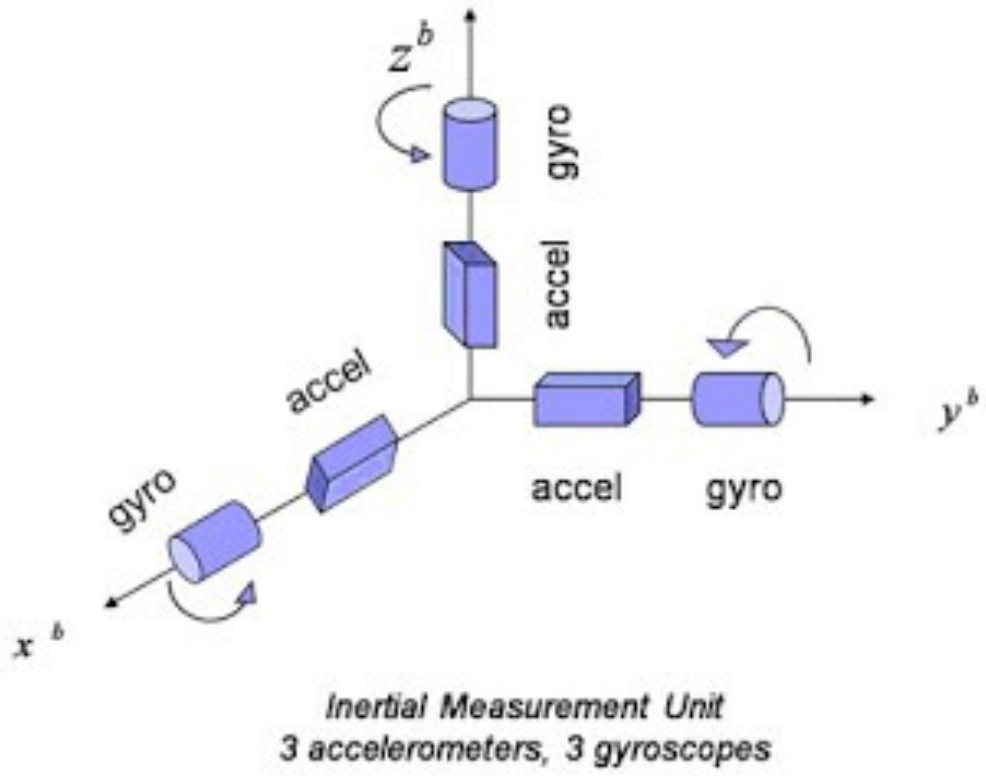


SLAM: different sensors

SLAM: different sensors

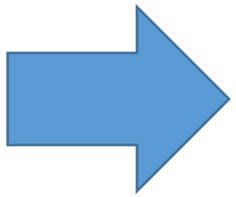
- Inertial sensors

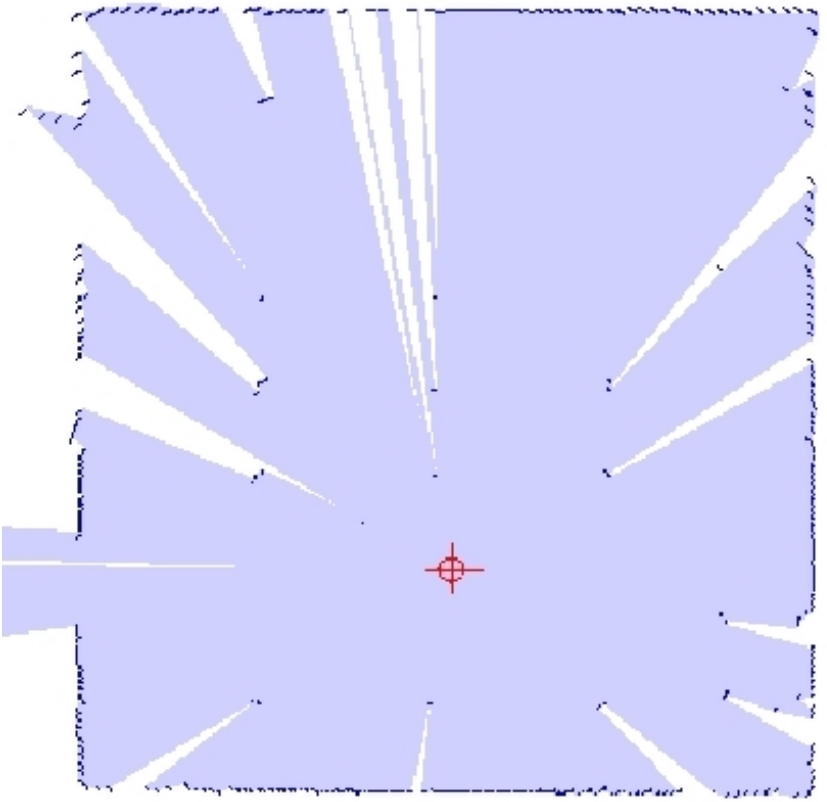




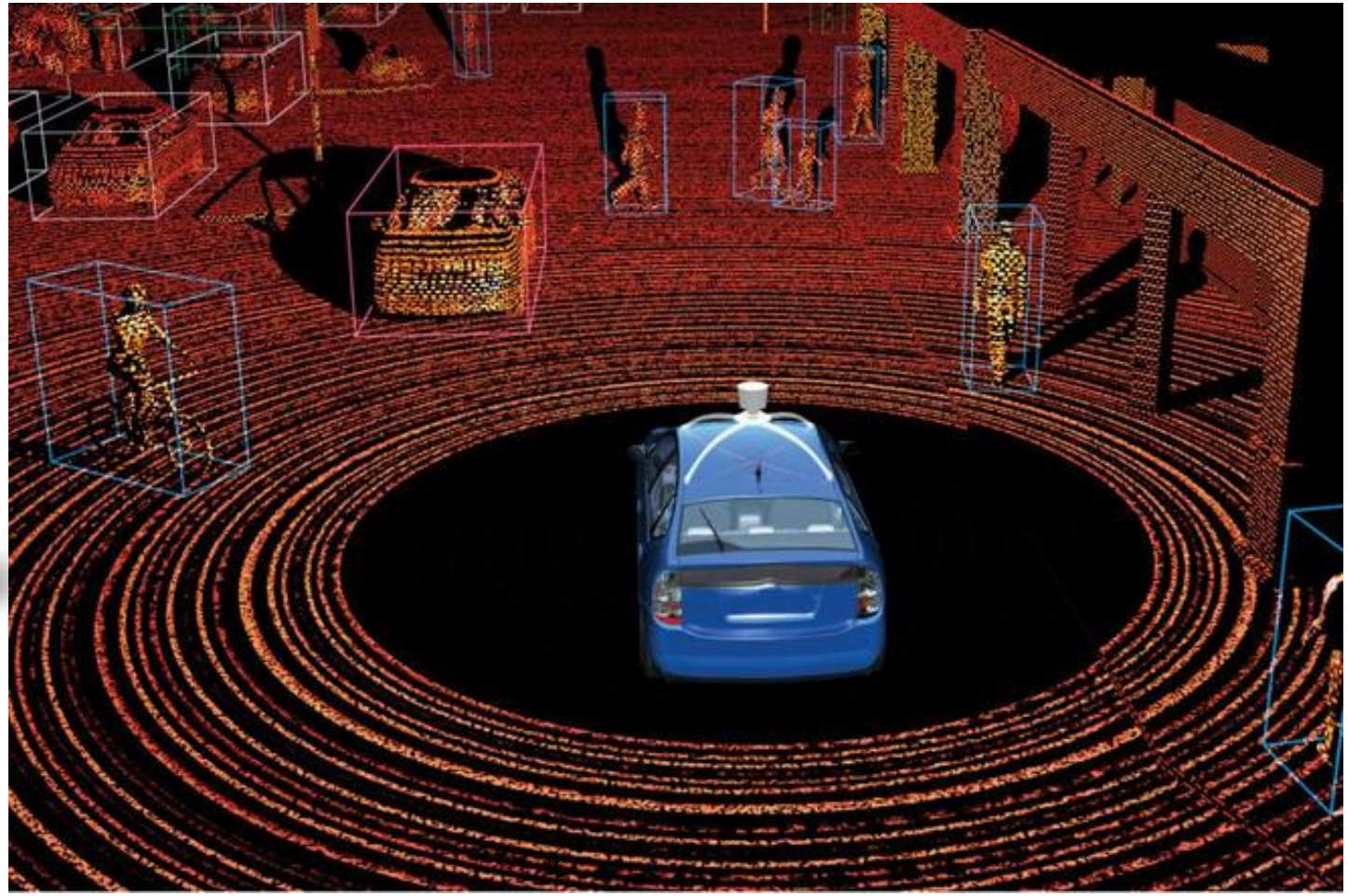
Inertial Measurement Unit
3 accelerometers, 3 gyroscopes

SLAM: different sensors

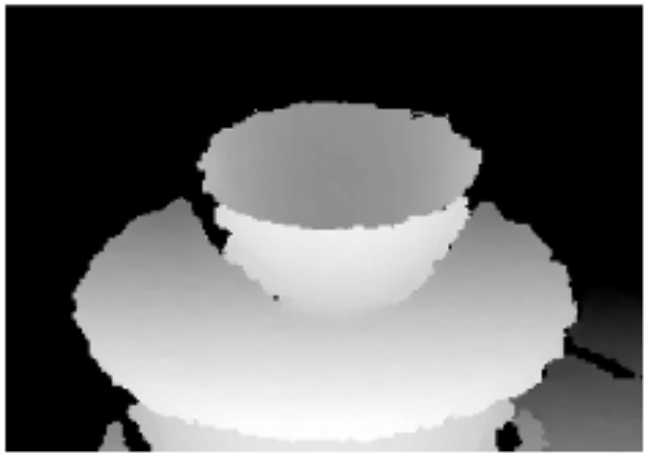




SLAM: different sensors



SLAM: different sensors



KINECT
for XBOX 360.

Curriculum

- Focus:
  - Visual SLAM!

Week	Tuesday course	Thursday course
18th February	Introduction (what is SLAM, curriculum, course structure (homeworks, projects), course webpage	Homogeneous coordinates, Transformations, etc.
25th February	Filtering methods (GF, PF)	Filtering methods (GF,PF)
4th March	Pose-only SLAM, Graph SLAM	Introduction to the projects
11th March	Camera as a sensor, camera calibration	Introduction into Visual SLAM, feature extraction, tracking, and matching
18th March	Feature extraction, tracking, and matching	Case study: MonoSLAM (why filter?)
25th March	Bootstrapping: The Relative Pose Problem	Full visual odometry pipeline, Non-linear optimization, Bundle adjustment
1st April	Non-linear optimization, Bundle adjustment	Place recognition, loop closure
8th April	Place recognition, loop closure, the absolute pose problem	Case study: ORB SLAM
15th April	Dense Tracking and Mapping (DTAM), Photometric vs geometric errors, semi-dense opt.	RGBD SLAM, Iterative closest points (Laser-point cloud registration), TSDF
22nd April	SLAM with Stereo and Multi-Perspective cameras	Midterm exam
29th April	Visual-Inertial SLAM	Project discussions/buffer
6th May	Dynamic and Multi-body SLAM	Project discussions/buffer
13th May	Semantic SLAM	Project Presentations

Content: Filtering methods

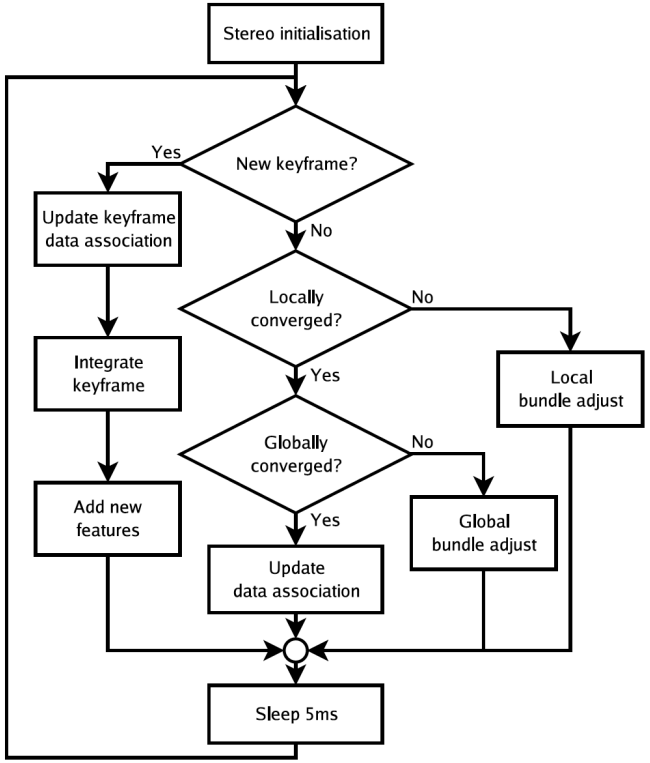
https://www.youtube.com/watch?v=mimAWVm-0qA

- Seminal work: MonoSLAM
- Pros:
  - Real-time execution
  - Map maintenance
- Cons:
  - Coupled tracking and mapping
  - EKF linearlisation errors
  - Low efficiency

[Source: Davison, Reid, Molton, Stasse, *MonoSLAM: Real-time Single Camera SLAM,* TPAMI'07]

Content: Full visual SLAM pipelines

- PTAM



https://www.youtube.com/watch?v=Y9HMn6bd-v8

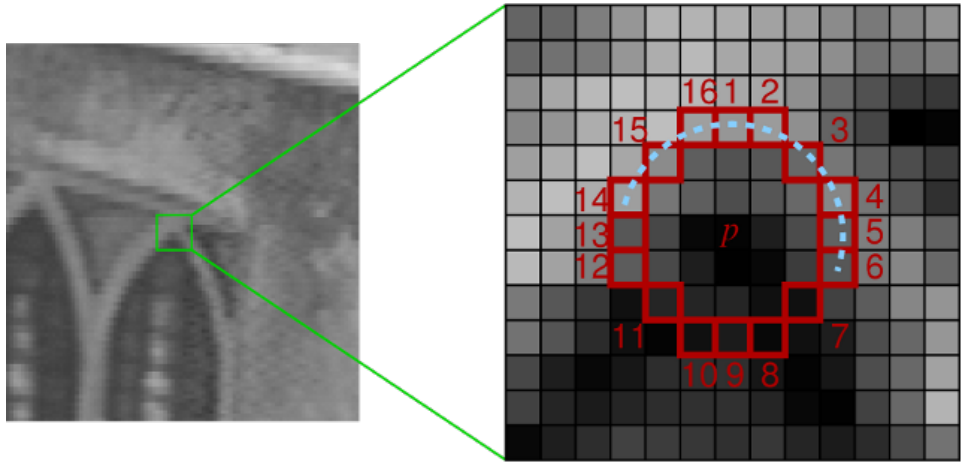
Content: Full visual SLAM pipelines

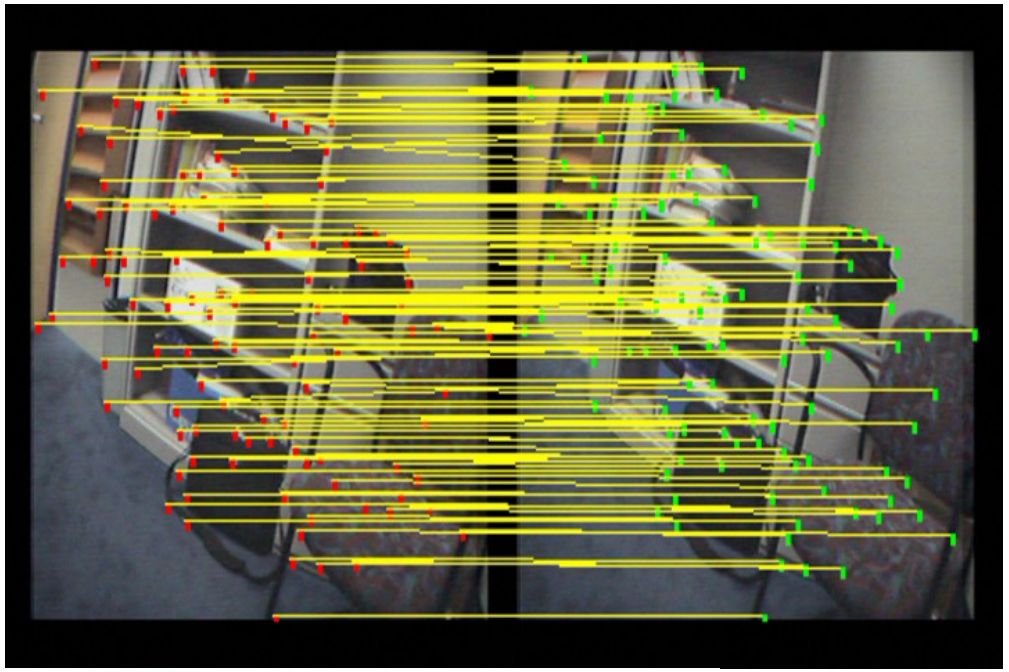
- ORB-SLAM: Efficient binary keypoints
  - Permits addition of vocabulary tree
    → view-point change resilient place recognition/relocalization
    → loop closing for drift compensation
    → efficient feature matching

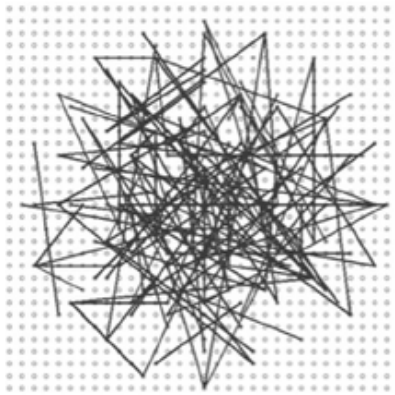
https://www.youtube.com/watch?v=ufvPS5wJAx0

Content: Feature extraction

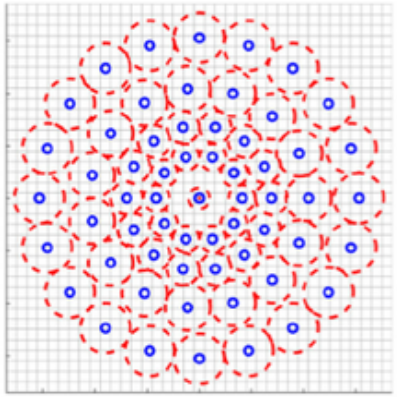
- Real-time operability





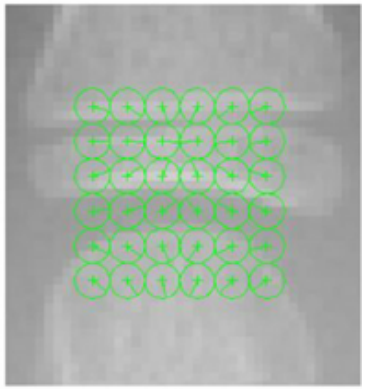


(i)



(ii)

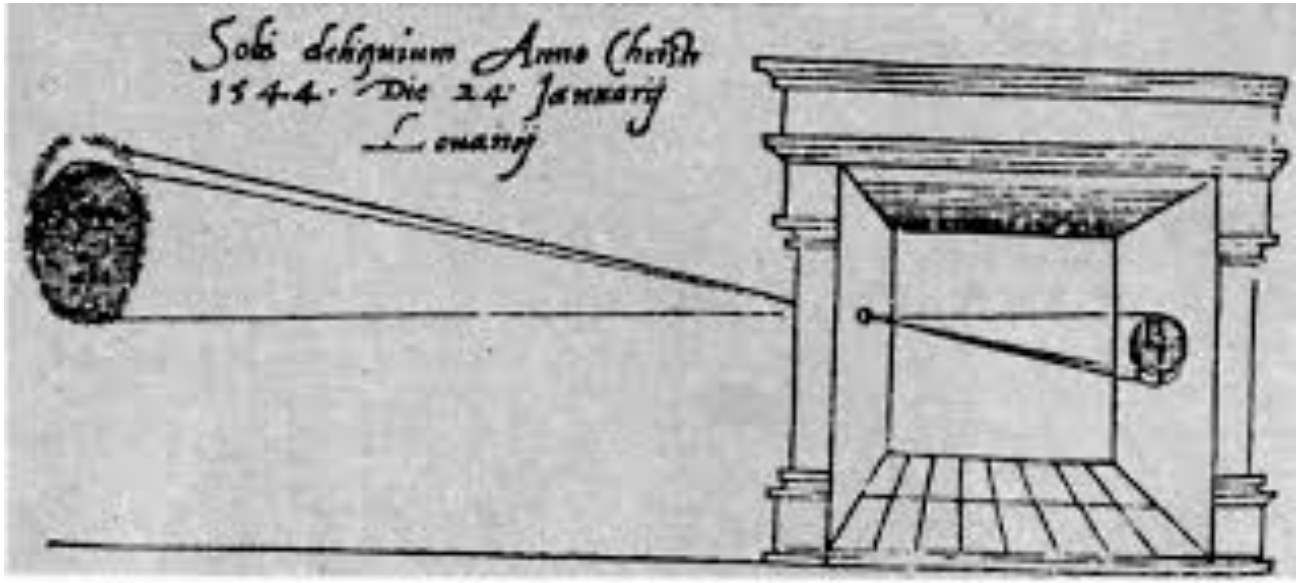
(iii)



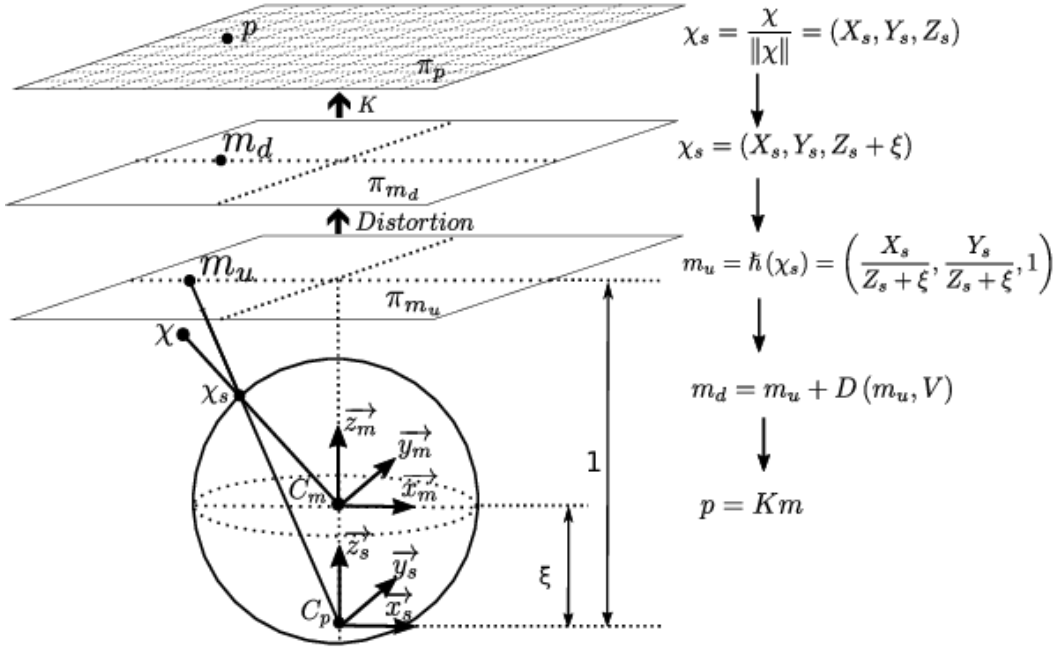
(iv)

Content: Camera geometry

- From the “camera obscura” to omni-directional, generalized camera models

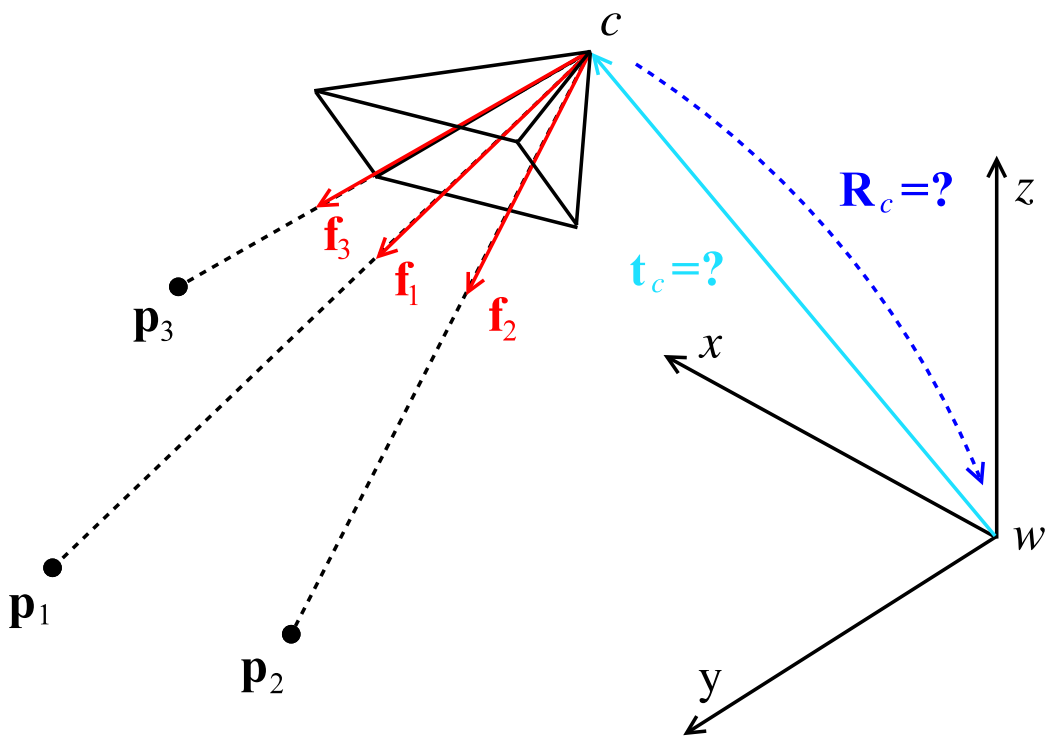


Camera obscura. R.G. Frisius, 1545

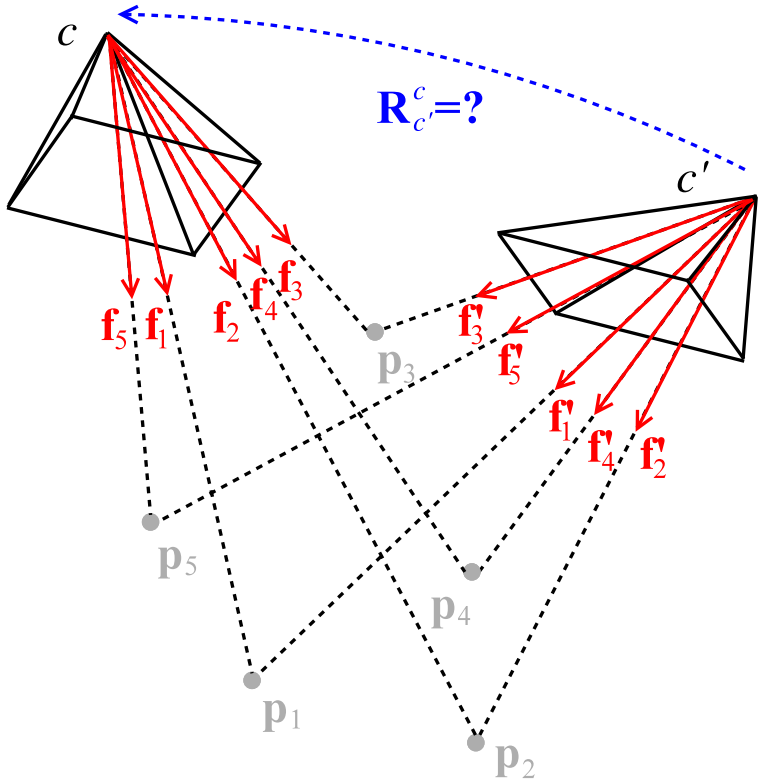


Content: Camera pose estimation

- The fundamental building blocks of structure from motion



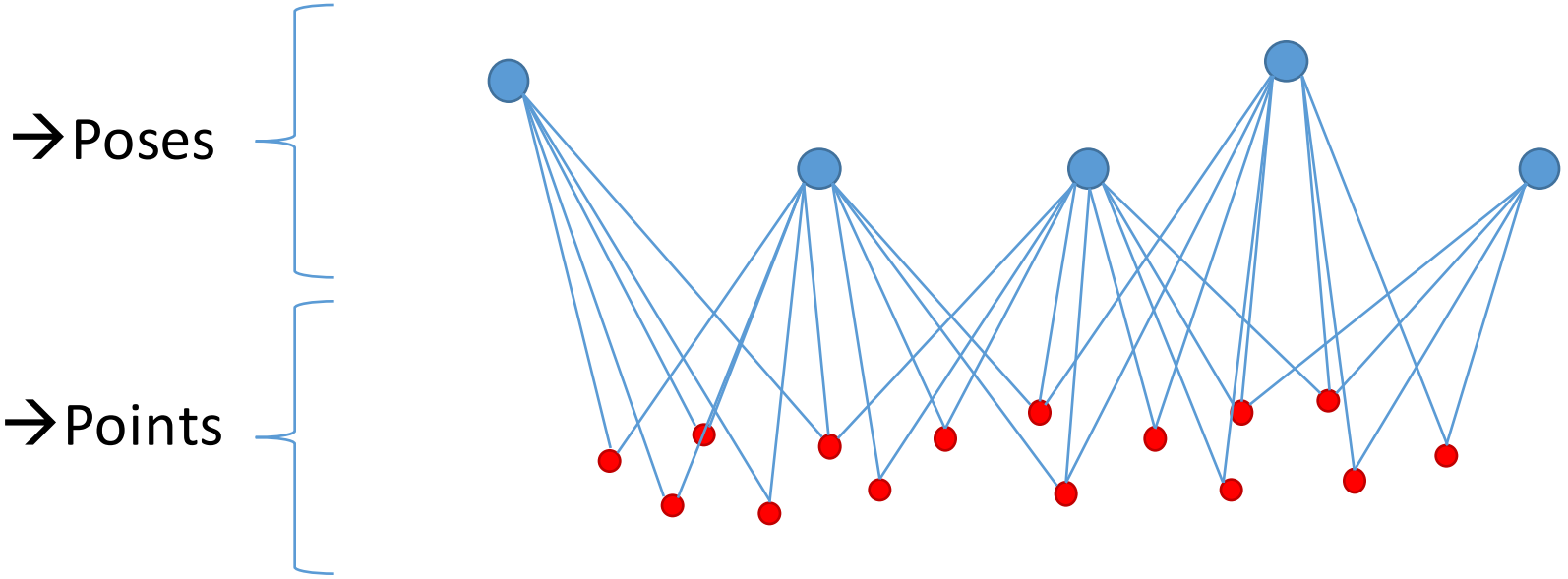
- Absolute Pose



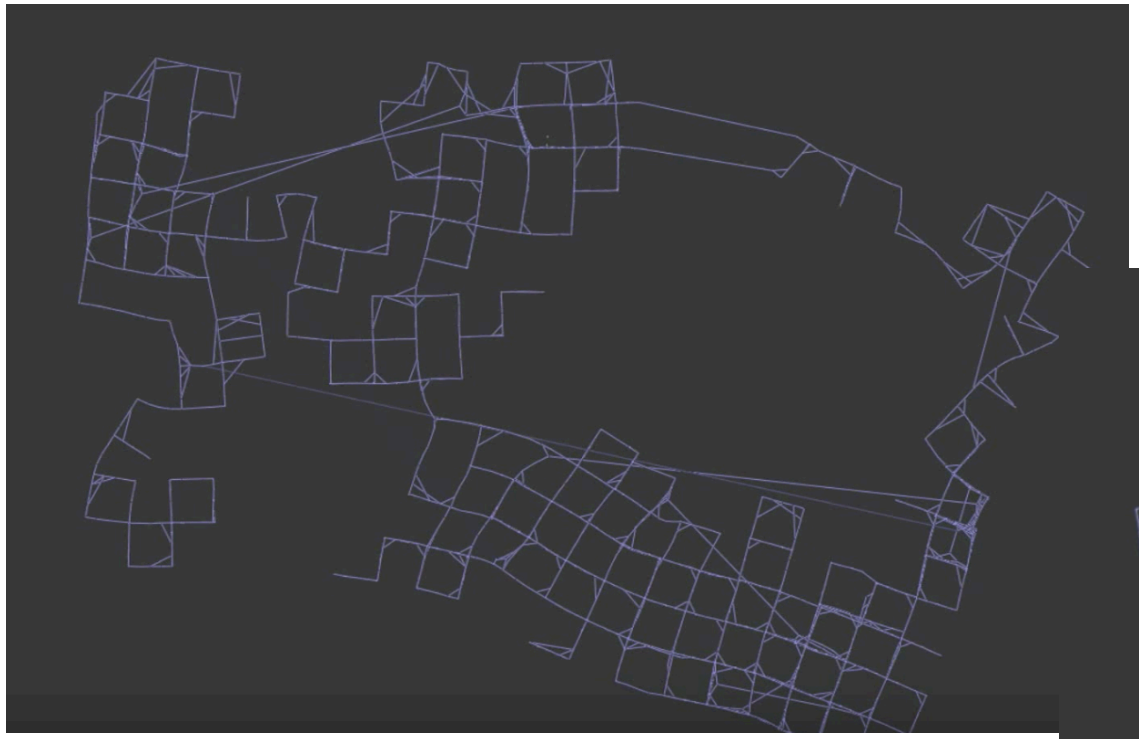
- Relative Pose

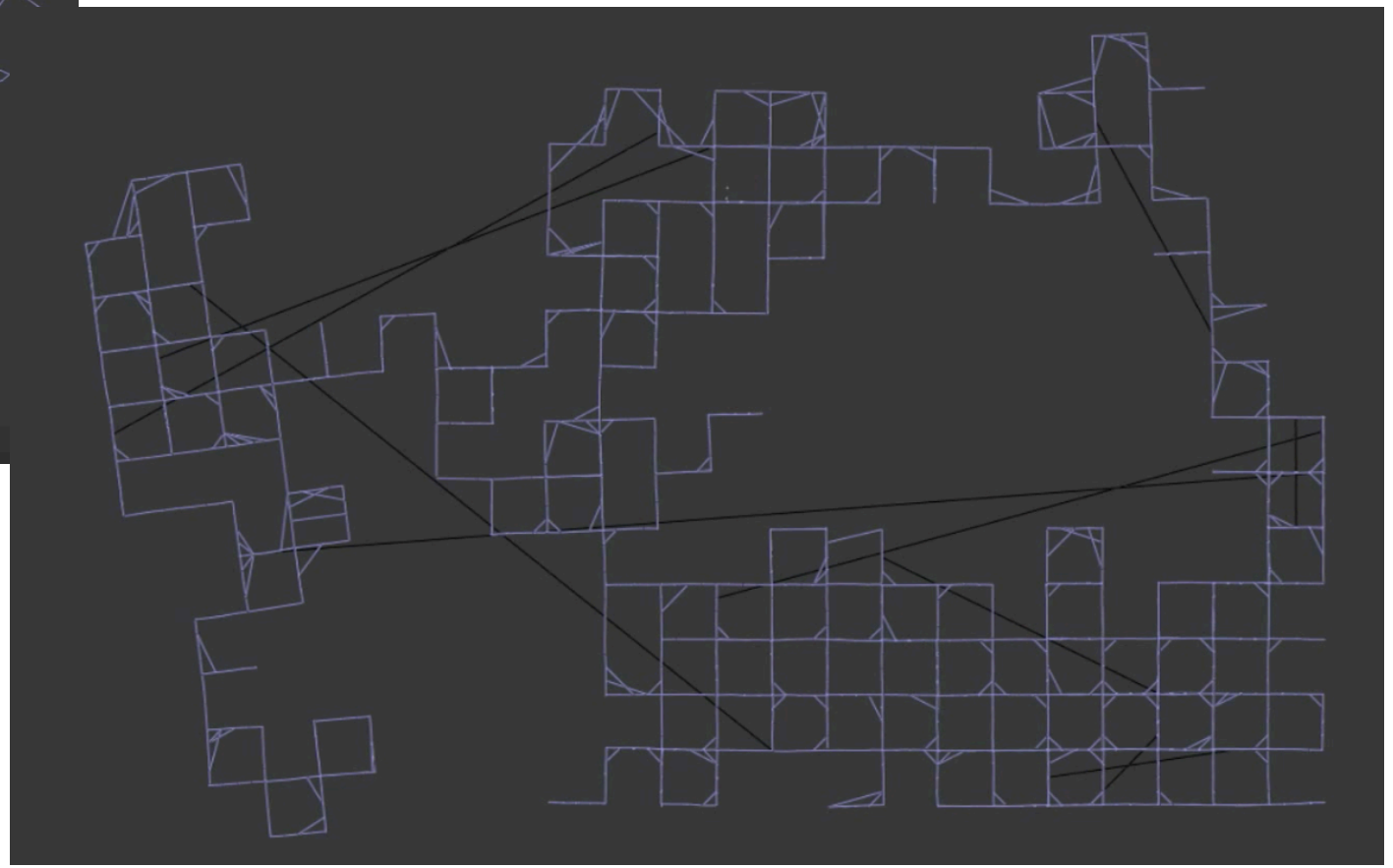
Content: Bundle adjustment

- Simultaneous optimization of poses and structure

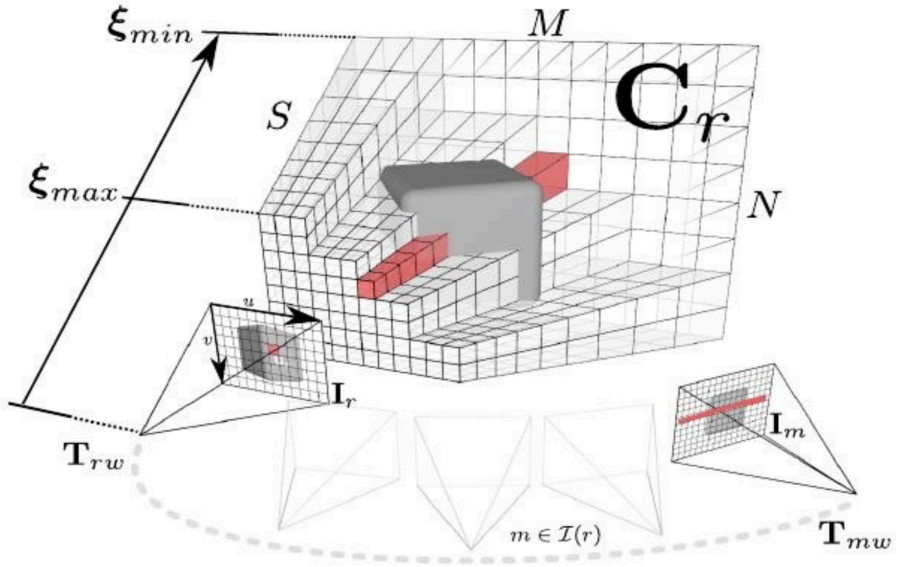


Content: Loop closures, graph relaxation





Content: Dense Tracking and Mapping



https://www.youtube.com/watch?v=Df9WhgibCQA

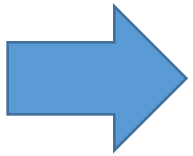
[Newcombe, Lovegrove, Davison, ICCV'11]

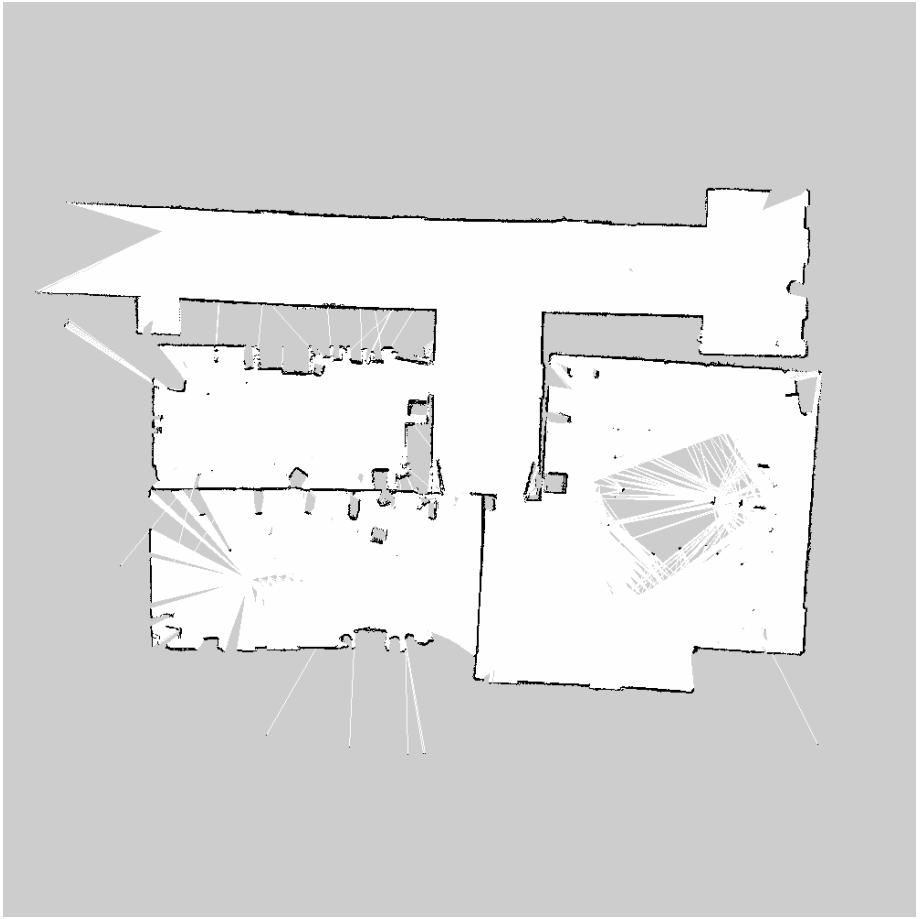
Content: RGBD-SLAM

https://www.youtube.com/watch?v=quGhaggn3cQ

Content: SLAM with 2D Lidars

- Gmapping





Content: SLAM with 3D Lidars

https://www.youtube.com/watch?v=08GTGfNneCI

[Wide-Area Indoor and Outdoor Real-Time 3D SLAM, Erik Nelson, UC Berkeley Dept. of EECS, Lawrence Berkeley National Laboratory]

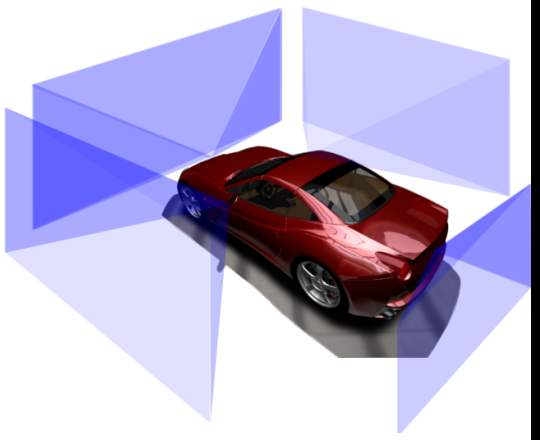
Content: Representations

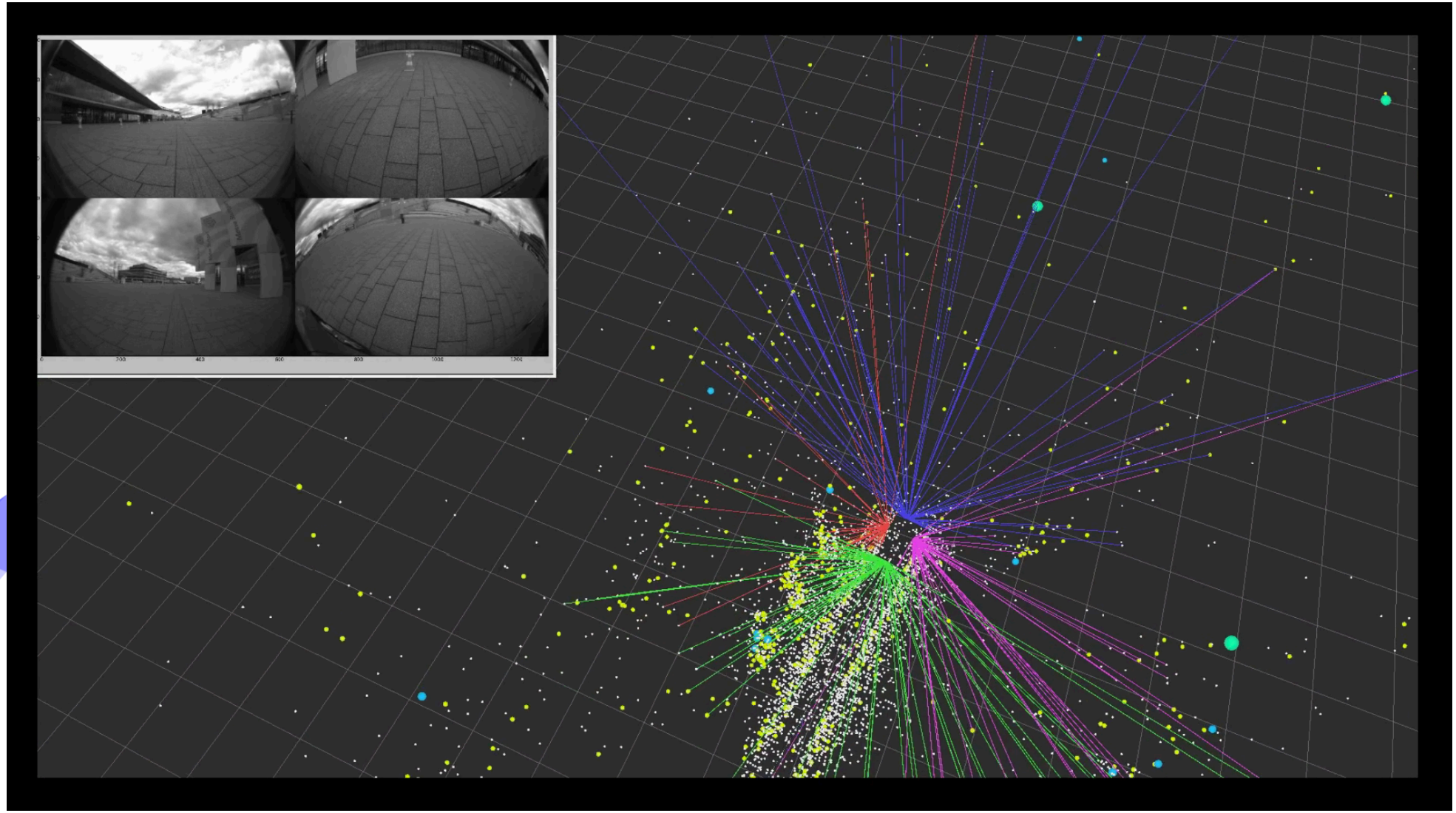
https://www.youtube.com/watch?v=GnuQzP3gty4

Content: SLAM with multi-perspective cams

MPL
Mobile Perception Lab

V-CHARGE





Content: SLAM with multi-senor systems

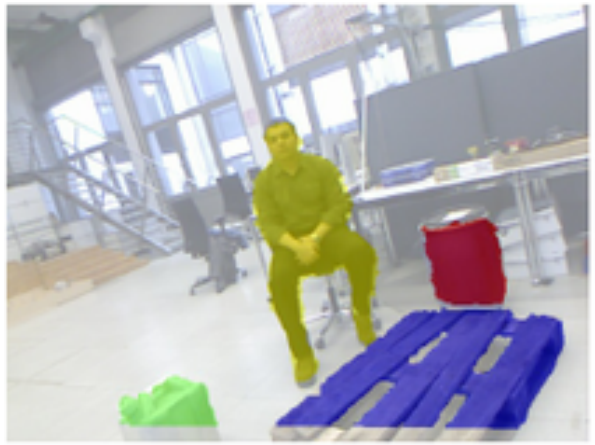
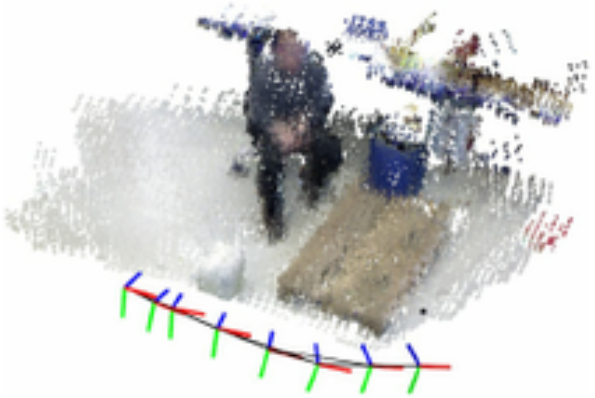
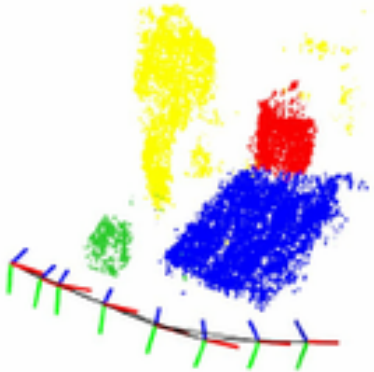
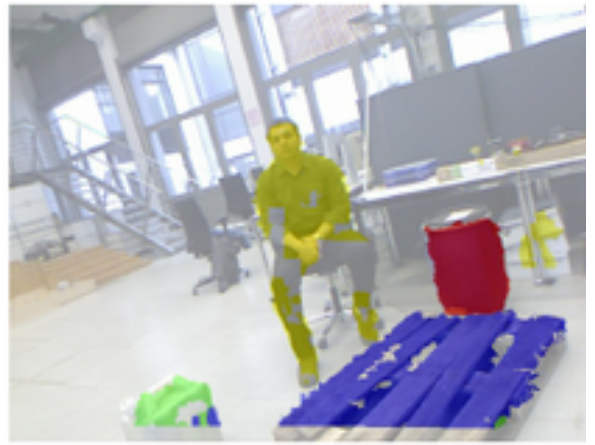
- Visual-inertial SLAM: OKVIS

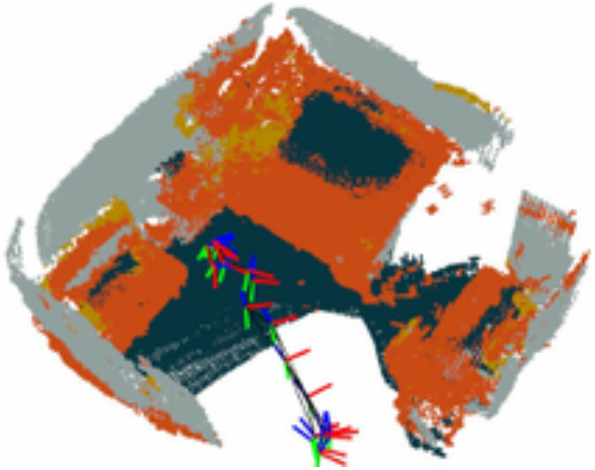
https://www.youtube.com/watch?v=TbKEPA2_-m4

Content: SLAM in dynamic environments

https://www.youtube.com/watch?v=i1eZekcc_lM

Content: Semantic SLAM


CS284: Course overview

- Items:
  - Next to regular lectures, we will also have some case studies where published frameworks are investigated in more detail. Papers will be distributed.
  - About 4 homeworks will have to be finished during the semester (involves coding in C++ and Python, using some off-the-shelf tools)
  - Semester-project! To be presented at the end of the semester! (possible topics will be presented in week 3, teams of 2 or 3)
  - Midterm exam (written exam) (depending on number of students, TBD)

- Grading scheme: 32% Homeworks, 5% Class attendance, 28% Midterm, 35% Project

CS284: Lectures

- Tuesdays 10:15-11:00 & 11:10-11:55, 1D-106:
  - Main lecture!

- Thursday 10:15-11:00 & 11:10-11:55, 1D-106:
  - Another lecture
  - Introduction/Review of homework
  - Discussion of Semester projects
  - Midterm exam
  - Case studies

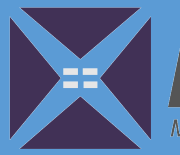
- Attendance is mandatory
  - Will be probed, and will make up for part of the score
  - If absent, medical certificate is required

CS284: Homeworks

- Students will receive individual gitlab accounts used for
  - Receiving templates & test-cases
  - Submitting homeworks

- Strict deadlines will be applied
  - Sufficient time for each homework will be granted
  - We will pull all repositories straight after the deadline
  - Late submission policy:
    - 50% penalty if submitted before next day Monday 11:59pm
    - 100% penalty if no submission by 11:59pm on that day
  - Modifications to the deadlines are possible if sufficient demand exists

CS284: Projects



- Possible topics will be presented in week 3 or 4
- Students may propose own projects
- Makes up for large part of your grade!
- Projects have to be submitted by the last week
- Projects have to be presented in the final lecture
- Projects should happen in teams of two or three

CS284: Course overview

- TAs:
  - Hu Lan (hulan@shanghaitech.edu.cn)
  - Yu Peihong (yuph@shanghaitech.edu.cn)

- Course webpage:
  - Piazza: ShanghaiTech, Spring semester, CS284
  - https://piazza.com/shanghaitech.edu.cn/spring2019/cs284/resources
  - Will contain
    - Lecture slides (including these slides)
    - Homeworks
    - Q&A forum
  - **Please enrol by yourself if I fail to do so!**

- Contact if problems:
  - lkneip@shanghaitech.edu.cn
  - First try to find answer by yourself
  - Then use Piazza
  - Then contact TAs
  - Then come to office hour (Wednesdays, 17:00-18:00)

Academic integrity

- Unless explicitly noted, work turned in should reflect your independent capabilities!
- No cheating
  - Do not share your homework/gitlab PW under any circumstances
  - No “fake solutions” (**we will check!**)
  - **No plagiarism** (copying of part/complete solution from somewhere else) (**we will check!**)
  - **Serious consequences, including the possibility of being expelled!**