Robot Perception

Introduction

Dr. Chen Feng
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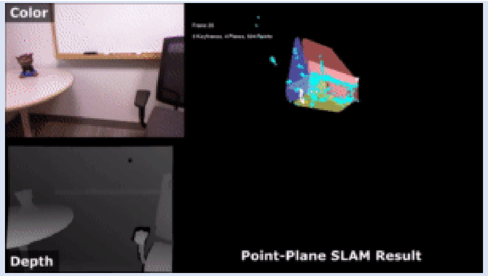
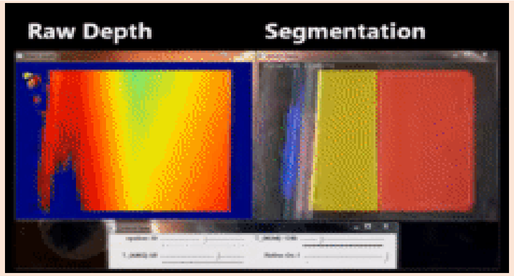
ROB-GY 6203, Fall 2022

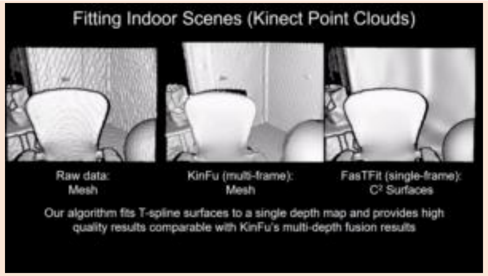
AI4CE Lab’s Research in Spatial AI (Vision, Learning, & Robotics)



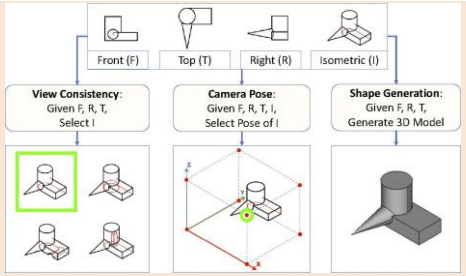
PP-SLAM, ICRA’13



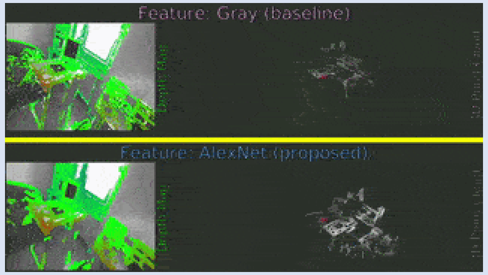
PEAC, ICRA’14



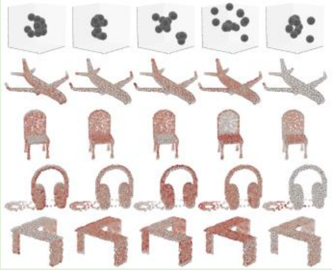
FasTFit, CAD’17



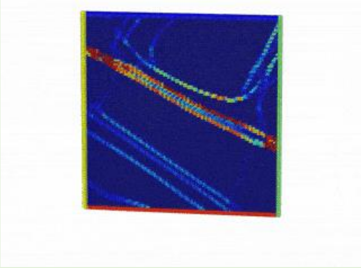
SPARE3D, CVPR’20



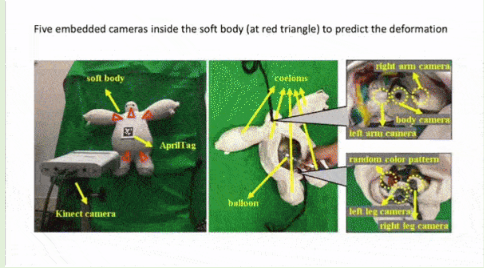
DMT, 3DV’17



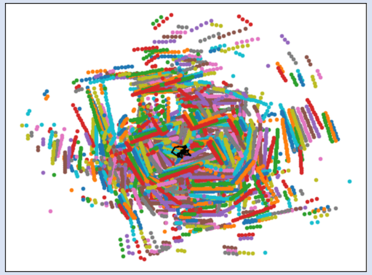
KCNet, CVPR’18



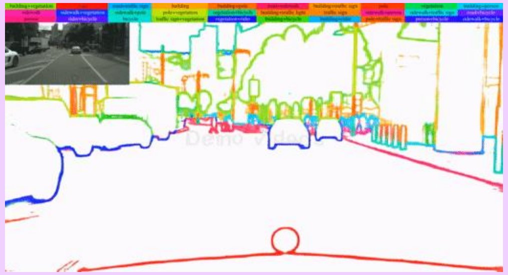
FoldingNet, CVPR’18



DeepSoRo, RAL’20

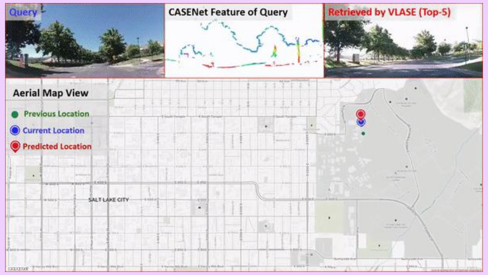


DeepMapping, CVPR’19



CASENet, CVPR’17

SEAL, ECCV’18



VLASE, IROS’18

Course Information

- Syllabus

- Slack

- Students:
  - 3 PhD students, 67 Master students
  - 53 Robotics, 12 ECE/CE, 2 CUE/CUSP, 1 CS

Prerequisites

- Need-to-have
  - Linear Algebra
  - Probability
  - Vector Calculus
- Should-have
  - Assignments: Python (unless you are a fast learner)
  - Project: Python/MATLAB/C/C++/Java/…
- Nice-to-have
  - Image processing
  - Machine learning

Course Objectives

- Describe robot perception models/algorithms and their applicable problem types.
- Compare assumptions in each model/algorithm and their strengths and weaknesses.
- Determine appropriate robot perception models/algorithms for a given problem.
- Formulate a robot perception problem formally.
- Solve the formulated problem with programming tools.

My Teaching Philosophy

- Focus on delivering the knowledge by explaining intuitions in solutions
  - I hope to teach you how to **formulate** problems before discussing the solutions
  - So you can apply the algorithms for new applications in your future career
  - **Expectation for you:**
    - read the given textbook (pick at least one) chapters/sections **before coming to the class**
- Hands-on robot perception experiences via project and homeworks
  - Project-based Learning
  - But this is **not** a programming course
  - So our assignments/exams are not programming heavy, but focus on the knowledge
  - **Expectation for you:**
    - Write codes and play with them **after the class** (use APIs wisely)
- To introduce state-of-the-art **research** in computer vision with a robotics and engineering context
  - **Expectation for you:**
    - **Take this course proactively**, not passively: you can **self-study ahead of** our weekly schedule!

Evaluation Methods

- **All deliverables are due before the start of the class.**
- 15%: 3 in-class quizzes, close-book (no more than 10min each)
- 15%: final open-book exam
- 30%: 2 homework (15% each)
- 40%: course project
  - 5% proposal (1page slide, quad chart style [Google slide template for proposal])
  - 10% mid-term report (2~3 pages, ICRA style [overleaf template for project report])
  - 15% final report (4~6 page, ICRA style)
  - 10% video presentation (5min)
    - Presentation: both the presentation slides and the video are important,.
      - Excellent: smooth, well-designed, properly detailed slides.
      - Poor: non-informative, over-simple or over-complex slides.
  - *each course project component will be rated as excellent/good/fair/poor by a committee

Course Project

- Course project (about 8 hours/week to accomplish a successful course project)
  - Select from a list of given topics
  - No need to include any hardware component, although encouraged if possible.
  - Your project could belong to **one and only one of the four types** listed below:
    - **Engineering** route:
      - Benchmarking (with new dataset)
      - Reimplementation (in a different programming language/library)
    - **Research** route:
      - Improvement (of existing robot perception algorithms)
      - Application (of existing algorithms on new problems)
  - Group project
    - 1<=#group-members<=4

Course Project Topics

- Any topics from Week-02 to Week-13 on the Syllabus
  - Examples:
  - Visual Place Recognition
  - Structure from Motion/vSLAM
  - Lidar-SLAM
  - Multi-modal computer vision
  - 3D Segmentation/Detection/Tracking
  - Deep Learning for Single-Image Depth Estimation
  - Deep Learning for Soft Objects
  - Robot Bin Picking using RGBD camera
  - Hand-Eye Calibration
  - Visual Servoing

Course Project Topics

- Anything related to AI4CE lab's research
  - Examples:
  - Simultaneous Navigation and Construction Benchmarking Environments
  - SPARE3D: A Dataset for SPAtial REasoning on Three-View Line Drawings
  - EgoPAT3D - An Egocentric Action Target Prediction Dataset
  - V2X-Sim: A Virtual Collaborative Perception Dataset and Benchmark for Autonomous Driving
  - DeepMapping: Unsupervised Map Estimation From Multiple Point Clouds
  - Fast Plane Extraction Using Agglomerative Hierarchical Clustering
  - FLAT: Fooling LiDAR Perception via Adversarial Trajectory Perturbation
  - Real-time Soft Body 3D Proprioception via Deep Vision-based Sensing

- Expandable upon request for PhD students

Course Project Examples from Fall’20

- Successful ones
  - 40: https://drive.google.com/file/d/1xbvF1kcH303Pn005Sp78KW43dq2cs9tA/view?usp=sharing
    - https://docs.google.com/presentation/d/1dNTDUru20dGE9T7KY6VTs-C0eUn8sCVTNp4r-hcztB0/edit?usp=sharing
  - 38: https://drive.google.com/file/d/1xbvF1kcH303Pn005Sp78KW43dq2cs9tA/view?usp=sharing
    - https://docs.google.com/presentation/d/1d3v9629K7zrnvmXVE6CUoTbyxGdeLOnT/edit?usp=sharing&ouid=108951929596838347120&rtpof=true&sd=true
  - 37: https://drive.google.com/file/d/1caTTZ24yxiyB9kg-bQaW8CSt4OKtKvY7/view?usp=sharing
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    - https://docs.google.com/presentation/d/16JVArWOOowuDHuV35ojTrxWkRyhBGCfTDKdsnWS7K2U/edit?usp=sharing
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  - 37: https://drive.google.com/file/d/1RaK_gmcjCt_qVCkV7yXoVC3Y3Gr07QeV/view?usp=sharing
- Not so successful ones
  - 31: https://drive.google.com/file/d/1PyeECvzVPVTwMeRD9a-d3NeRQbNskpXW/view?usp=sharing
    - https://docs.google.com/presentation/d/1nHmatn6SbJ_xbAZ8gpZa7hPDPRcF5GFH/edit?usp=sharing&ouid=108951929596838347120&rtpof=true&sd=true
  - 31: https://drive.google.com/file/d/1LLpkOtY2raSrUWNEPTWRS3RGZpng63jt/view?usp=sharing
    - https://docs.google.com/presentation/d/1SdRb-IHg2l-7J4O4b9-4nnA5Liu0IvzP/edit?usp=sharing&ouid=108951929596838347120&rtpof=true&sd=true
  - 31: https://drive.google.com/file/d/1tZwtJ1Mwnb0gJwLobvX6pmK7RQkEOaS0/view?usp=sharing
    - https://docs.google.com/presentation/d/1EvDP0u6NMLofLbjKnZu5fv9H6ci7QDyN/edit?usp=sharing&ouid=108951929596838347120&rtpof=true&sd=true

Useful Resources

- Wikipedia
  - Good way to learn new concepts
  - But do not trust it wholeheartedly

- CVonline: https://sites.google.com/site/cvonlinewiki
  - A dedicated list of wiki links to computer vision
  - And a list of vision-related online books
  - Some maybe outdated

- Paper with code: https://paperswithcode.com/

- Google/Bing/Google-Scholar should be your best friend!

Related Conferences

- CVPR: Computer Vision and Pattern Recognition
- ICCV/ECCV
- ICRA: IEEE International Conference on Robotics and Automation
- IROS
- 3DV
- ISARC: International Symposium on Automation and Robotics in Construction

Open-Source Libraries & Tools

- OpenCV
- PCL: Point Cloud Library
- Open3D
- NumPy/Eigen
- Google Ceres, G2o
- Scikit-learn
- PyTorch, TensorFlow/Keras

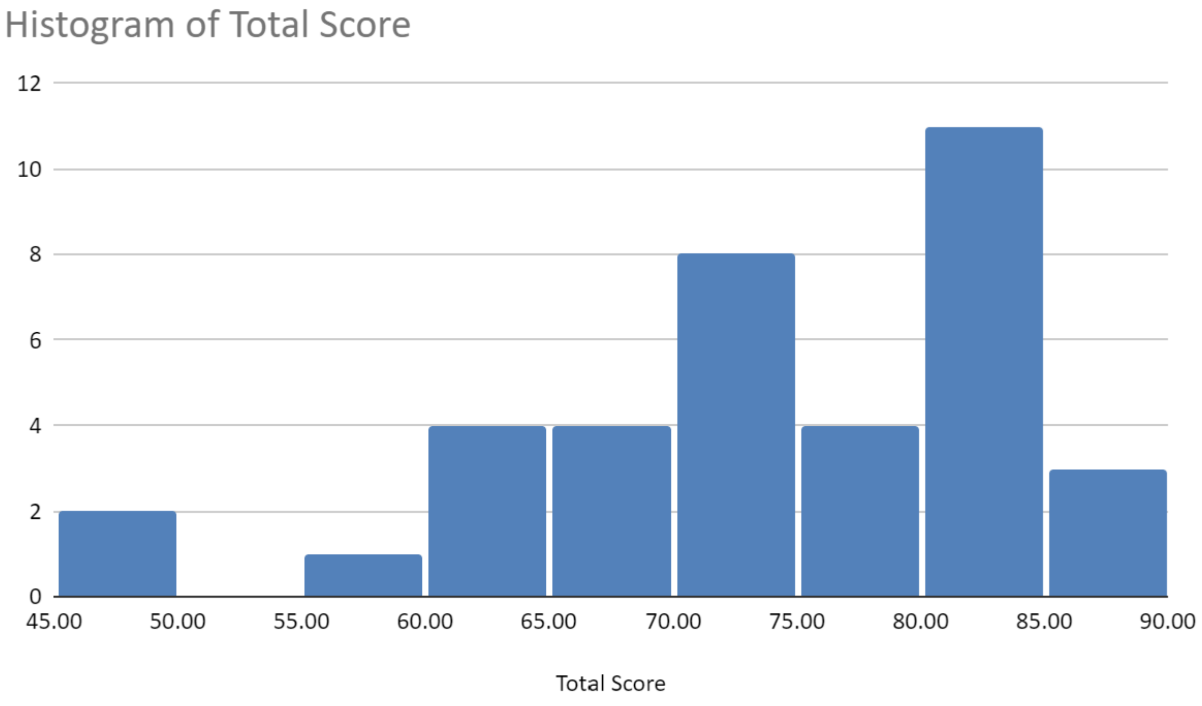
- MeshLab/CloudCompare
- COLMAP

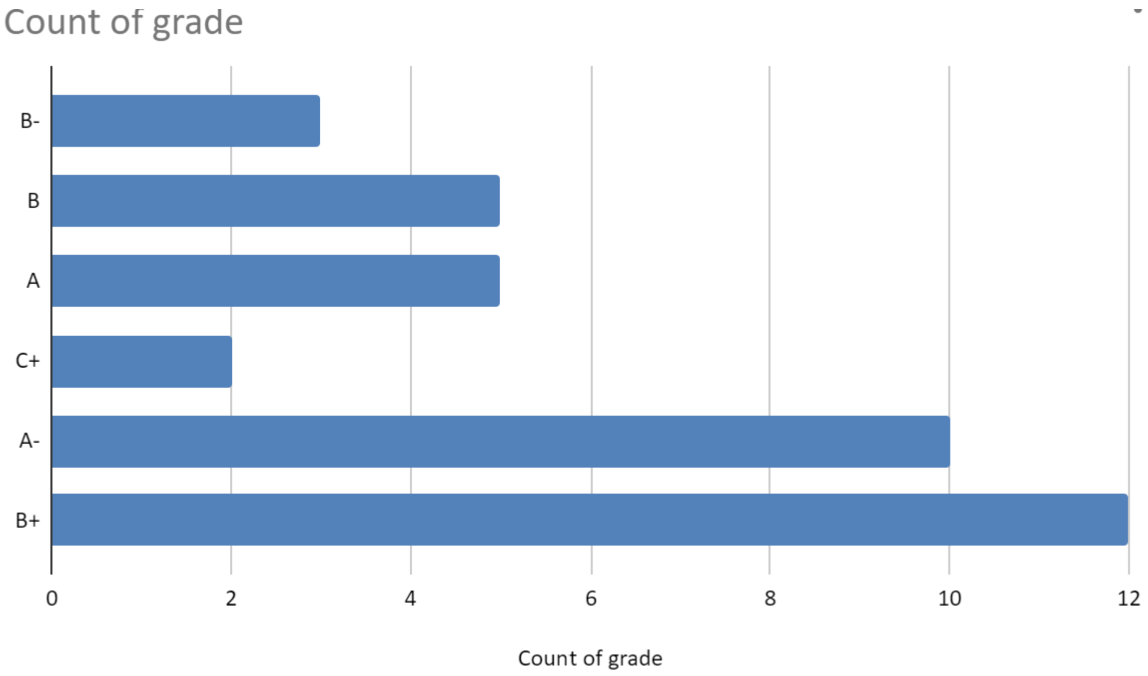
Q & A / Office hours

- Always use Slack first
  - DM the TAs if the question only applies to yourself
  - Use #qna is the question (and answers) might help more students
- If slack is not enough, we can make 1on1/Zoom appointments
  - We will not accept any appointments without discussion on slack first.
  - We have a large cohort, so first come, first served

Statistics from Fall'21

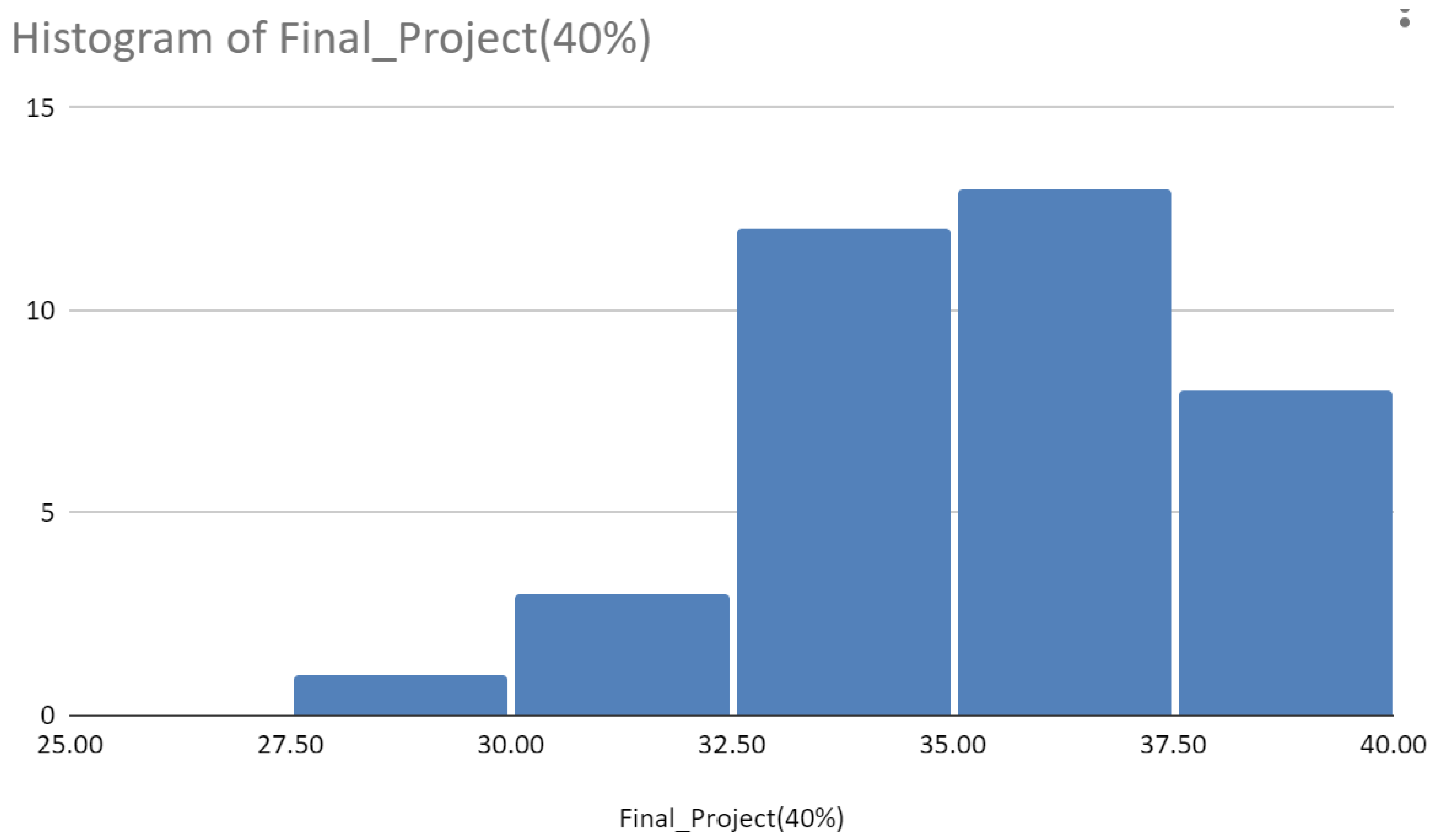
- Overall Course Score/Grade Distribution





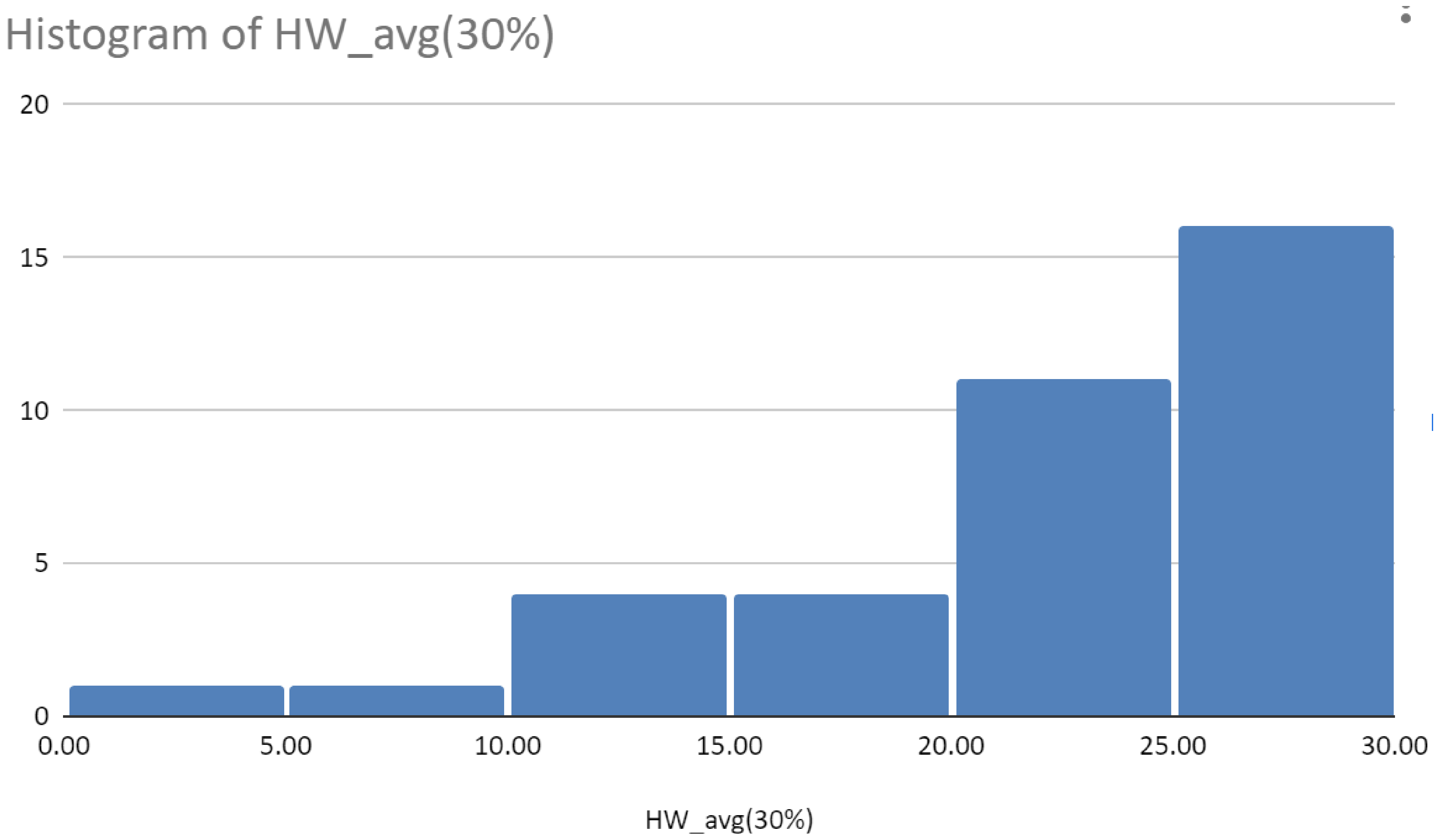
Statistics from Fall’21

- Course Project Grade Distribution



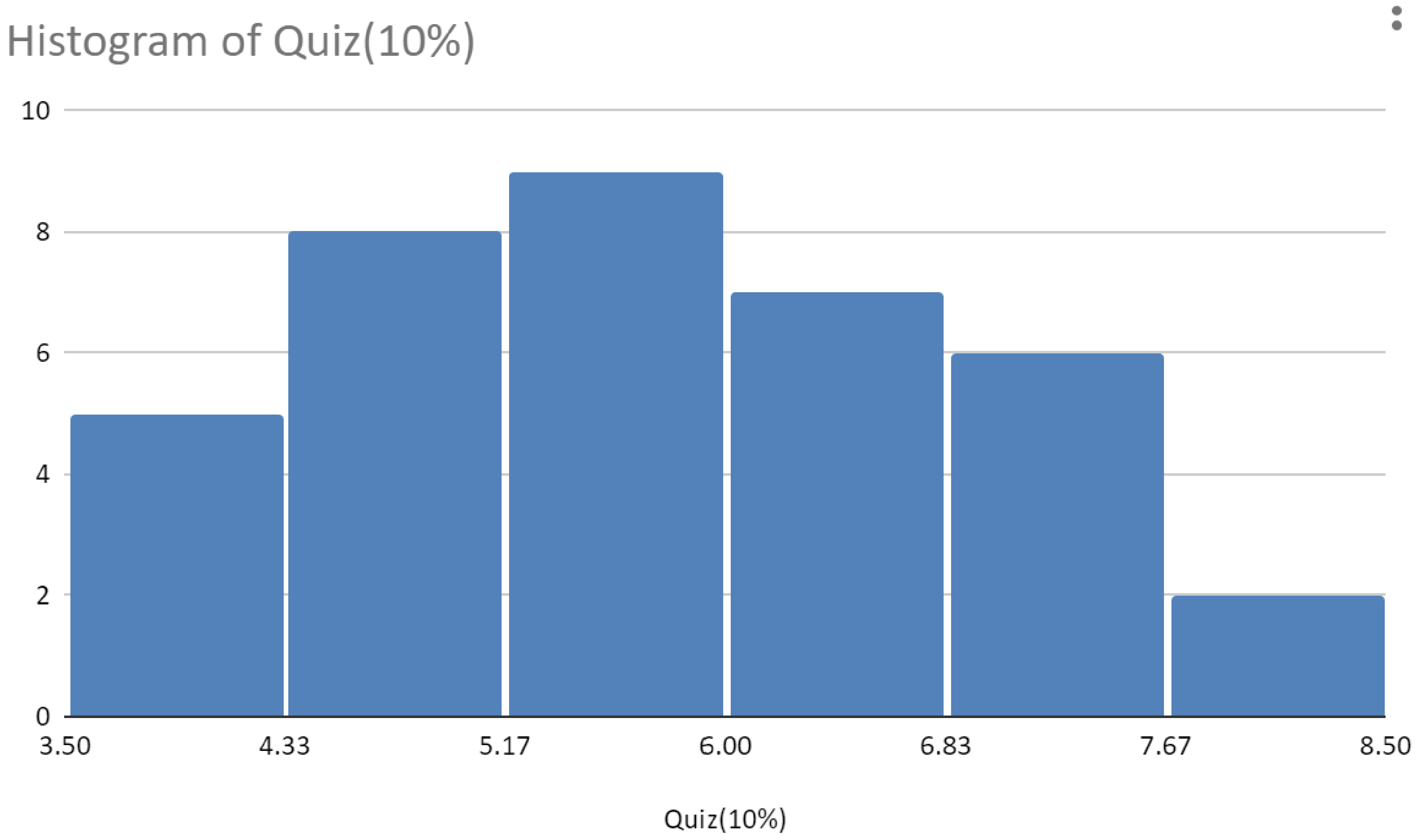
Statistics from Fall’21

- HW Grade Distribution



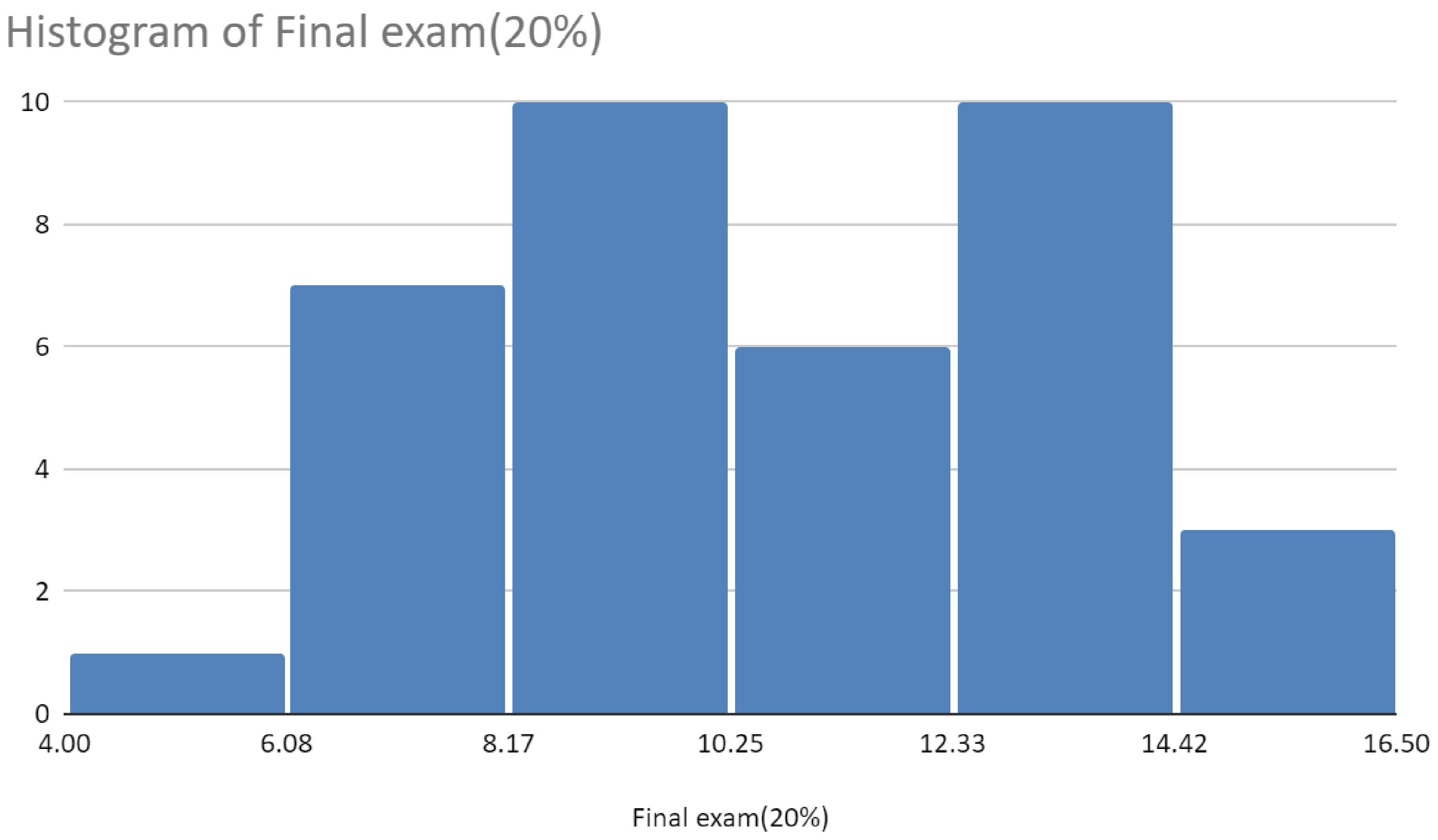
Statistics from Fall'21

- Quiz Grade Distribution



Statistics from Fall’21

- Final Exam Grade Distribution



Definition of Robot Perception in This Course

- Robot
  - A machine capable of carrying out a complex series of actions automatically
  - Regardless of how it looks
  - With a bit of a stretch in scale, an automated system also counts
- Perception
  - The *awareness* of the elements of environment through physical *sensation*
  - The process of becoming *aware* of something through the *senses*

Definition of Robot Perception in This Course

- Robot Perception
  - The hardware and software
  - to sense and process raw signals
  - to become aware of the states of a system itself and/or its surroundings
  - which enables the system to take proper actions to fulfil its design goals

- Shortened version
  - **Observing data** to **understand situations** for achieving system objectives

Types of Robot Perception

- Visual
  - Hardware: cameras, LIDAR (line-of-sight sensors)
  - Software: **computer vision, machine learning**
  - The focus of this course
- Auditory
- Tactile

Related Disciplines – Can you link different research areas?

Artificial Intelligence

NLP/Speech

Image Processing

Neuroscience
Cognitive Science

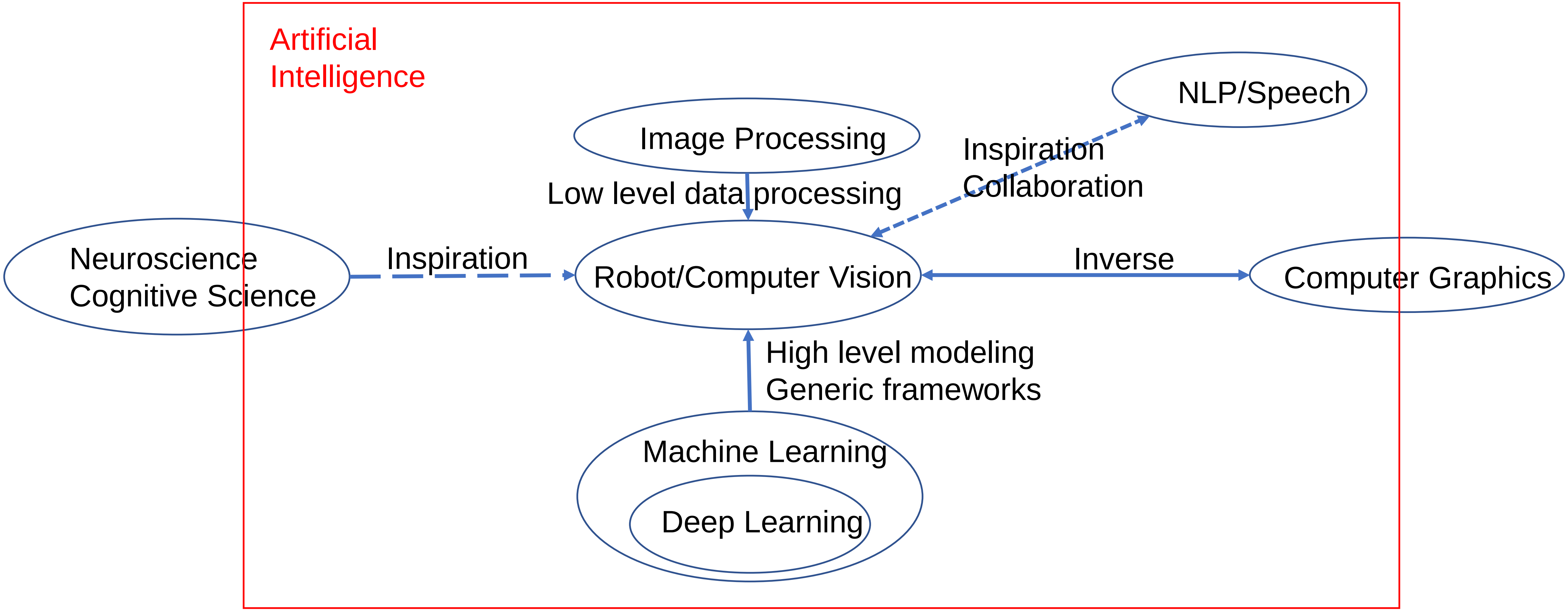
Robot/Computer Vision

Computer Graphics

Machine Learning

Deep Learning

Related Disciplines



A Brief History of Computer Vision

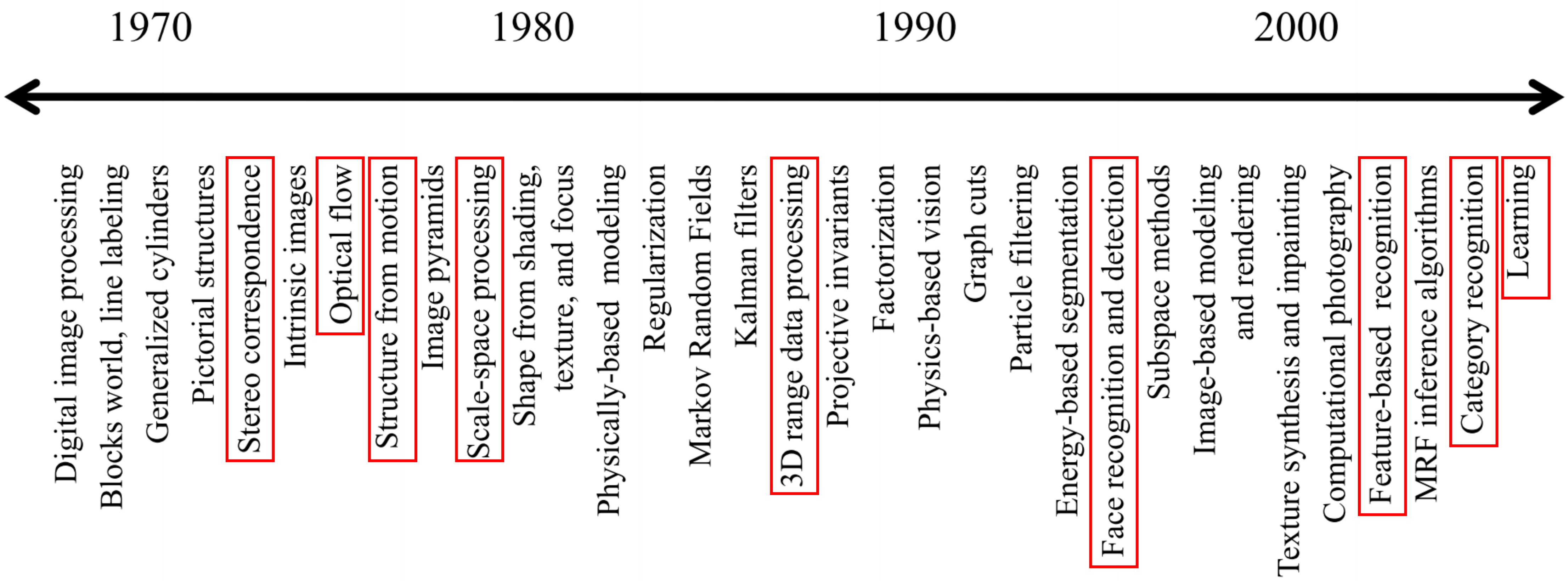


Image from: Szeliski 2011

Main Topics in Computer Vision

- Shape/Structure
- Pose
- Segmentation
- Detection
- Tracking
- Recognition

Motivating Examples

- Humanoid/Legged Robots
- Manufacturing
- Transportation
- Civil/Construction Engineering
- Space Exploration
- Architecture
- Agriculture
- Medical/Health
- Entertainment

DARPA Robotics Challenge

Video from: https://youtu.be/wX0KagJ1du8

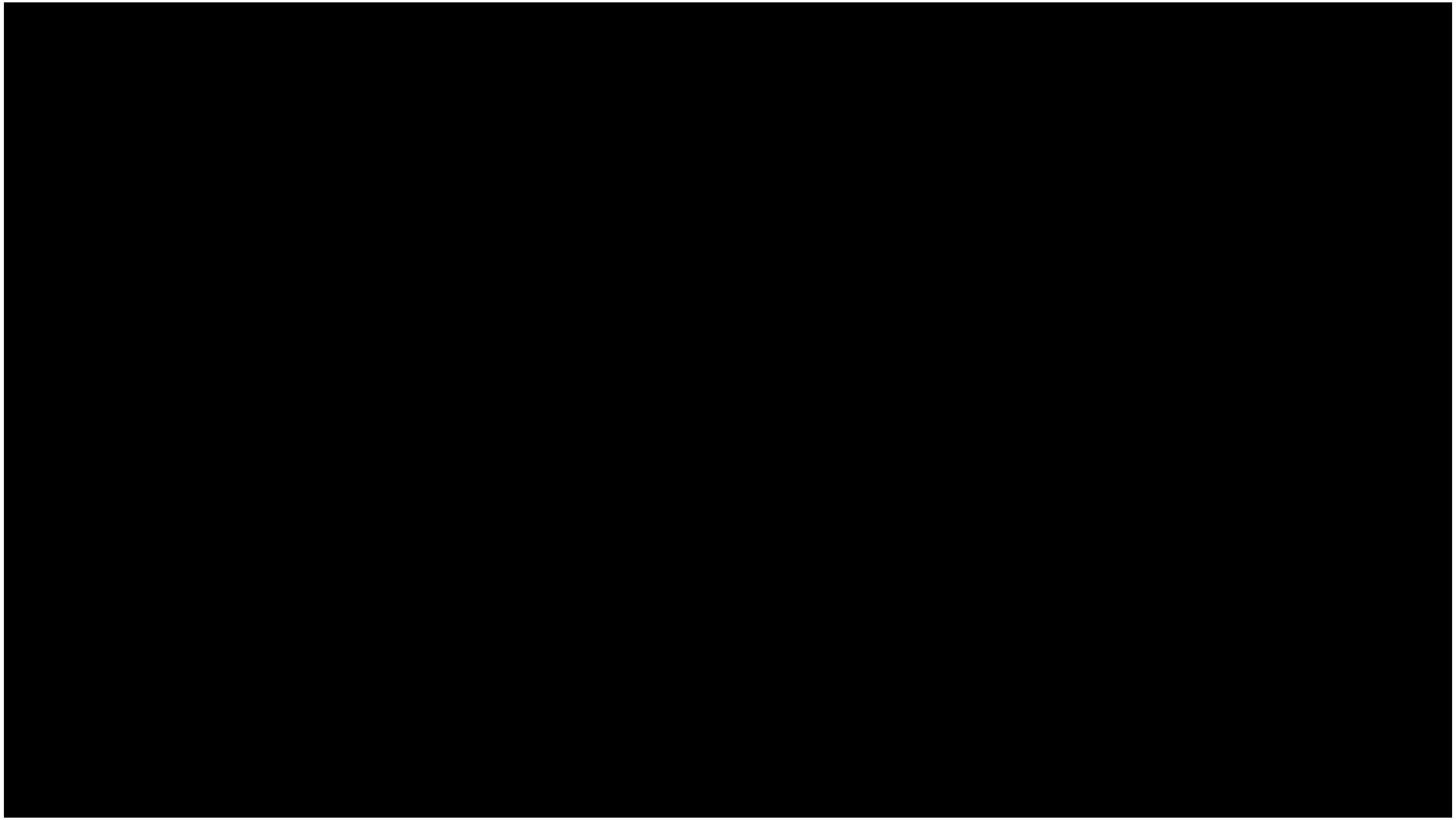
Boston Dynamics

Video from: https://youtu.be/Ve9kWX_KXus

Drones in the lab

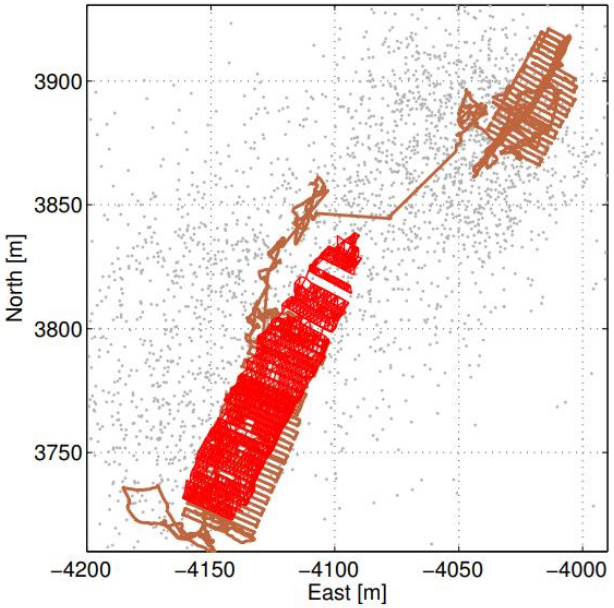
Video from: https://youtu.be/w2itwFJCgFQ

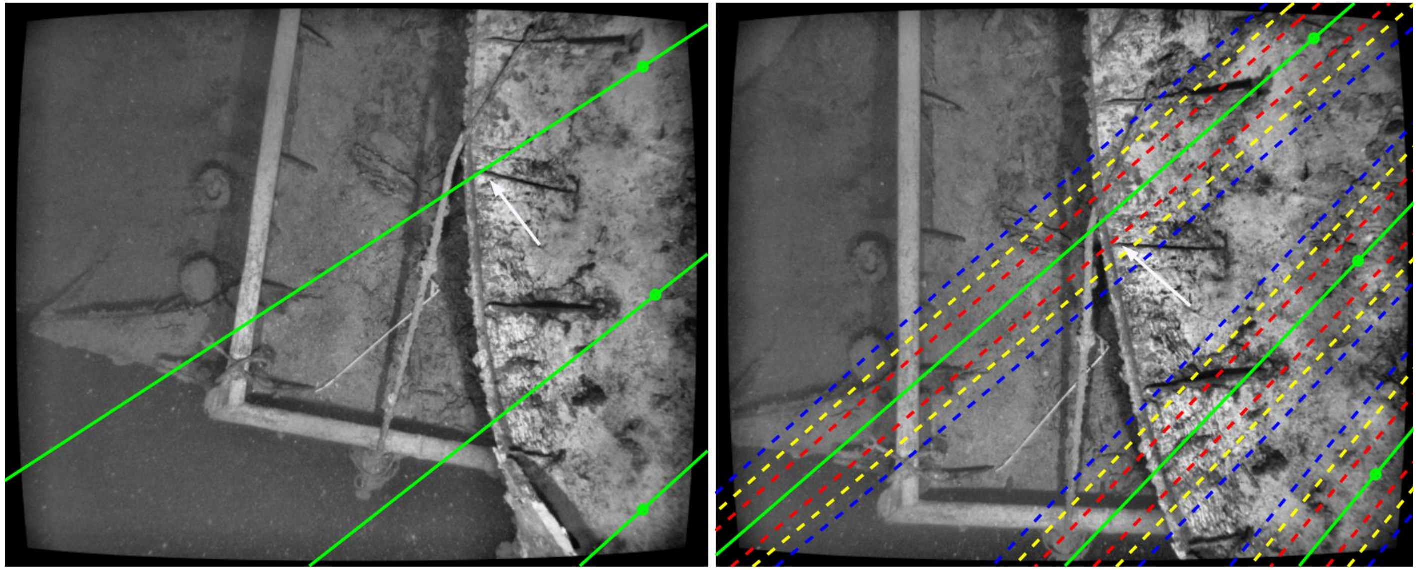
Drones in the Wild



Video from: https://youtu.be/p1d_ptE6yrc

Underwater Robots





Eustice, R., Singh, H., Leonard, J. J., Walter, M. R., & Ballard, R. (2005). *Visually Navigating the RMS Titanic with SLAM Information Filters.* In *Robotics: Science and Systems* (Vol. 2005, pp. 57-64).

Roomba

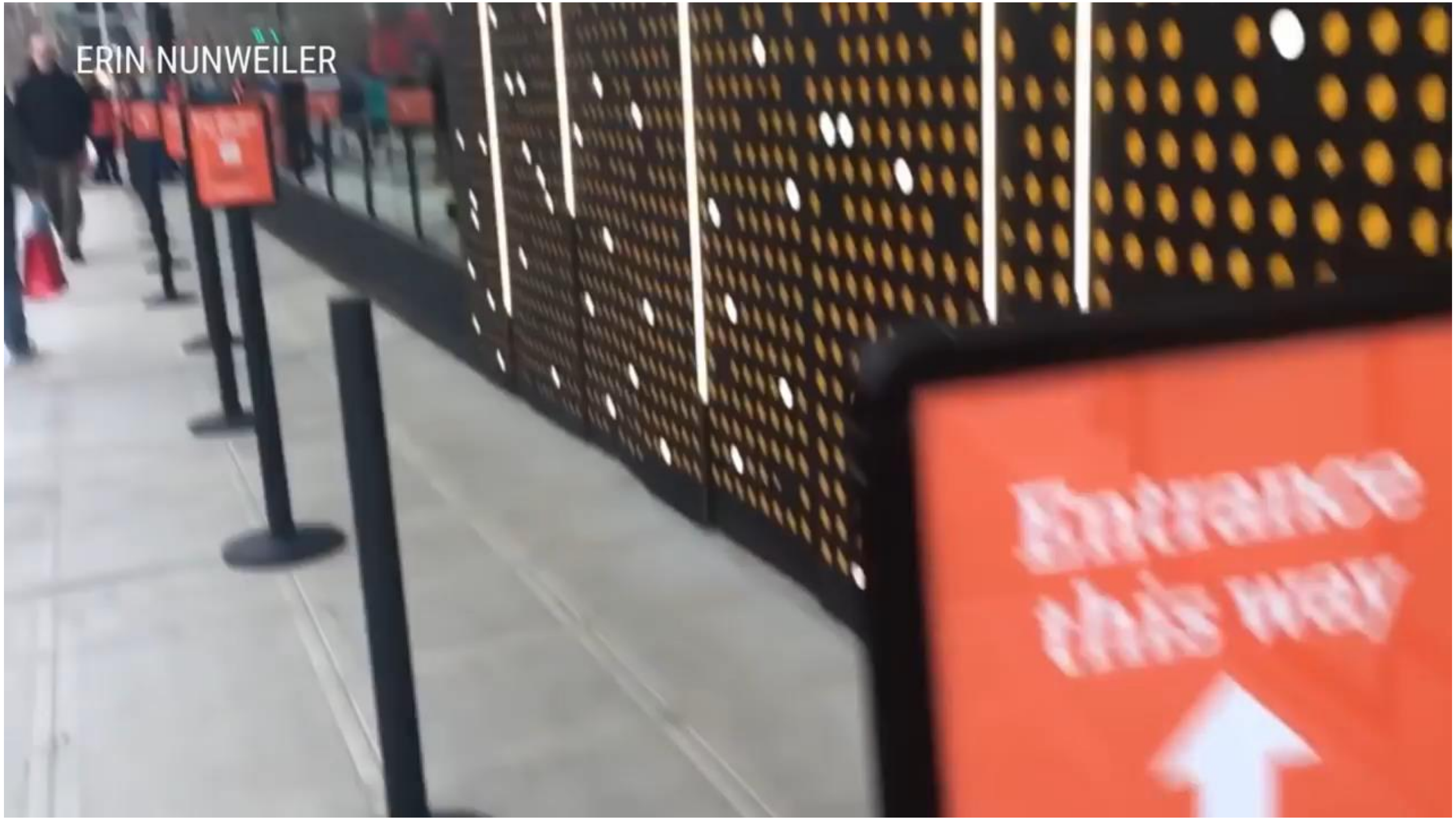
Video from: https://youtu.be/tZ0bq-jIg-o

Video from: https://youtu.be/oj3Vawn-kRE

Amazon Robotics Challenge

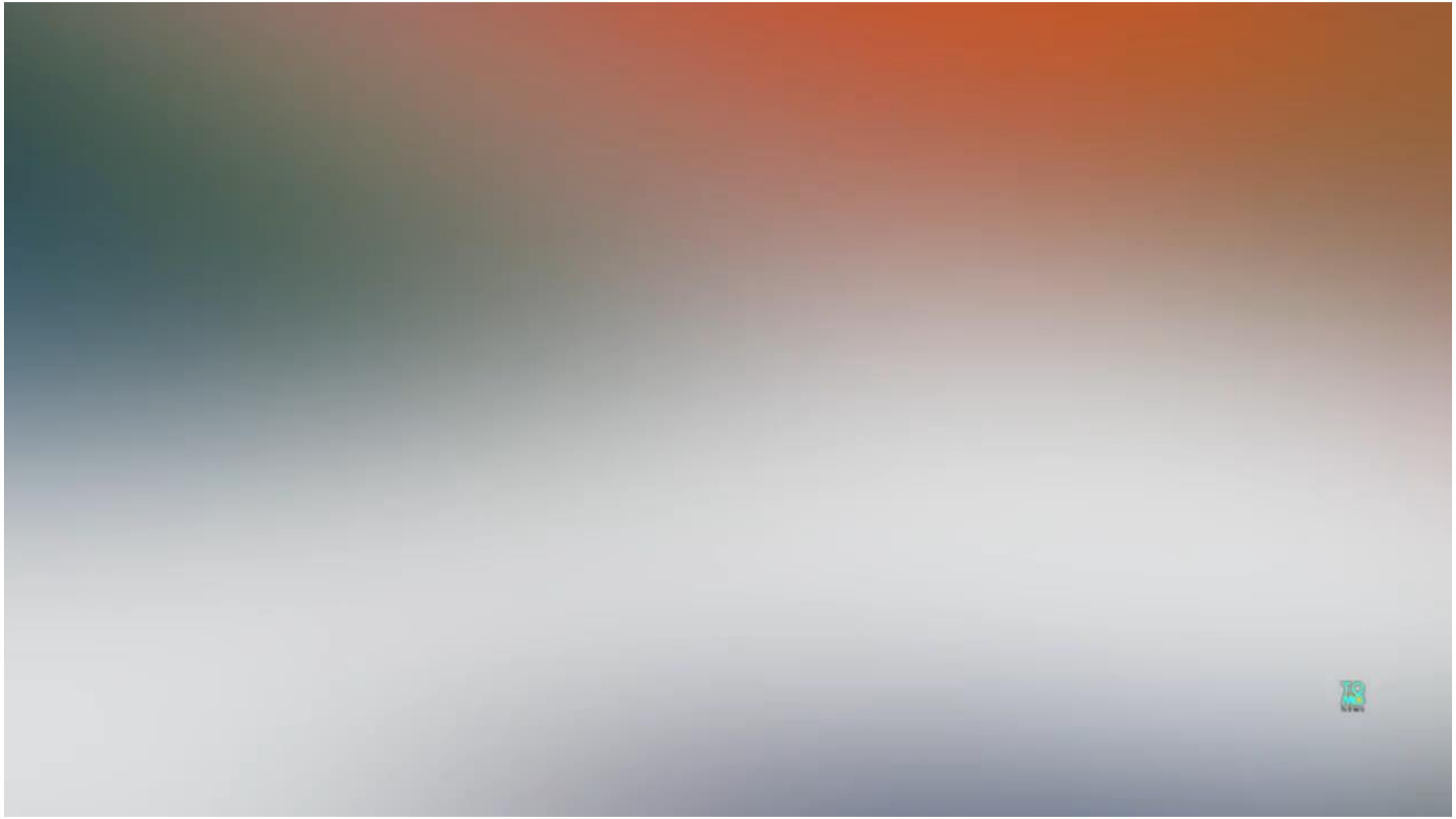
Video from: https://youtu.be/AljePt7Mh6U

Amazon Go



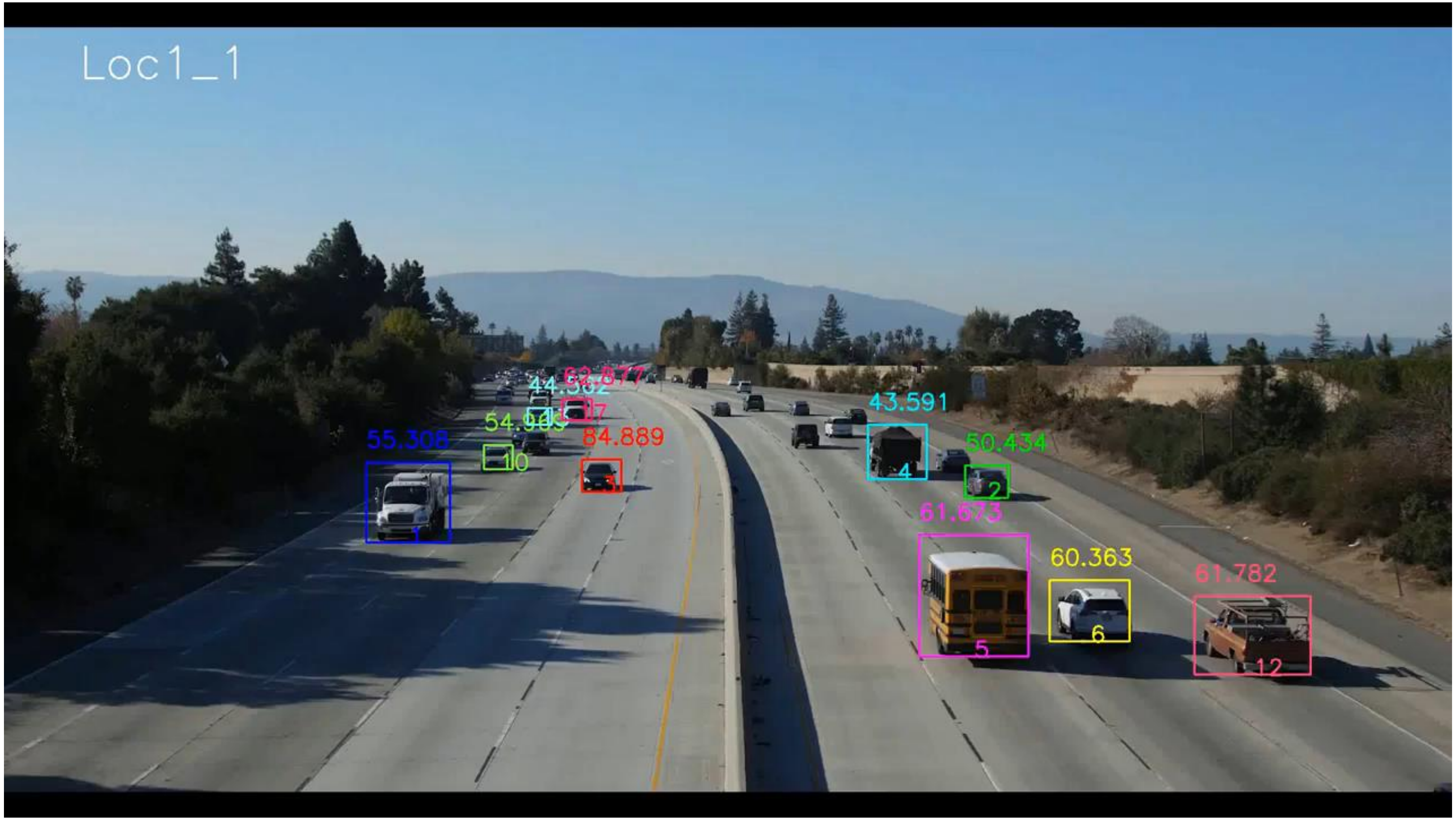
Video from: https://youtu.be/zdbumR6Bhd8

Autonomous Driving



Video from: https://youtu.be/7oCe0aLye-U

Transportation Surveillance



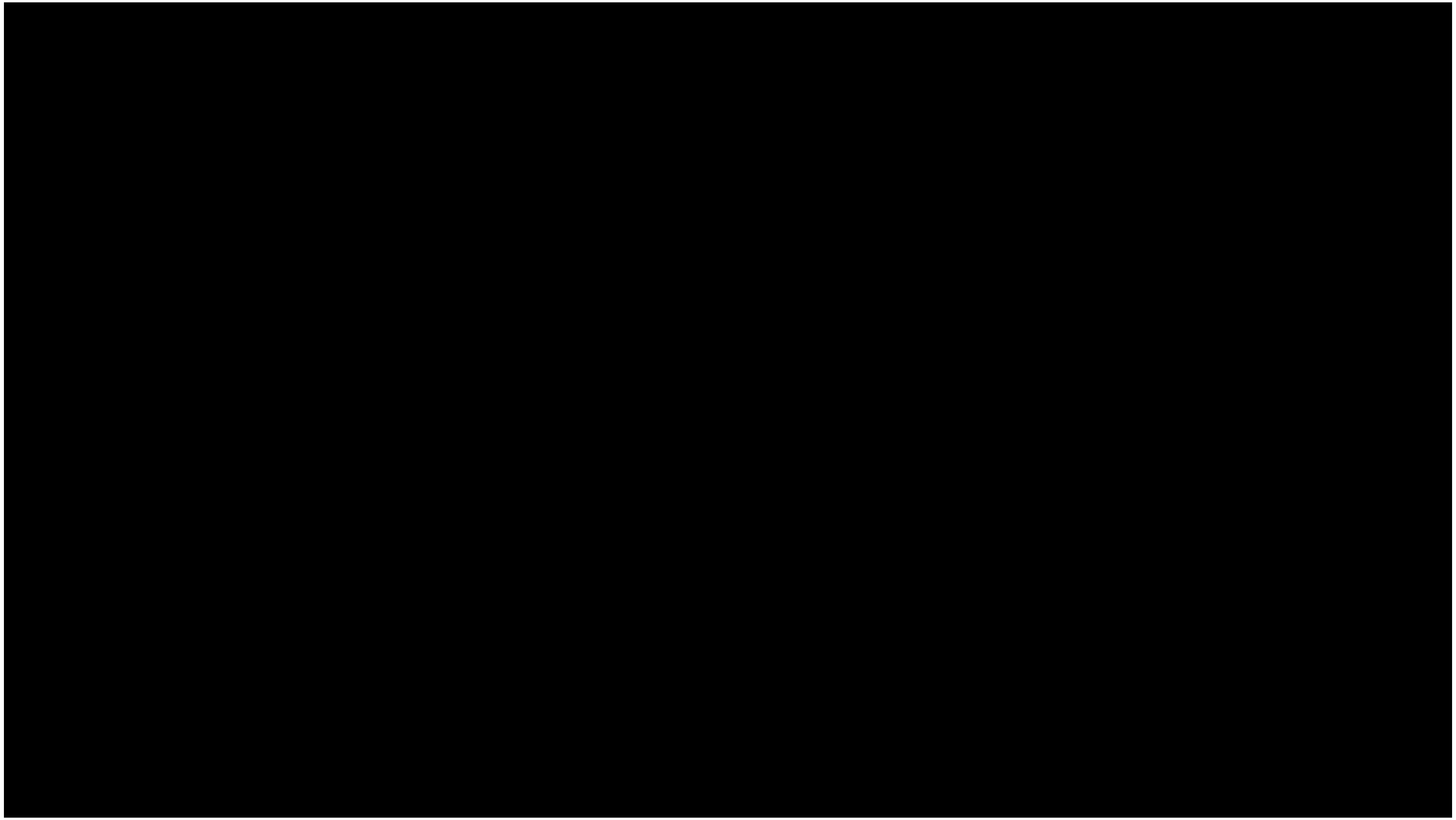
Video from: https://youtu.be/_i4numqiv7Y

Space Exploration

https://mars.jpl.nasa.gov/mer/gallery/artwork/rover1browse.html

Video from: https://youtu.be/kr58r0b5LKM

Smart Jobsite Surveillance

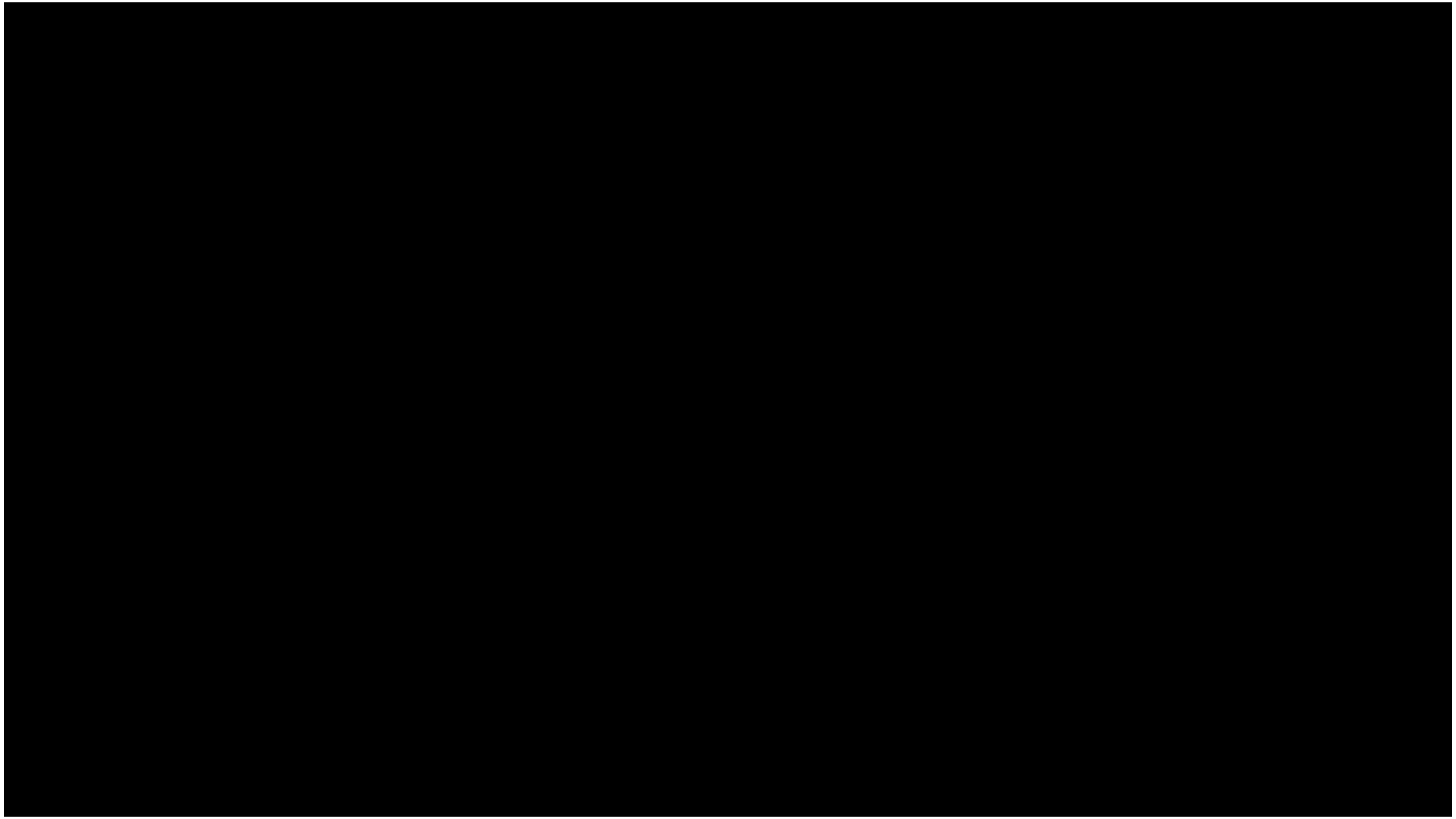


Video from: https://youtu.be/pL-c00M2CnI

Robotic Jobsite Scanner

Video from: https://www.doxel.ai

Grit Blasting Robot

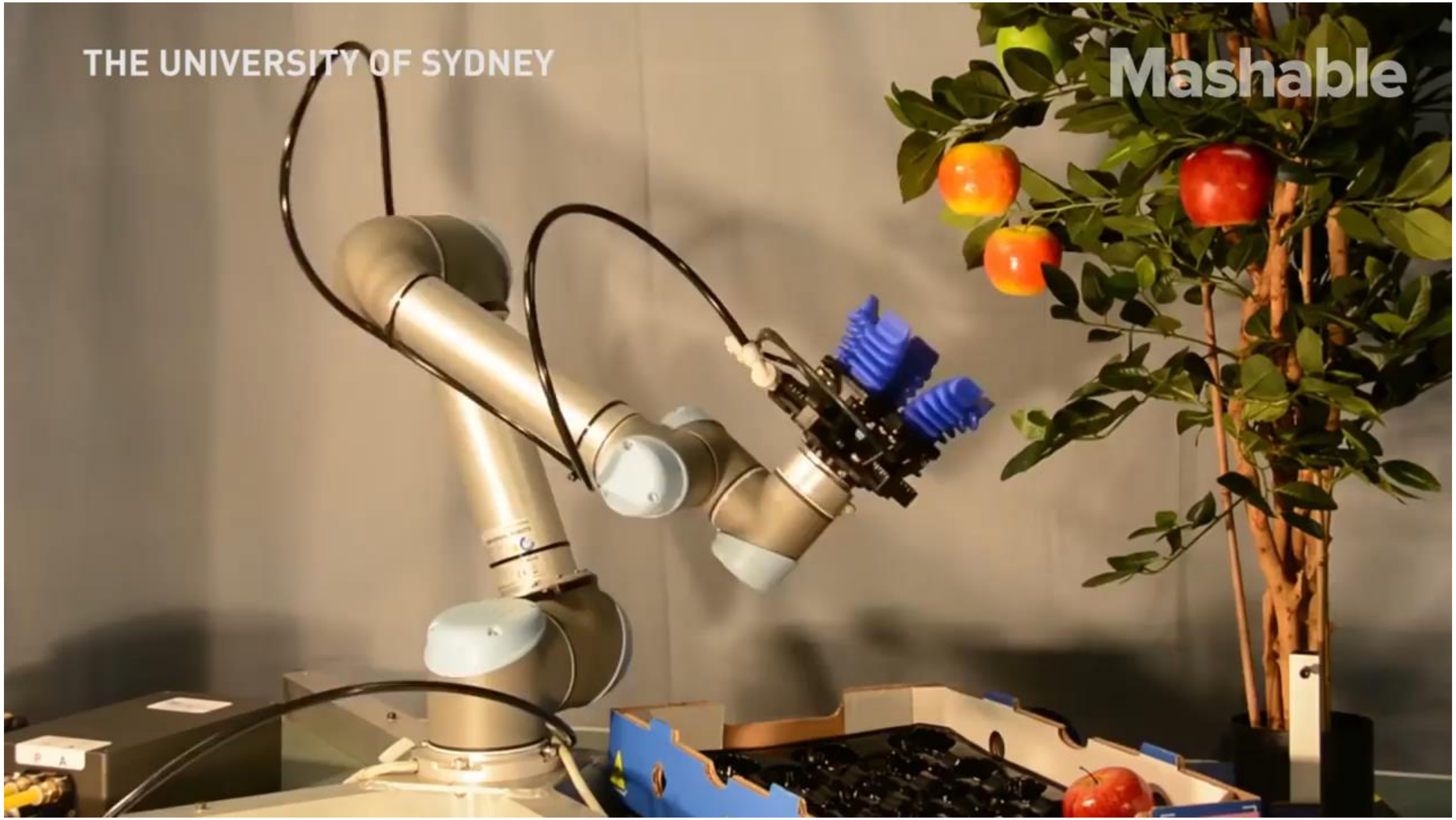


Video from: https://youtu.be/zREgx4NsA_Q

Architecture

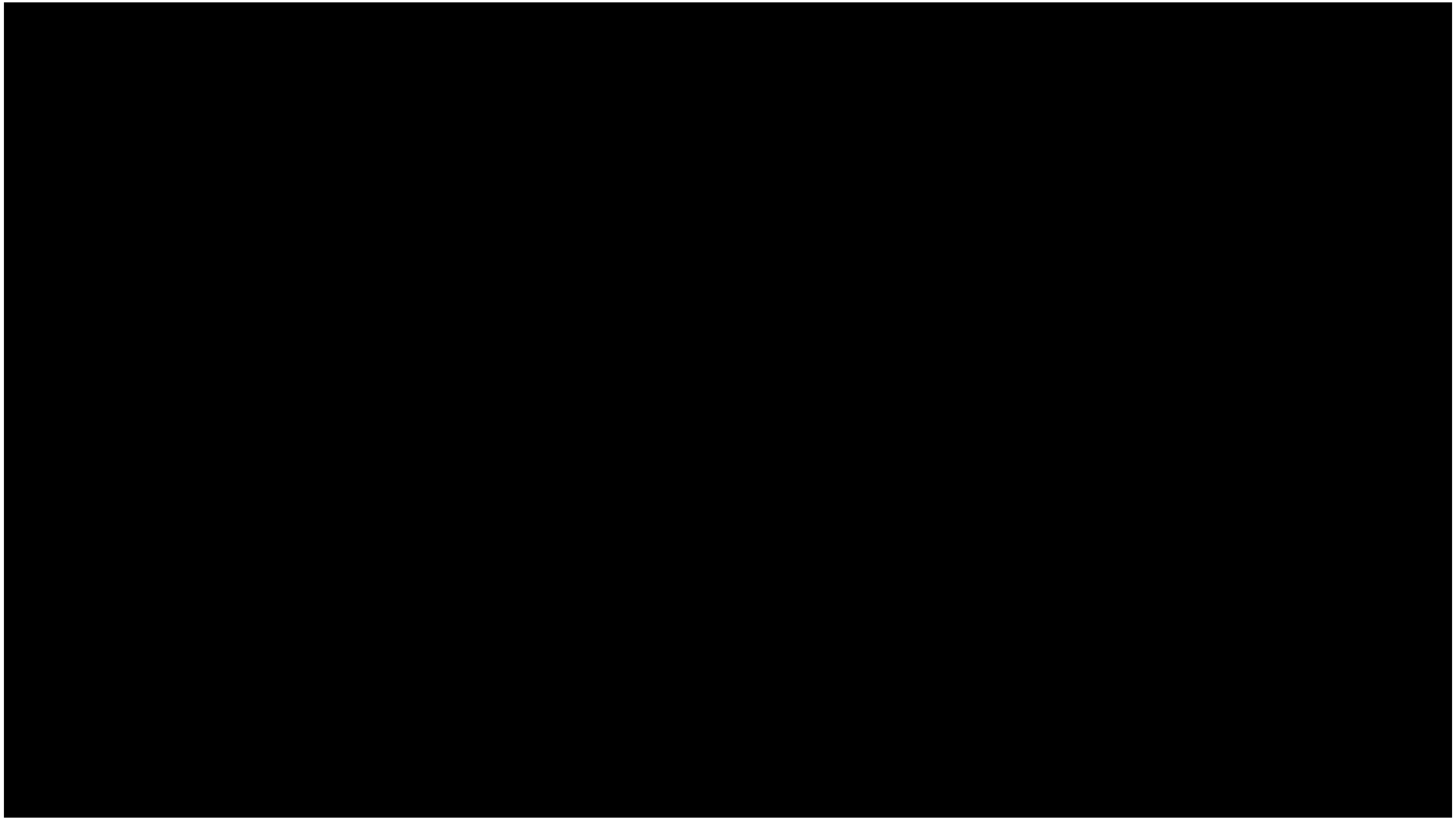
Video from: https://youtu.be/TCJOQkOE69s

Agriculture



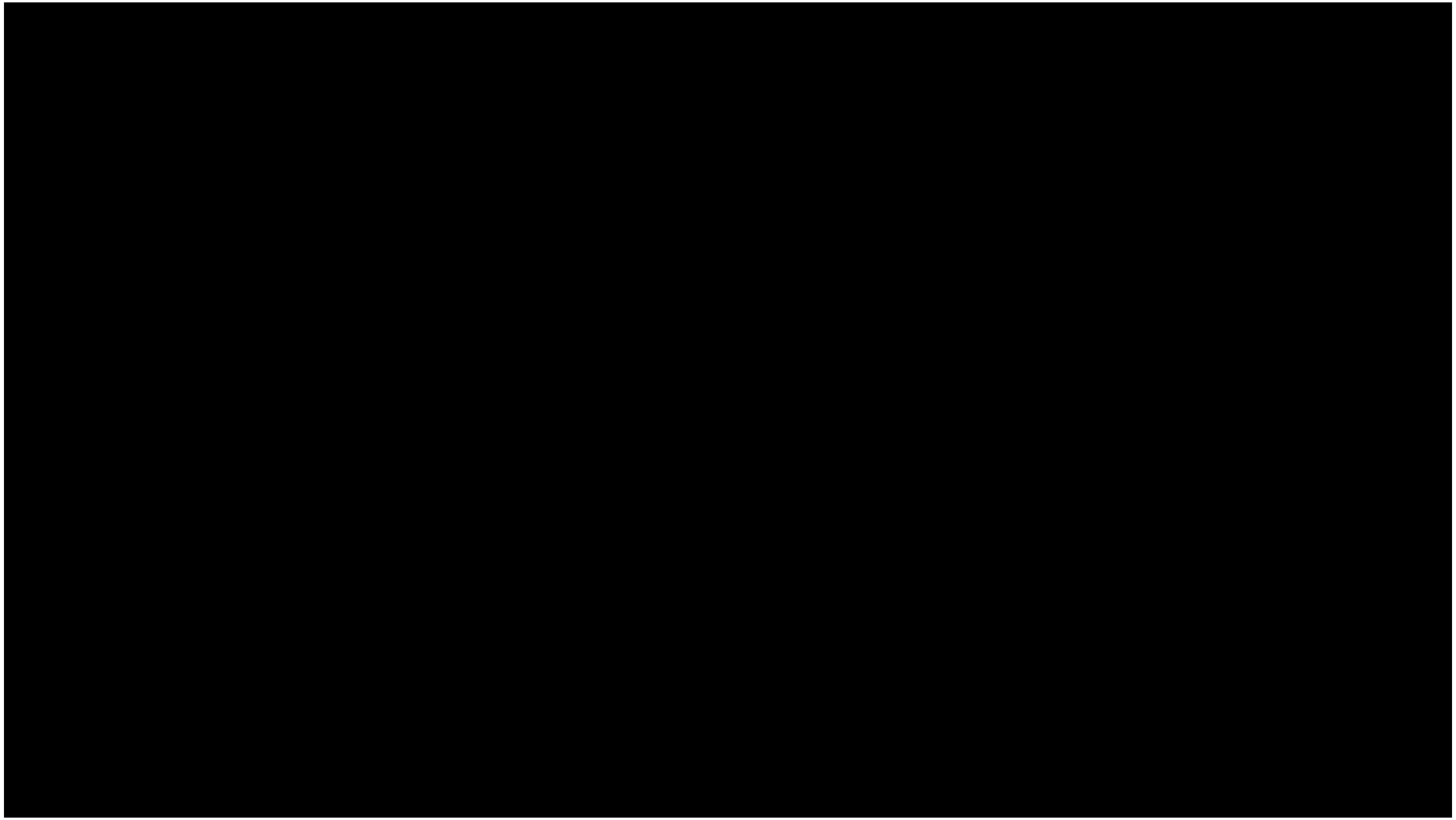
Video from: https://youtu.be/NO8PmqEI0cc

Surgical Robot



Video from: https://youtu.be/R17lsiIRjbM

Hollywood AR Car



Video from: https://youtu.be/OnBC5bwV5y0

Vision for Tactile Sensing

Video from: https://youtu.be/aKoKVA4Vcu0

LinkedIn job posts

Jet Propulsion Laboratory
California Institute of Technology

Robotics Engineer - New Grad

NASA Jet Propulsion Laboratory · Pasadena, CA, US

Posted 1 day ago · 82 views

2 company alumni work here

Robotics engineers use multi-disciplinary skills to develop robotic systems for space or terrestrial applications. These systems are remotely-controlled or autonomous machines that sense, understand, and take useful actions in unknown and unstructured environments. Typical sub-disciplines include computer vision and perception, multi-sensor estimation and control,

Senior Engineer Machine Vision Products

FANUC America Corporation · 3900 W Hamlin Rd, Rochester Hills, MI 48309, US

Posted 1 week ago · 37 views

Robotics Perception Validation Engineer

Volt Workforce Solutions · Pittsburgh, Pennsylvania

Posted 2 weeks ago · 68 views

Be an early applicant

Robotics Research Hardware Engineer (NCG)

NVIDIA · Redmond, WA, US

Posted 5 days ago · 64 views

Save Apply

experiments. Experience with core robotics areas such as manipulation, vision, control, etc. is a significant plus. Candidates should have deep and

gauges, tactile sensing, cameras (depth, binocular, high-speed, high-resolution, calibration, communication, etc.), real-time

Systems QA Robotics Automation Engineer

Apple · Cupertino, CA, US

Posted 2 days ago · 30 views

- Developing and executing testing using computer vision.

Advanced Robotics R&D Engineer Intern Summer 2019

Amazon Robotics · North Reading, MA, US

Posted 1 week ago · 578 views

The Intern Will Be Responsible For

- Identifying creative solutions for challenging research problems in robotics and computer vision

Robotics Engineer - SLAM

Big Cloud · Sunnyvale, California

Posted 6 days ago · 28 views

Save | Easy Apply

Chris Bradbury can refer you
Get referred to **increase your chances** of landing an interview.
Ask for a referral

Job description

An exciting autonomous driving start-up is expanding its team. They need world-class machine learning researchers to help them solve complex problems in machine learning, computer vision, data engineering and robotics. They just closed an impressive series A and have an incredible technical leadership team.

They're looking for candidates with real-world experience of robot

How you match
Criteria provided by job poster

Skills
- Computer Vision
- Machine Learning
- Robotics
- SLAM

Senior Robotics Engineer

Quest Groups LLC · San Francisco Bay Area

New · Posted 20 hours ago · 75 views

Be an early applicant

Save | Easy Apply

Job description

We are building the future of construction.
Our mission is to take the latest sensors from self-driving cars, retrofit them into proven equipment from the job site, and develop a suite of autonomous software designed specifically for the requirements of construction and earthmoving. And over the last two years, with a team of a dozen dedicated engineers, roboticists, and construction experts, that's what we've done. It hasn't been easy—in fact, no one has ever done what we're doing—but with

Job Description
- As a robotics engineer on our team you'll be designing, developing, testing and improving our autonomous track loader (ATL). You'll be a generalist, doing everything from optimizing controllers to designing high-level planners for new to construction tasks to improving the accuracy of our object recognition systems. You'll have a significant impact on the product road map, and you'll deploy code every day.

Qualifications
- BS, MS or PhD in computer science or related field
- 2+ years of software development experience
- Proficiency in Python
- Experience with distributed systems
- Familiarity with ROS is a plus
- Knowledge of computer vision is a plus
- Mechanical engineering experience is a plus, but not required
- Controls experience is a plus, but not required

Compensation & Benefits
- Competitive equity and salary (we believe great engineers are worth it)
- Free catered lunch and snacks in the office
- In-office gym

Robotics Engineer

The Mackenzie Group, LLC · Detroit, Michigan, United States

Posted 1 week ago · 135 views

Save | Easy Apply

Job description

The Mackenzie Group has been retained by a Detroit area automation company to fill a ROBOTICS ENGINEERING position. If you are interested in this exciting opportunity, please respond.

Skills Required/Details:
- Strong and recent background in two of the following robots: Fanuc, ABB, Kuka, or Comau.

How you match
Criteria provided by job post

Skills
- Computer Vision
- Programming
- Robotics
- Electrical Troublesho

Robotics Software Engineer

Fox Robotics · Austin, Texas

Posted 2 days ago · 1,368 views

Save | Easy Apply

Job description

Develop navigation and perception capabilities on a mobile robot. You will need to rapidly integrate and evaluate third party libraries, keep abreast of current research, and develop core autonomy capabilities.

Requirements
- strong C++ programming skills
- experience with localization and mapping algorithms
- experience with 3D obstacle avoidance and navigation algorithms

Bonus points for
- proven ability to ship working robotic applications

How you match
Criteria provided by job po

Skills
- Computer Vision
- C++
- Mobile Robotics
- Machine Learning
- Robotics
- Algorithms
- Localization
- Computer Hardwar

Computer Vision Engineer - Robotics

Harnham · Greater Pittsburgh Area

Posted 2 weeks ago · 271 views

Save | Easy Apply

Sam Brown can refer you
Get referred to **increase your chances** of landing an interview.
Ask for a r

Job description

Computer Vision Engineer - Robotics
Pittsburgh, PA
$150,000 - 180,000 + Benefits + Equity

Harnham has been retained by a rapidly growing and well funded start up with over 40 employees globally and 10 million in initial funding. Focusing on localization and mapping as well as image processing, their mission is to develop robotic solutions, allowing robots to better perceive, understand and navigate in both indoor and outdoor environments.
Very much focused on C++ programming, you'll be an integral part of their

How you match
Criteria provided by job poster

Skills
- Research
- Computer Vision
- C++
- Robotics
- Algorithms
- SLAM
- Computer Hardware

Stanley Black & Decker

Robotics Engineer Intern

Stanley Black & Decker, Inc. · Atlanta, GA, US

Posted 5 days ago · 165 views

Reporting to the Technical Manager of Robotic Systems, the Robotics Engineer engages in design and development of one or more areas related to advanced sensors and sensing technologies, algorithms development for perception, AI, robotic vision, control and data analysis, and integration of modern methods of navigation and path planning (specially with application to obstacle avoidance and autonomous operations.)

In this role, the ideal candidate is expected to have the following technical qualifications:

- BSc, MSc or PhD in Mechanical/Electrical/Robotic Engineering or Computer Science preferred, Bachelor's degree with appropriate additional years of experience also acceptable.
- Interest and/or experience developing robots and/or autonomous mobile systems. Hands on design/build experience of robot/UAV systems highly desired.
- Ability to do research in Robotics vision and or computational

MT MoTek TECHNOLOGIES

Robotics Engineer (LiDAR / Computer Vision / C++)

MoTek Technologies · San Francisco Bay Area

Posted 3 weeks ago · 99 views

Save | Easy Apply

Bastian SOLUTIONS

Robotics Computer Vision Engineer

Bastian Solutions · Boise, ID, US

Posted 2 weeks ago · 193 views

Robotics Engineer - Relo to Austin

CyberCoders · New York City, NY, US

Posted 3 days ago · 12 views

Be an early applicant

Job description

Robotics Engineer

Location: Austin, TX (relocation assistance)

Salary: $80,000 - $120,000 + equity

Top Reasons to Work with Us

- Be part of the founding team.
- Influence the direction of the company and product.
- Experience with robotics
- Chance to live in amazing Austin, Texas!

What You Will Be Doing

- Writing our core software stack
- Have an interest in:
- Web Based Applications
- Navigation for dynamic door enveironments
- Machine Learning and data visualization
- Manipulation in semi-structured environments
- Computer vision on real systems

What You Need for this Position

- Experience with deploying algorithms on real robots
- ROS

Seniority Level
Entry level

Industry
Hospital & Health Care

Employment Type
Full-time

Job Functions
Information Technology

ar

Amazon Robotics Software Engineer - Automomous Mobility

Amazon Robotics · North Reading, MA, US

Posted 1 week ago · 136 views

Job description

As an Amazon Robotics software engineer on the Autonomous Mobility team, you will own key components of navigation, vision, control, and coordination for single and multi-agent systems. You will collaborate cross-functionally to define clear requirements, deliverables, and test cases in an exciting, highly innovative environment.

Software Engineer, Researcher / Robotics

MoTek Technologies · Palo Alto, California

Posted 3 weeks ago · 160 views

Save | Easy Apply

Jerald Baker can refer you

Get referred to **increase your chances** of landing an interview.

Ask for a r

Job description

Software Engineer, Researcher / Robotics - Level 5 Autonomous Driving

Our software allows our vehicles to perceive the world around them, make the right decision for every situation, and deliver people safely to their destinations. We think deeply and solve complex technical challenges in areas like robotics, perception, decision-making and deep learning, while collaborating with hardware and systems engineers. If you're a software engineer or researcher who's curious and passionate about Level 5 autonomous driving, we'd like to meet you.

In this researcher/robotics role you'll:

- Work with world-class experts in the field of autonomous vehicles and advance the state of the art in areas such as computer vision, sensor fusion, machine learning, object tracking, and motion planning.

We'd like you to have:

- MS/PHD in Robotics, Computer Science, or equivalent practical experience.
- Experience in hands-on robotics research and expertise in one or more of the following: computer vision, LIDAR, object tracking, sensor fusion, perception, machine learning, motion planning, and control.
- Experience in data structures and advanced algorithms.
- Experience programming in C++ and with robust, safety-critical, efficient code.
- Experience with field robotics and systems design.

How you match

Criteria provided by job poster

Skills

- Research
- Computer Vision
- C++
- Machine Learning
- Robotics
- Algorithms
- Sensor Fusion
- Object Tracking
- Computer Hardware
- Automotive

Level of education

- Doctor of Philosophy

Contact the job poster

Jerald Baker 1st

Technical Recruiter

Message

Job Details

Software Engineer, Researcher/Robotics

Waymo · Ann Arbor, MI, US

Posted 1 week ago · 1,965 views

In This Researcher/robotics Role You'll

- Work with world-class experts in the field of autonomous vehicles and advance the state of the art in areas such as computer vision, sensor fusion, machine learning, object tracking, and motion planning

Job description

Waymo is the self-dr
and easy for people a
sensor technology de
first fully self-driving
public from A to B at

Software Engineering
Our software allows o

We'd Like You To Have

- MS/PHD in Robotics, Computer Science, or equivalent practical experience
- Experience in hands-on robotics research and expertise in one or more of the following: computer vision, LIDAR, object tracking, sensor fusion, perception, machine learning, motion planning, and control
- Experience in data structures and advanced algorithms
- Experience programming in C++ and with robust, safety-critical, efficient code
- Experience with field robotics and systems design

Robotics Research Engineer

CyberCoders · Pittsburgh, PA, US

Posted 1 day ago · 8 views

Be an early applicant

NICE

- Experience with distributed computing, inter-processor communication, or low-level networking
- Experience with voting architectures, safety-critical systems, reliable computing, or redundant processing
- Experience in developing spacecraft electronics systems or flight software
- Experience with applications such as GPS-denied navigation, localization, SLAM, computer vision, and deep learning
- Experience with basic systems engineering principles, risks, and requirements development

SP1419: Simulation of Multimodal Sensors

MERL is seeking a motivated intern to assist in generating simulated multimodal data for machine learning applications. The project involves integrating several existing software components to generate optical and radar data in a variety of sensing scenarios, and executing the simulations under a variety of conditions. The ideal candidate should have experience with C++, Python, and scripting methods. Some knowledge or experience with Blender, computer graphics, and computer vision would be preferred, but is not required. Project duration is flexible in the range of 1-2 months. Intern has the choice of part-time or full-time occupation and may start immediately.

Research Areas: **Artificial Intelligence**, **Computer Vision**, **Signal Processing**
Host: **Petros Boufounos**

APPLY NOW

CV1462: Graph neural networks for computer vision

MERL is seeking a motivated intern to conduct research on graph neural networks and computer vision. The ideal candidate should have experience with Pytorch/Tensorflow, and scripting methods. Some knowledge or experience with graph neural networks would be preferred, but is not required. Project duration is flexible in the range of 2-4 months. Intern has the choice of part-time or full-time occupation and may start immediately. Candidates in their junior or senior years of a Ph.D. program are encouraged to apply.

Research Areas: **Computer Vision**, **Signal Processing**
Host: **Siheng Chen**

APPLY NOW

PhD Research Intern, Computer Vision/LiDAR (Fall 2019)

Lyft • Palo Alto, CA, US

Responsibilities

- You and your team will work on core perception algorithms such as sensor calibration, objection detection, tracking, segmentation, and state space estimation.
- You will build indoor and outdoor calibration algorithms for camera, LiDAR, IMU and radar.
- Develop segmentation and classification algorithms on LiDAR point cloud data.
- Implement state-of-the-art CV models based on latest publications in computer vision, perception and machine learning.
- Develop sensor fusion algorithms for radar, LiDAR, and vision modalities.
- Participate in team advancement of tools and infrastructure to evaluate the performance of perception stack and track it over time.

Experience

- Experience achieving significant results as demonstrated by grants, fellowships, patents, as well as first-authored publications at leading workshops or conferences such as CVPR, ICML, ICLR, ECCV/ICCV or NeuralPS
- Hands-on experience building computer vision/machine learning applications on camera using LiDAR, IMU and radar data.
- Demonstrated production-quality Python or C++
- Collaborate with internal partners and promote openness to new / different ideas

Software Engineering Intern – Computer Vision & Deep Learning

SAVE

NVIDIA
Santa Clara, CA

Apply on Hiredinny

Over 1 month ago Internship

NVIDIA's invention of the GPU in 1999 sparked the growth of the PC gaming market, redefined modern computer graphics, and revolutionized parallel computing. More recently, GPU deep learning ignited modern AI — the next era of computing — with the GPU acting as the brain of computers, robots, and self-driving cars that can perceive and understand the world. Today, we are increasingly known as "the AI computing company." We're looking to grow our company, and build our teams with the smartest people in the world. Join us at the forefront of technological advancement! We are currently seeking a software engineer intern with strong Computer Vision and Deep Learning fundamentals and robust C skills to contribute to the development of RTX Broadcast engine - a comprehensive suite of SDKs and libraries that enable AI-driven broadcast features. What you'll be doing: You will work alongside brilliant engineers on core technologies, and implement and optimize software to solve challenging...

READ MORE

Report this listing

Image Formation

+ Digital Image & Camera Selection

* Pinhole Camera Model

++ Projective Geometry Primitives

++ Transformations

+ Lens Distortion

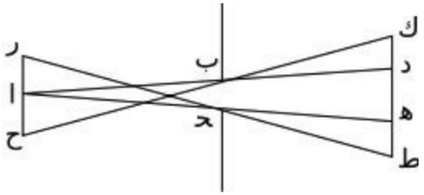
*: know how to code
++: know how to derive
+: know the concept

References

- FP2011:
  - Chapter 1, Section 3.1, 3.4, 3.5
- Sz2011:
  - Section 2.1, 2.3, 2.3.2, 6.3.5
- Co2011:
  - Chapter 2, Section 11.1.4
- HZ2003:
  - Section 2.2, 2.3, 2.4, 3.1, 3.4, 6.1
- Linear algebra:
  - Sz2011: section A.1.1, A.1.2, A.1.3, A.2, A.2.1
  - HZ2003: A5.1, A5.2, A5.3

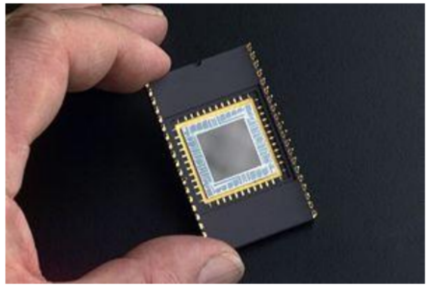
Historic Milestones of Camera

- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD**: Sony Mavica (1981)
- **First fully digital camera:** Kodak DCS100 (1990)



Alhacen's notes

Niepce, "La Table Servie," 1822



CCD chip

Slide by Rob Fergus

Digital Camera

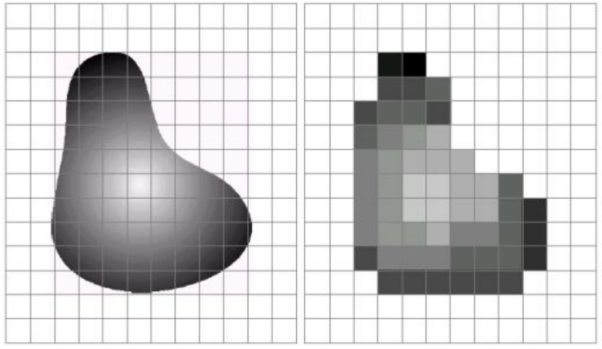


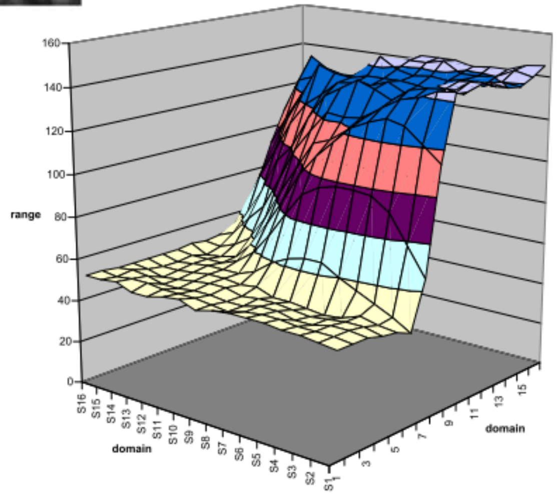
FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - Complementary metal oxide semiconductor (CMOS)

Slide by Steve Seitz

Digital Image

45	60	98	127	132	133	137	133
46	65	98	123	126	128	131	133
47	65	96	115	119	123	135	137
47	63	91	107	113	122	138	134
50	59	80	97	110	123	133	134
49	53	68	83	97	113	128	133
50	50	58	70	84	102	116	126
50	50	52	58	69	86	101	120



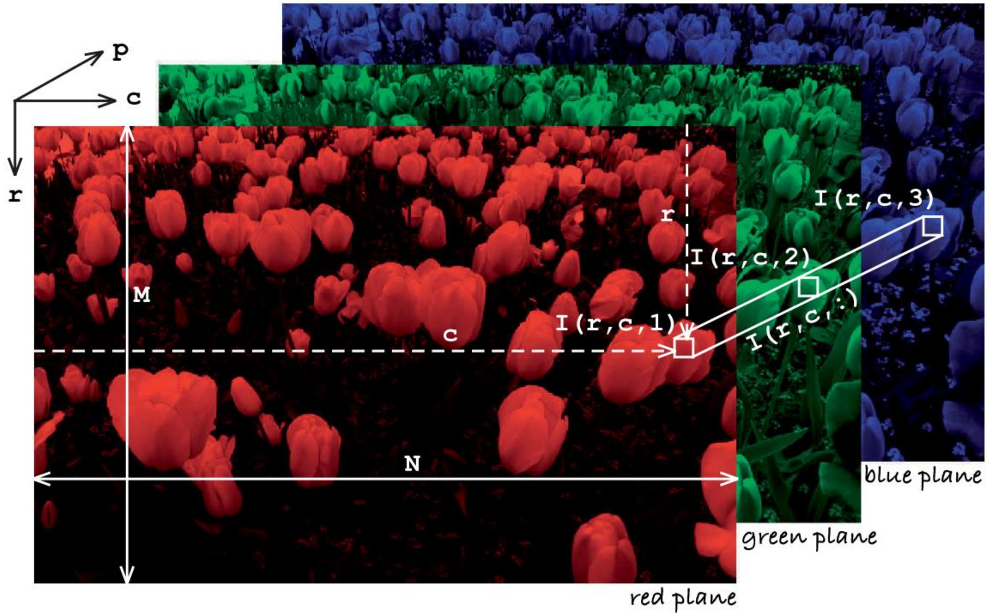


Image from Sz2011, Co2011

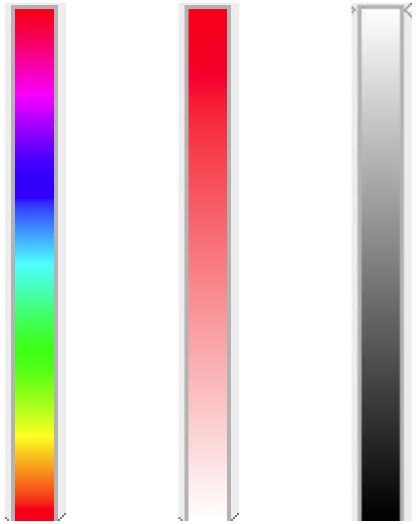
Color Space Transformations

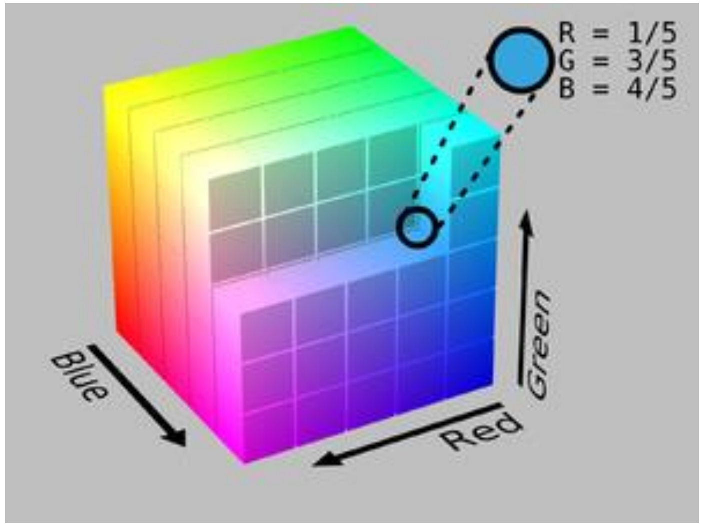
- RGB2Gray

$$\text{RGB[A] to Gray:} \quad Y \leftarrow 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B$$

$$0.2126R + 0.7152G + 0.0722B$$

- RGB2HSV





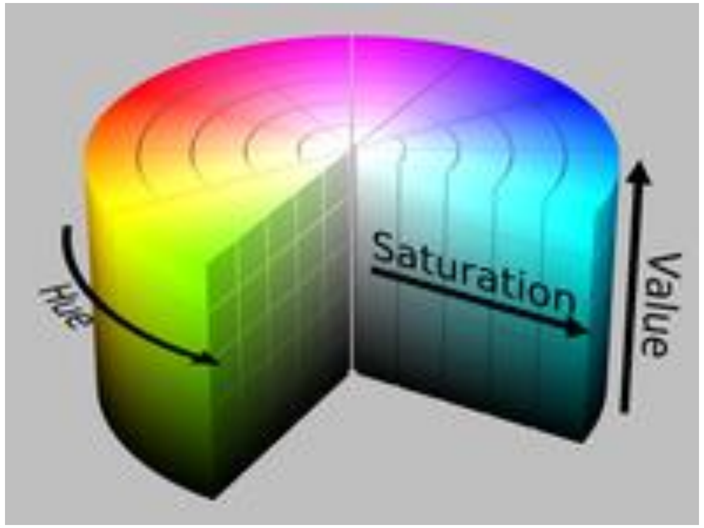
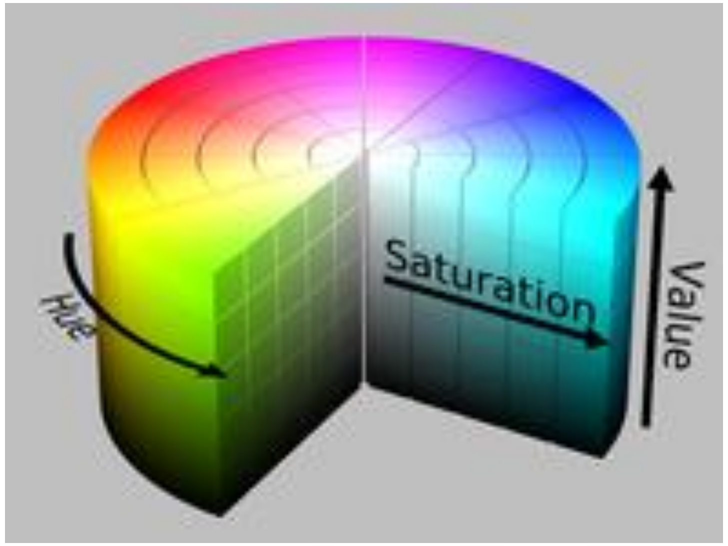


Image from Wiki & https://graphicdesign.stackexchange.com/a/16286

Color Space Transformations

- Higher values are shown as white pixels
- Lower values are shown as darker pixels

- Which one of b & c represents the Hue channel?



Hue

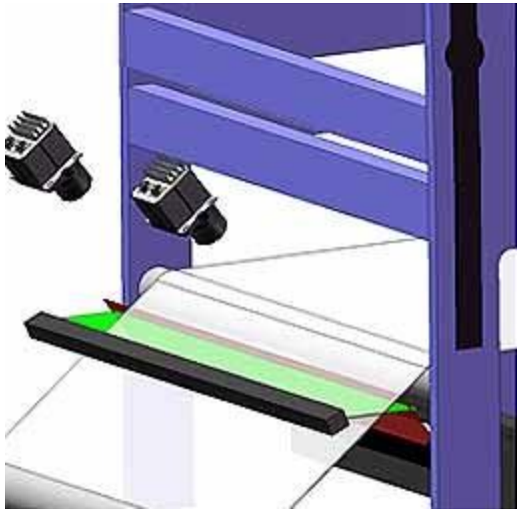
Saturation

Image from Corke 2011

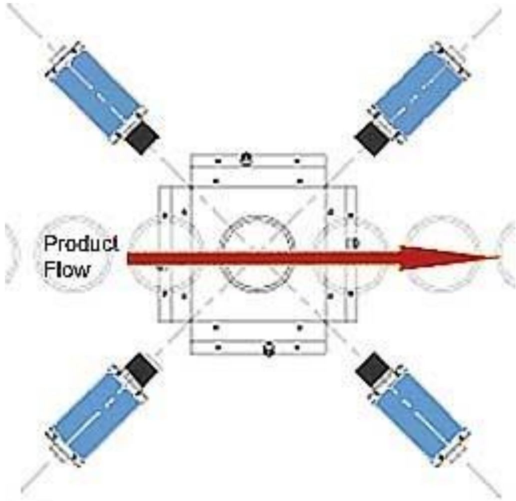
Choosing Machine Vision Cameras

- Area scan or Line scan?
- Color or Monochrome?
- CMOS or CCD?
- Global or Rolling Shutter?
- Frame Rate?
- Resolution?
- Connection Interface?
- Lens Focal length

Area Scan or Line Scan?



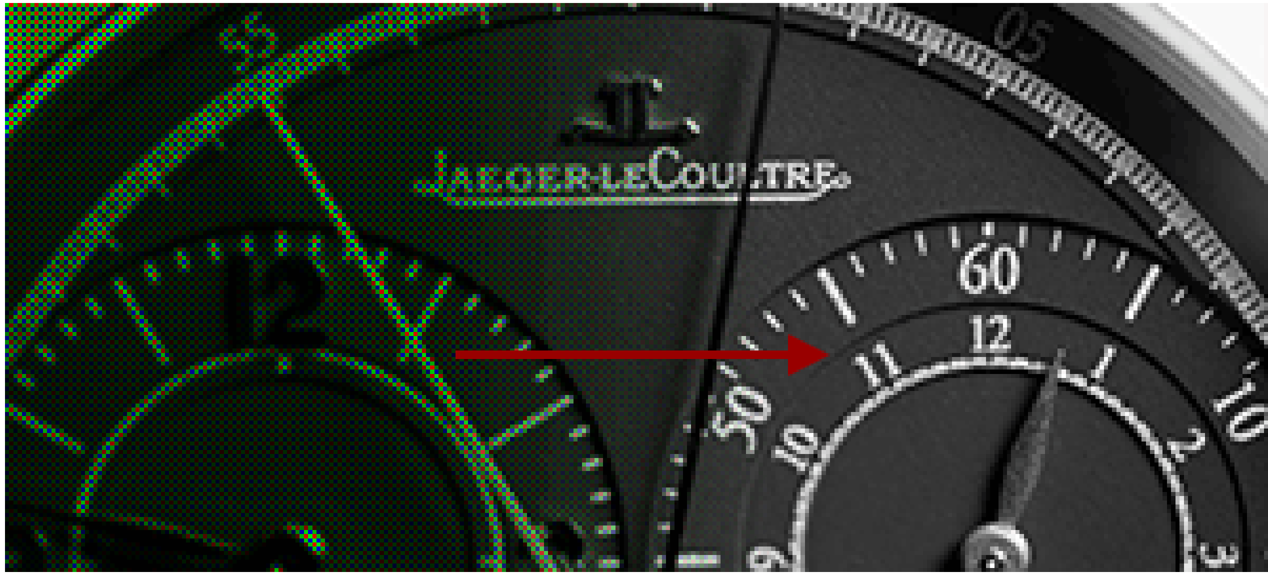
Line scan

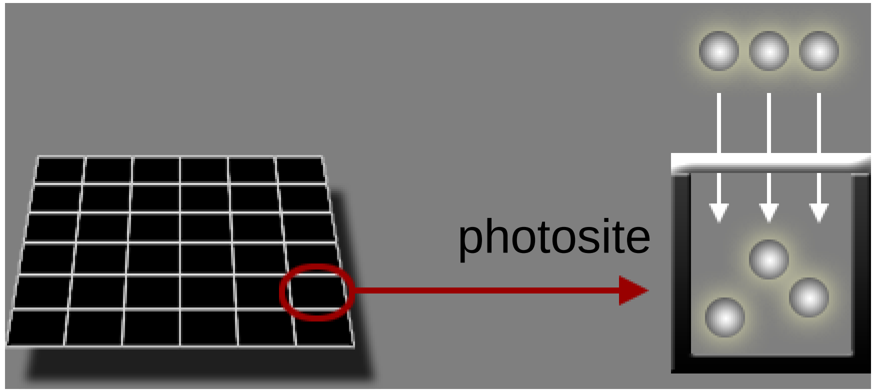


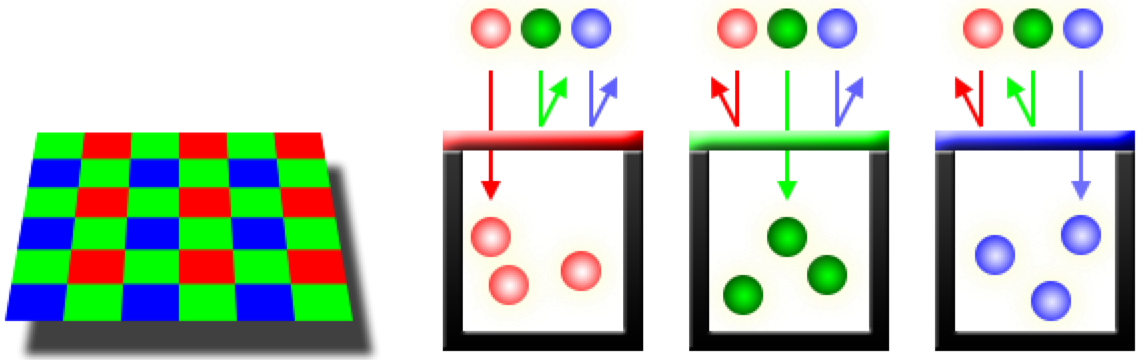
Area scan

Images from https://newtonlabs.com/line_systems.htm

Color or Monochrome?







Monochrome sensor

Color sensor (with color filter array)

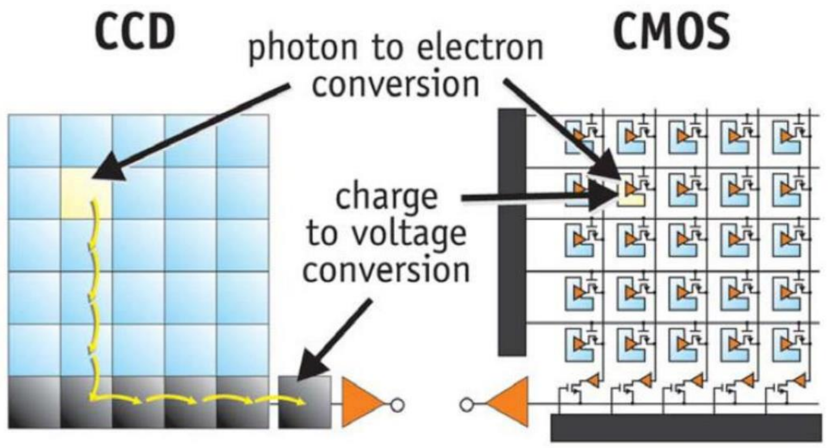
Images from http://www.red.com/learn/red-101/color-monochrome-camera-sensors

CMOS or CCD?

- CCD: charge coupled device
- CMOS: complementary metal oxide semiconductor
- Pros/Cons
  - Noise: CMOS > CCD
  - Light sensitivity: CMOS < CCD
  - Pixel quality: CMOS < CCD

  - Power consumption: CMOS < CCD
  - Speed/frame-rate: CMOS > CCD
  - Price: CMOS < CCD
- Current winner: CMOS

http://electronics.howstuffworks.com/digital-camera.htm

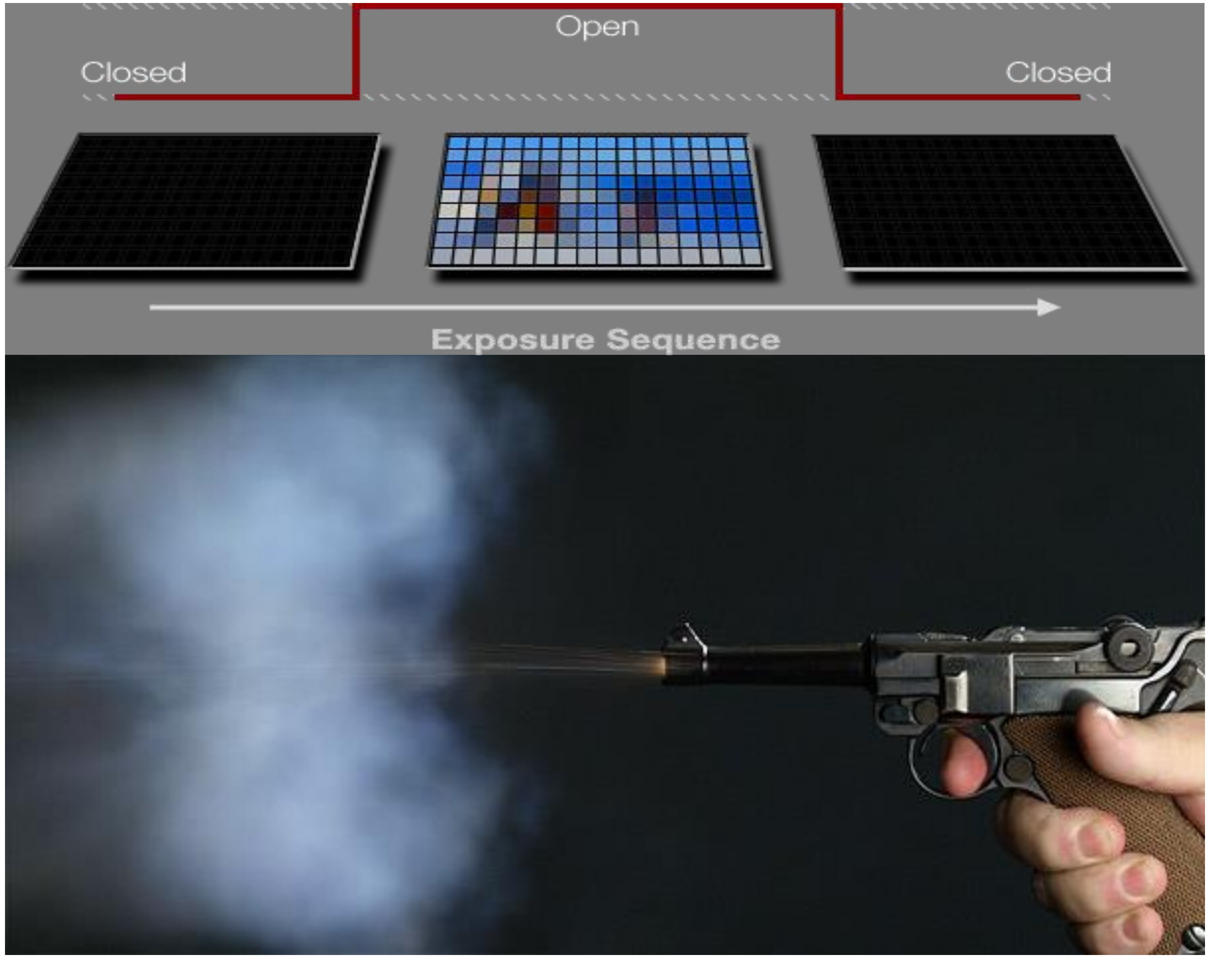


CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

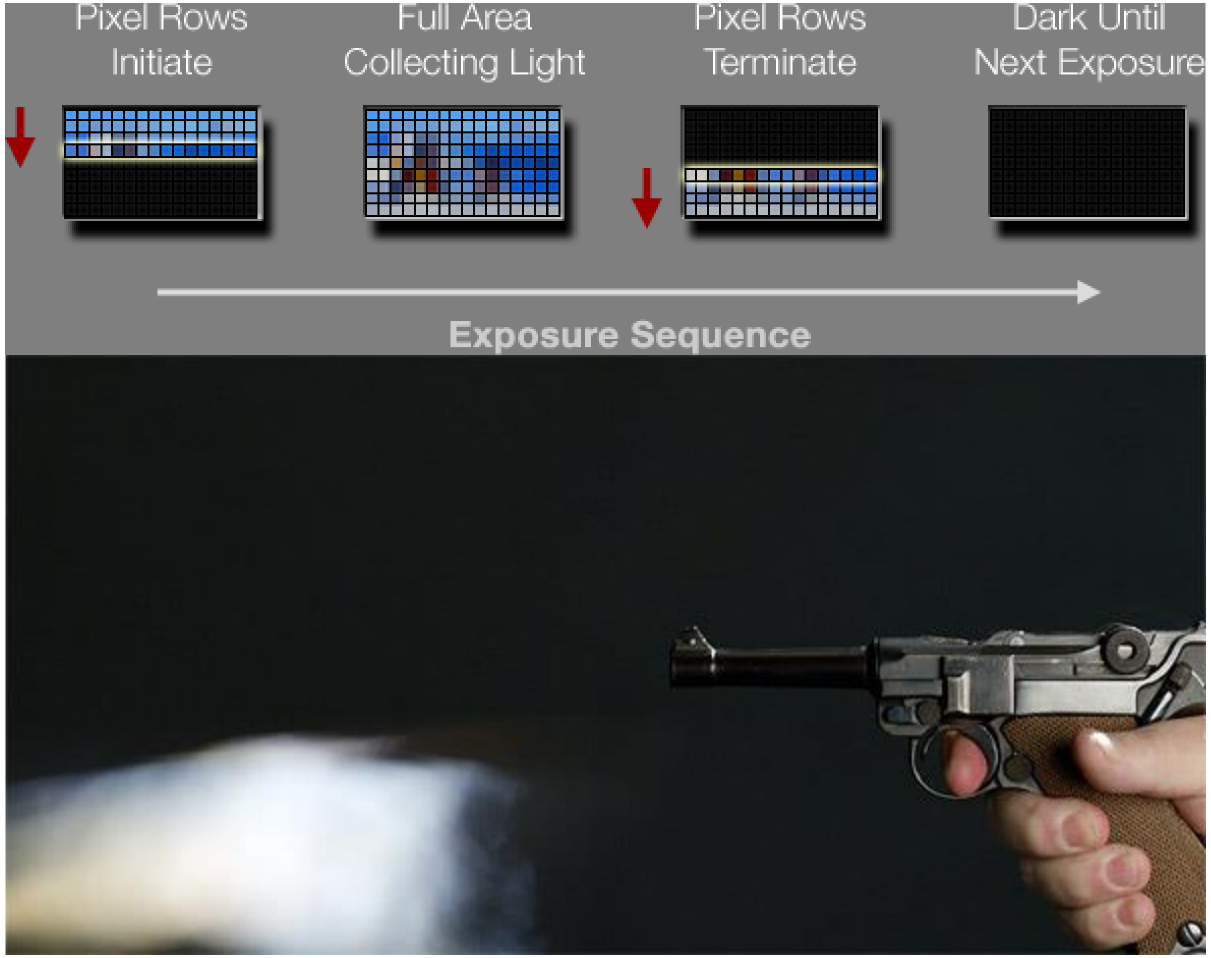
http://www.dalsa.com/shared/content/pdfs/CCD_vs_CMOS_Litwiller_2005.pdf

Image from Rob Fergus

Global or Rolling Shutter



Global Shutter



Rolling Shutter

Image from http://www.red.com/learn/red-101/global-rolling-shutter

Effect of Rolling Shutter with Fast Motion

- Is the photographer moving towards left, or right?
  - If rolling shutter moves from the top to bottom of the image

Image from https://www.bhphotovideo.com/explora/video/tips-and-solutions/rolling-shutter-versus-global-shutter

Other Factors

Interface	Cable Lengths	Bandwidth max. in MB/s.	Multi-Camera	Cable Costs	"Real-time"	"Plug & Play"
GiGE VISION	100 m	100				
USB3 VISION	8 m	350				
CAMERA Link	10 m	850				

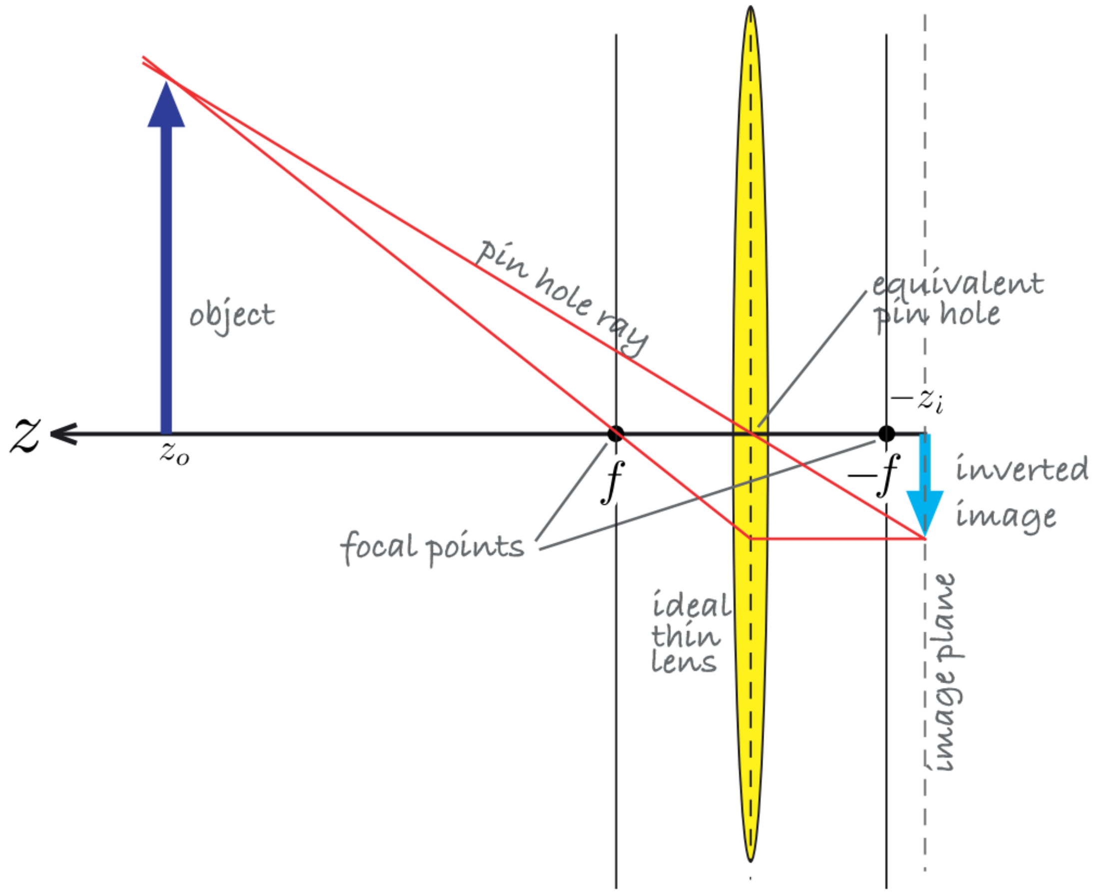
- Resolution
  - QVGA (320x240), VGA (640x480)
  - Choose based on your application!
- Frame rate
  - 15Hz, 30Hz, 60Hz
- Connection interface
  - USB3.0: 350MB/s, up to 8m cable (power + data), plug-and-play
  - GigE: 100MB/s, up to 100m cable, good for multiple cameras
- Focal length
  - Fixed: good for geometric vision (3D reconstruction/pose estimation)
  - Auto-focus

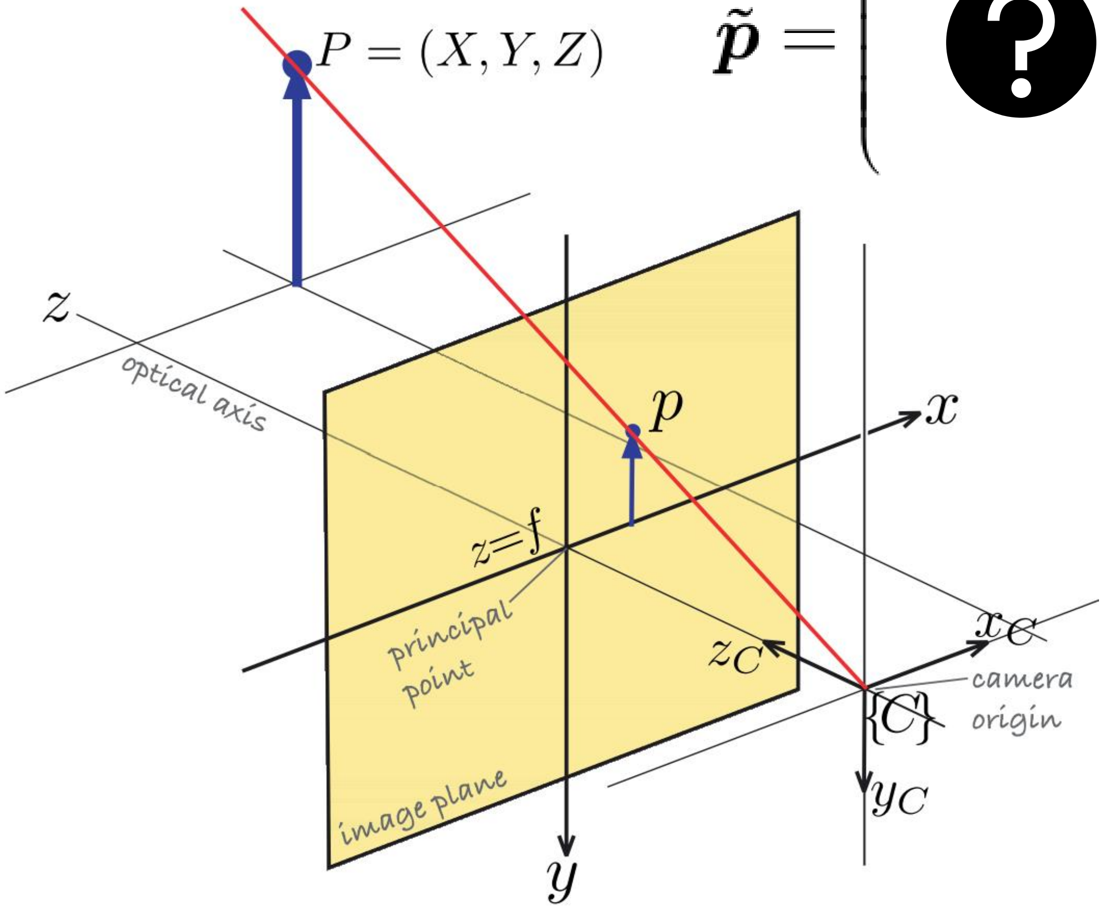
Image: https://www.qualitymag.com/articles/93861-how-to-choose-a-machine-vision-camera

Pinhole Camera Model

Image from http://thedelightsofseeing.blogspot.com/2010/10/pinhole-photography-and-camera-obscura.html

Evolution of Pinhole Camera Model

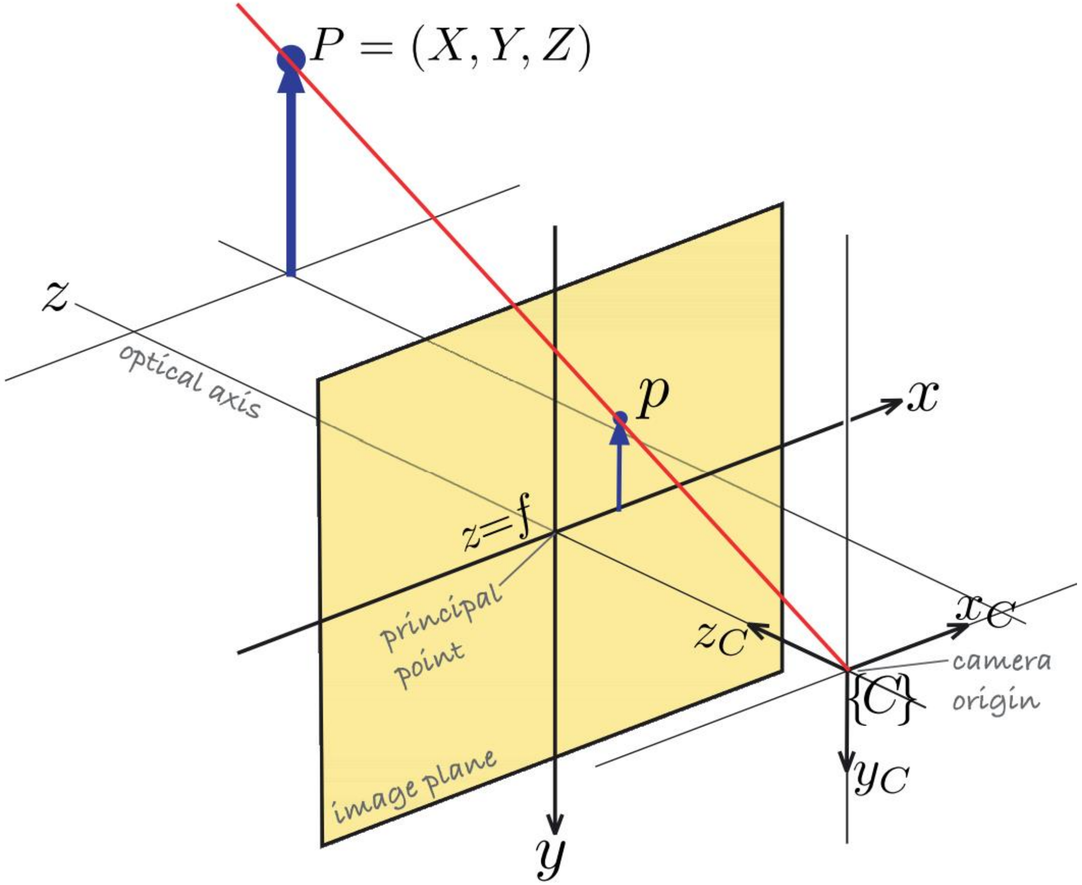




$$\tilde{\boldsymbol{p}} = \left(\quad ? \quad \right) \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

Image from Corke 2011

Evolution of Pinhole Camera Model

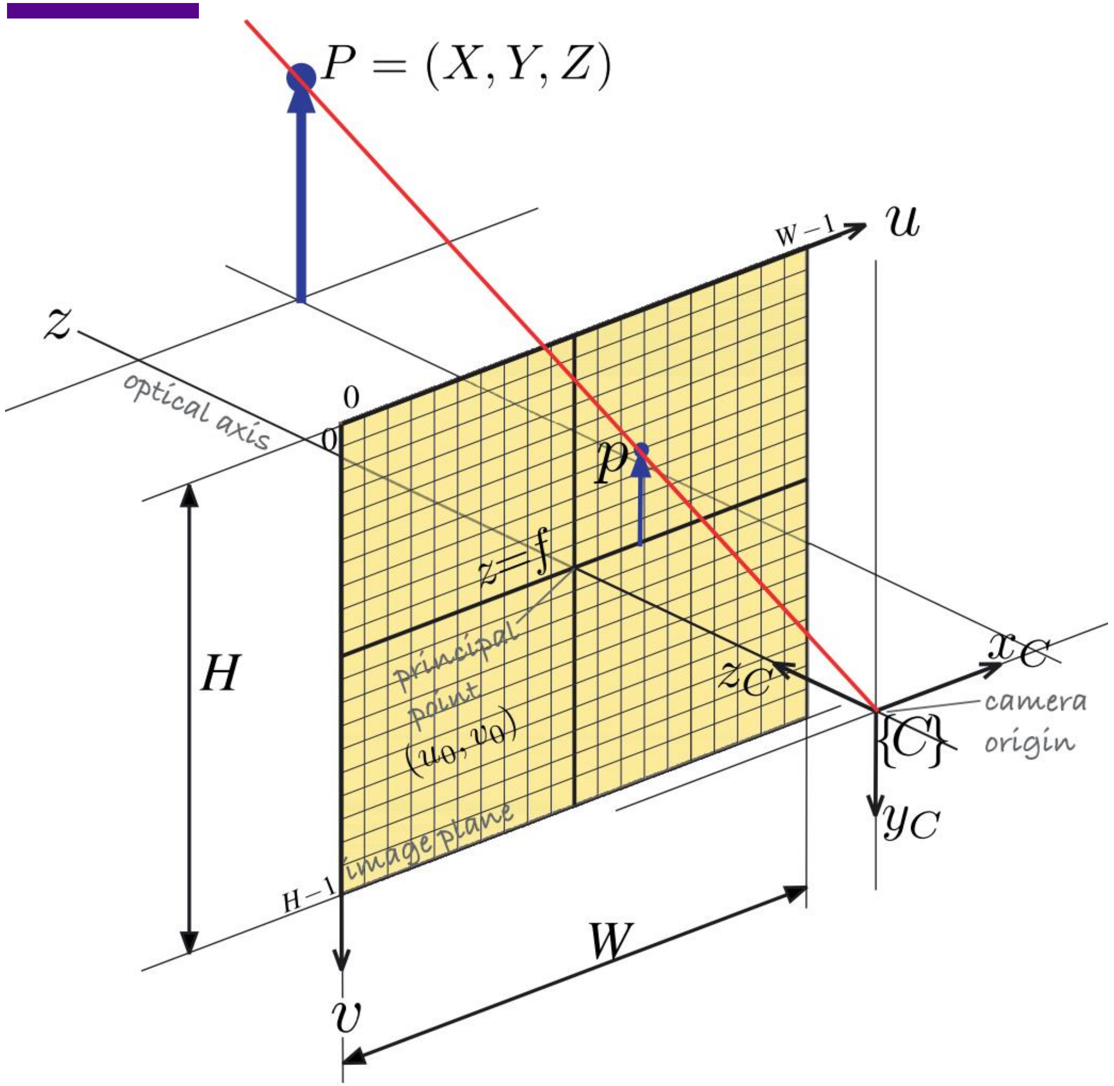


$$\tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$\tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^C\tilde{\boldsymbol{P}}$$

Image from Corke 2011

Evolution of Pinhole Camera Model

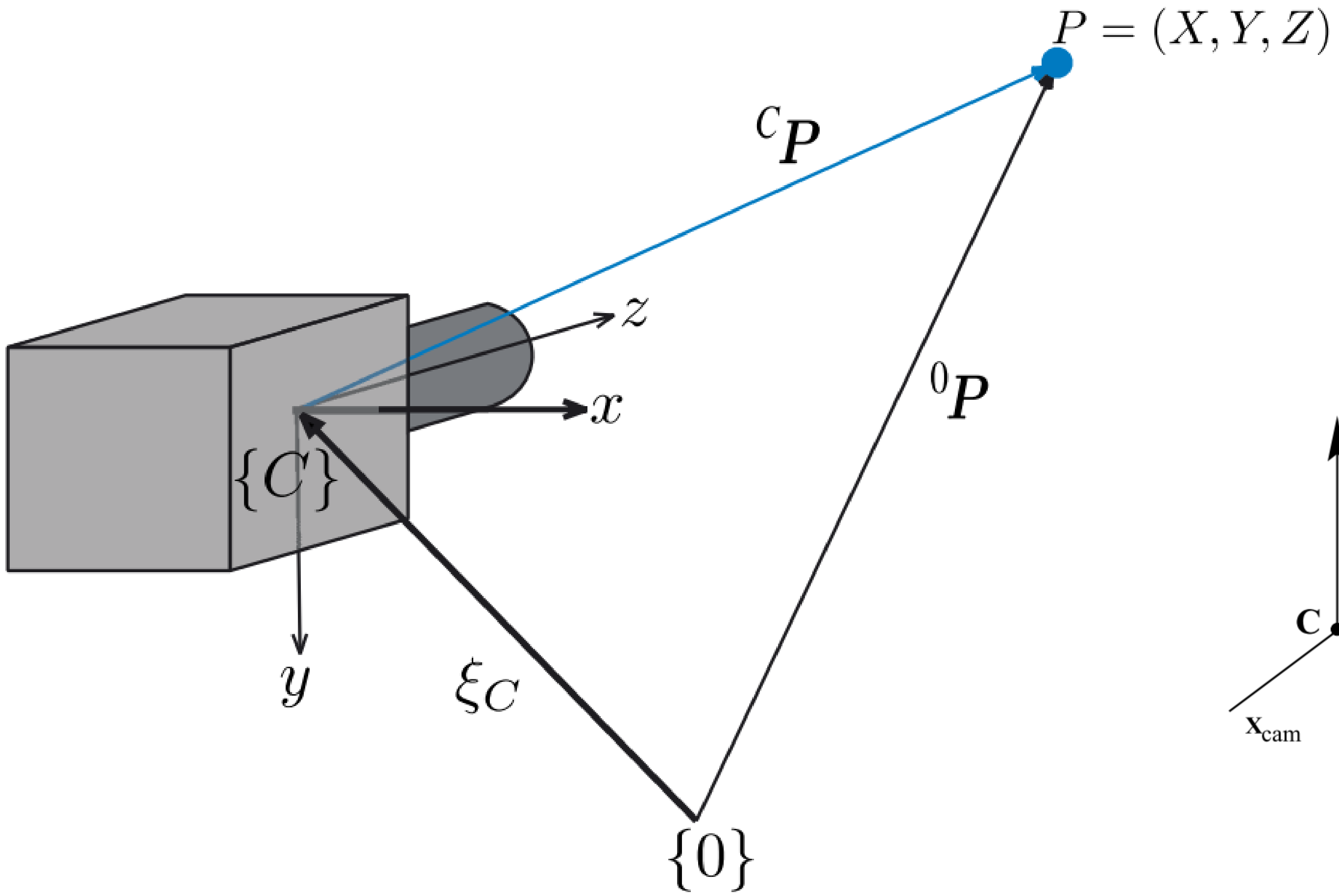


$$\tilde{\boldsymbol{p}} = \underbrace{\begin{pmatrix} 1/\rho_w & 0 & u_0 \\ 0 & 1/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}}_{\boldsymbol{K}} \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}$$

ρ_w and ρ_h are the width and height of each pixel

Image from Corke 2011

Camera Coordinate Frames



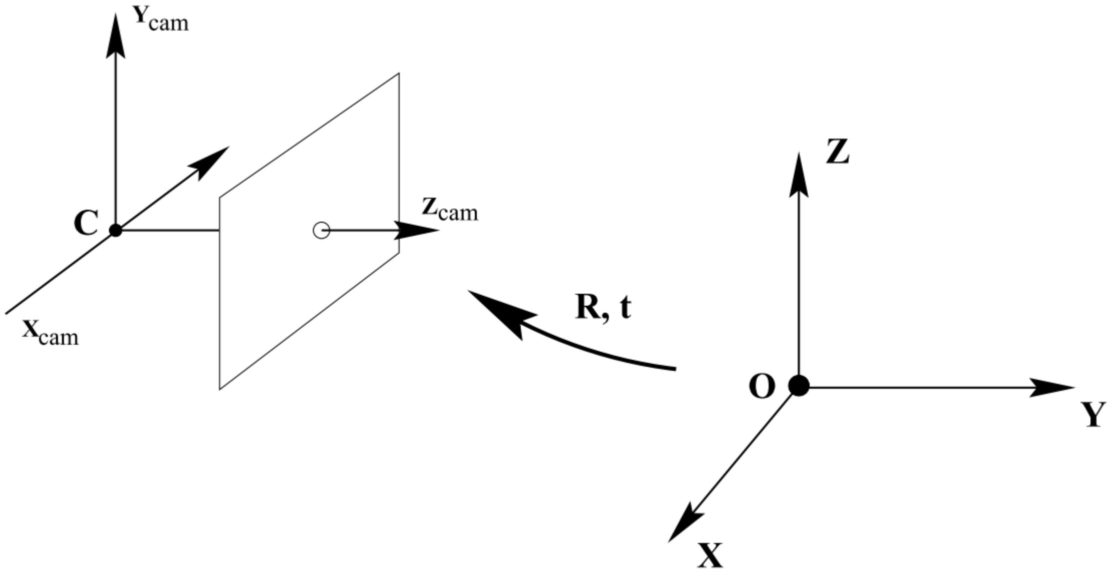


Image from Corke 2011

Camera Matrix

- Putting everything together

OpenCV $K\begin{bmatrix} R \mid t \end{bmatrix}$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\tilde{\boldsymbol{p}} = \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{\left({}^{0}\mathbf{T}_{C}\right)^{-1}}_{\text{extrinsic}} \tilde{\boldsymbol{P}}$$

$$= \boldsymbol{K}\boldsymbol{P}_0\, {}^{0}\boldsymbol{T}_C^{-1} \tilde{\boldsymbol{P}}$$

$$= \boldsymbol{C}\tilde{\boldsymbol{P}}$$

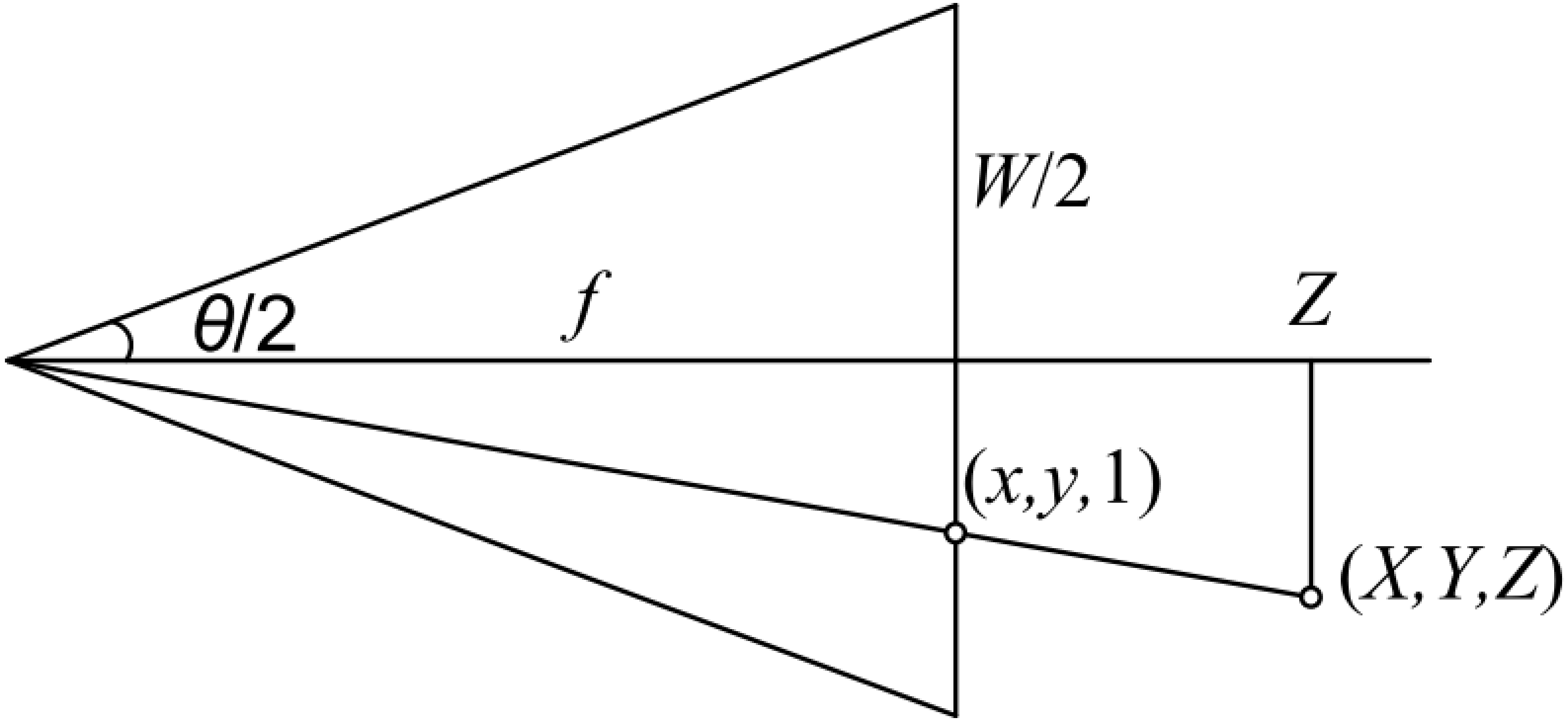
Image from Corke 2011

Simplifying Calibration Matrix K

Skew of un-orthogonal u- and v- axis

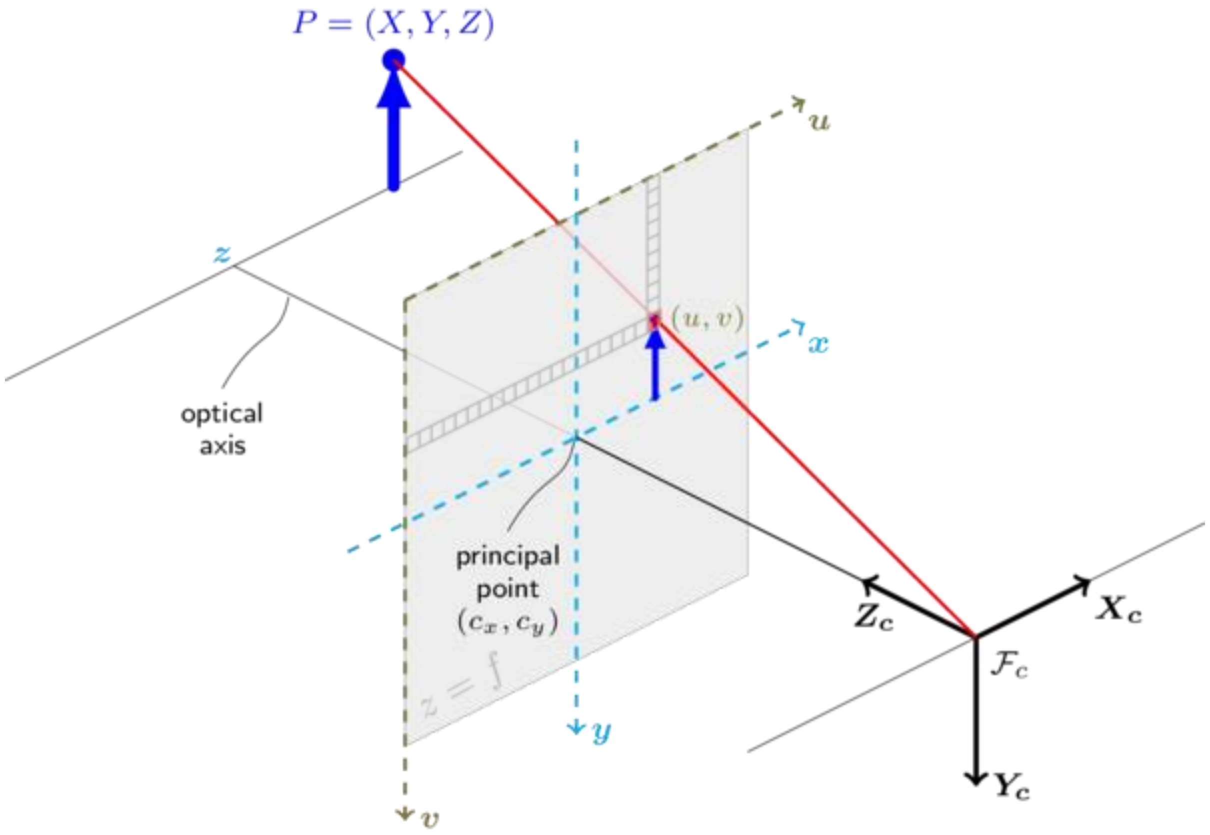
$$\boldsymbol{K} = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{K} = \begin{bmatrix} f & s & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{K} = \begin{bmatrix} f & 0 & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

The Unit of Focal Length



$$\tan\frac{\theta}{2} = \frac{W}{2f} \quad \text{or} \quad f = \frac{W}{2}\left[\tan\frac{\theta}{2}\right]^{-1}$$

Putting Everything Together in OpenCV



$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + t$$

$$x' = x/z$$

$$y' = y/z$$

$$u = f_x * x' + c_x$$

$$v = f_y * y' + c_y$$

https://docs.opencv.org/2.4/modules/calib3d/doc/camera_calibration_and_3d_reconstruction.html

Representing Geometric Primitives in Homogenous Coordinates

- Inhomogeneous point

$$\boldsymbol{x} = (x, y) \in \mathcal{R}^2$$

$$\boldsymbol{x} = (x, y, z) \in \mathcal{R}^3$$

- Homogeneous point

2D projective space $\mathcal{P}^2 = \mathcal{R}^3 - (0, 0, 0)$

$$\tilde{\boldsymbol{x}} = (\tilde{x}, \tilde{y}, \tilde{w}) \in \mathcal{P}^2$$

$$\tilde{\boldsymbol{x}} = (\tilde{x}, \tilde{y}, \tilde{w}) = \tilde{w}(x, y, 1) = \tilde{w}\bar{\boldsymbol{x}},$$

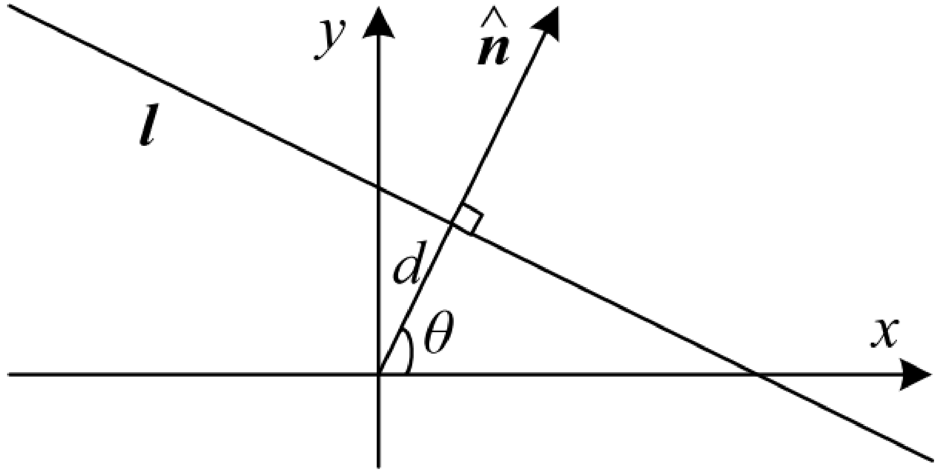
  - Points at infinity (or ideal points): $\{(\tilde{x}, \tilde{y}, \tilde{w}) | \tilde{w} = 0\}$

Representing Geometric Primitives in Homogenous Coordinates

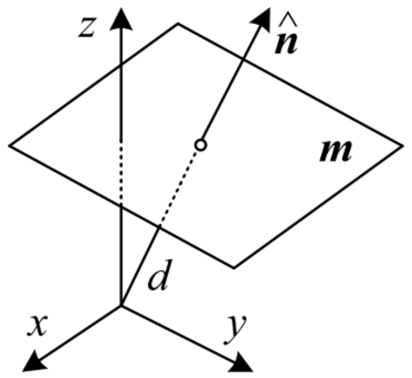
- Homogeneous 2D line

$$\bar{\boldsymbol{x}} \cdot \tilde{\boldsymbol{l}} = ax + by + c = 0$$

$$\tilde{\boldsymbol{l}} = (a, b, c)$$



- Homogeneous 3D plane



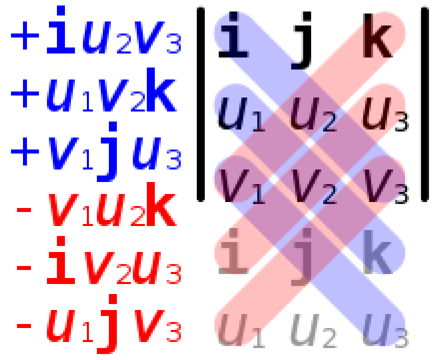
Advantages of Homogenous Coordinates

- Joints and intersections
  - Intersection point of two lines

$$\tilde{x} = \tilde{l}_1 \times \tilde{l}_2$$

  - Line jointing two points

$$\tilde{l} = \tilde{x}_1 \times \tilde{x}_2$$



- Duality between 2D lines and 2D points

Advantages of Homogenous Coordinates

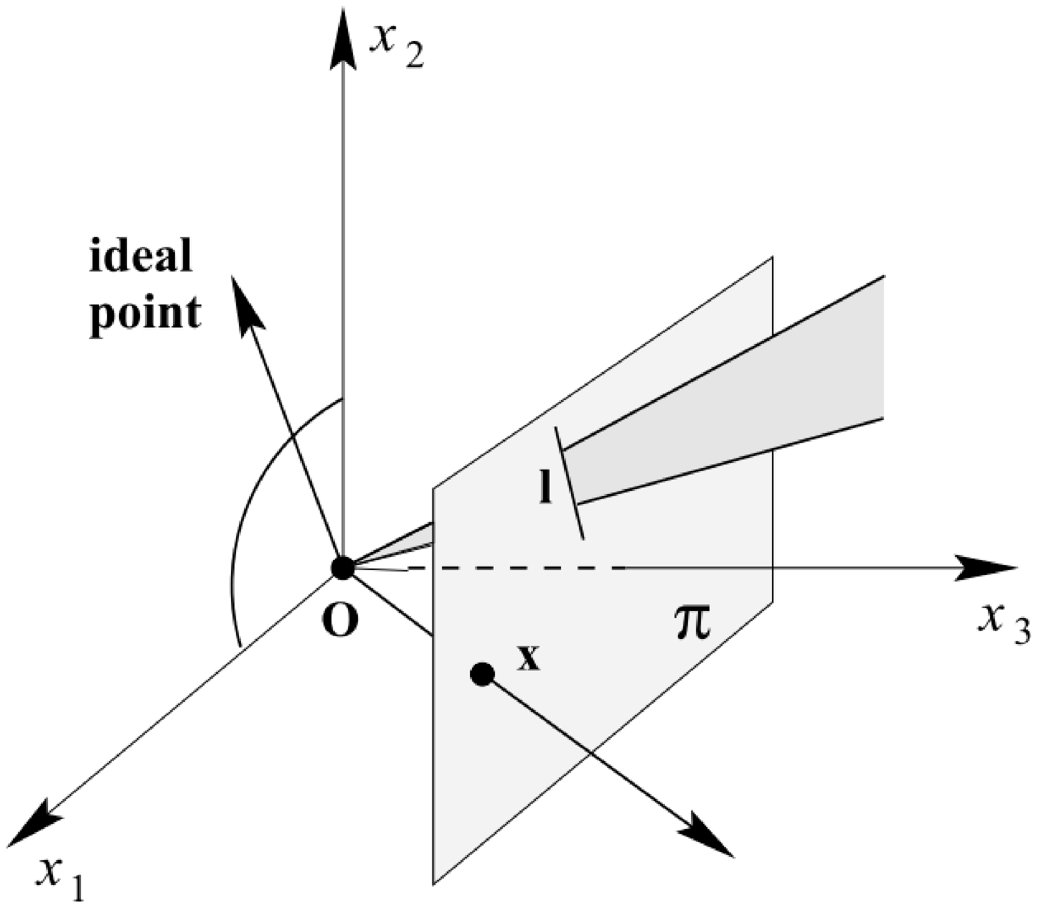
- Intersection of parallel lines $ax+by+c=0$ and $ax+by+c'=0$?
  - Point at infinity $(b, -a, 0)^\mathsf{T}$
- Line at infinity (or ideal line)?

$$\mathbf{l}_\infty = (0, 0, 1)^\mathsf{T}$$

  - The set of all ideal points
  - The set of directions of lines

Projective Space

- Projective geometry
  - The study of the geometry of projective space
  - **A point** in 2D projective space
    - Can be seen as **a ray** passing through the origin in 3D Euclidean space
  - No need to distinguish between points/lines at infinity and ordinary points/lines
  - One of the most important theoretic foundation of geometric computer vision



2D-to-2D Transformations

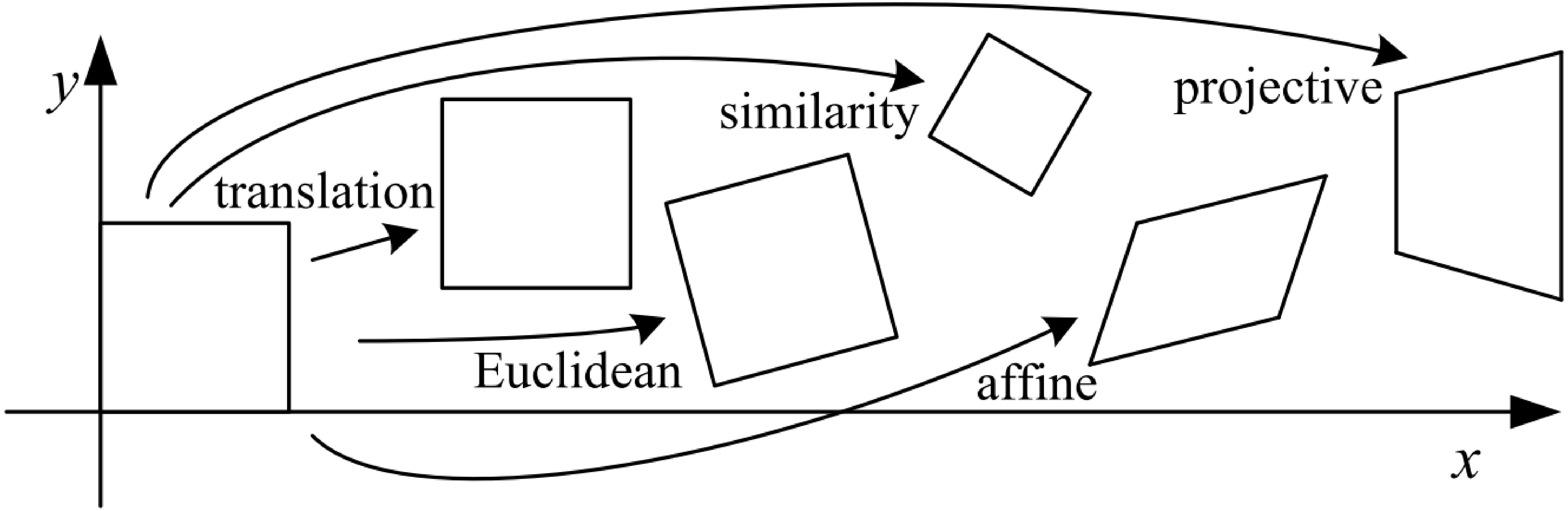


Image from: Szeliski 2011

Hierarchy of 2D Transformations

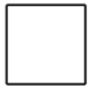
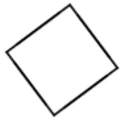
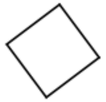
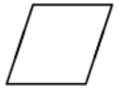
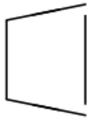
Transformation	Matrix	# DoF	Preserves	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	2	orientation	
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	3	lengths	
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	4	angles	
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{2\times 3}$	6	parallelism	
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{3\times 3}$	8	straight lines	

Image from: Szeliski 2011

Hierarchy of 3D Transformations

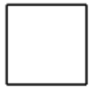
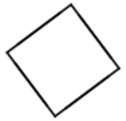
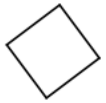
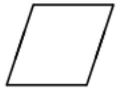
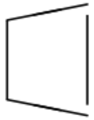
Transformation	Matrix	# DoF	Preserves	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{3\times 4}$		orientation	
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{3\times 4}$		lengths	
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{3\times 4}$		angles	
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{3\times 4}$		parallelism	
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{4\times 4}$		straight lines	

Image from: Szeliski 2011

3D Rotation Representation

- Orthonormal matrix

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \qquad R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

3D Rotation Representation

- Euler angles
  - 3 successive rotations
  - Eulerian: with repetition in axis
    - XYX, XZX, YXY, YZY, ZXZ, ZYZ
  - Cardanian: without repetition
    - XYZ, XZY, YZX, YXZ, ZXY, ZYX
  - 12 types
    - And you should always check handedness, intrinsic or extrinsic rotation

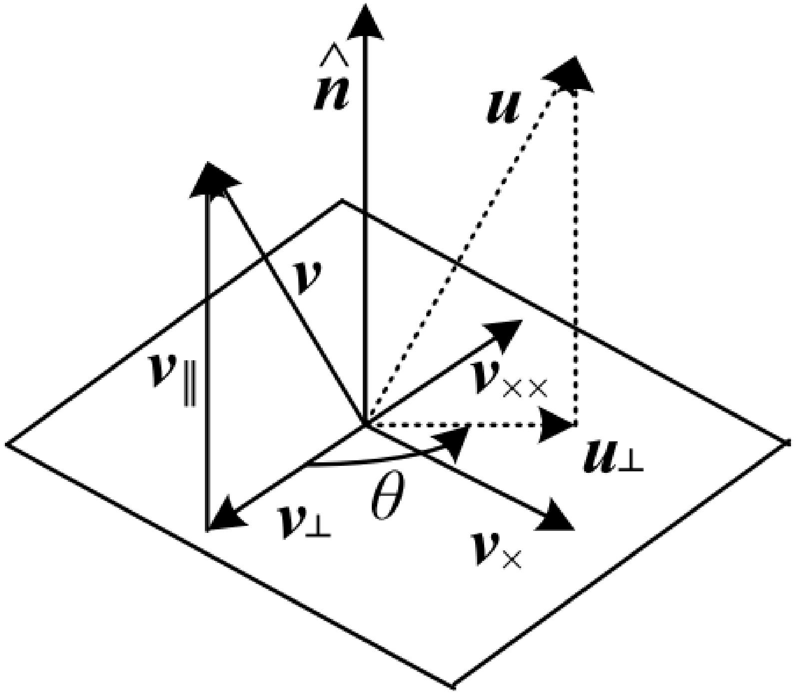
$$\boldsymbol{R} = \boldsymbol{R}_z(\phi)\boldsymbol{R}_y(\theta)\boldsymbol{R}_z(\psi)$$

3D Rotation Representation

- Axis-angle

$$\boldsymbol{R}(\hat{\boldsymbol{n}}, \theta) = \boldsymbol{I} + \sin\theta[\hat{\boldsymbol{n}}]_\times + (1 - \cos\theta)[\hat{\boldsymbol{n}}]_\times^2$$

$$[\hat{\boldsymbol{n}}]_\times = \begin{bmatrix} 0 & -\hat{n}_z & \hat{n}_y \\ \hat{n}_z & 0 & -\hat{n}_x \\ -\hat{n}_y & \hat{n}_x & 0 \end{bmatrix}$$



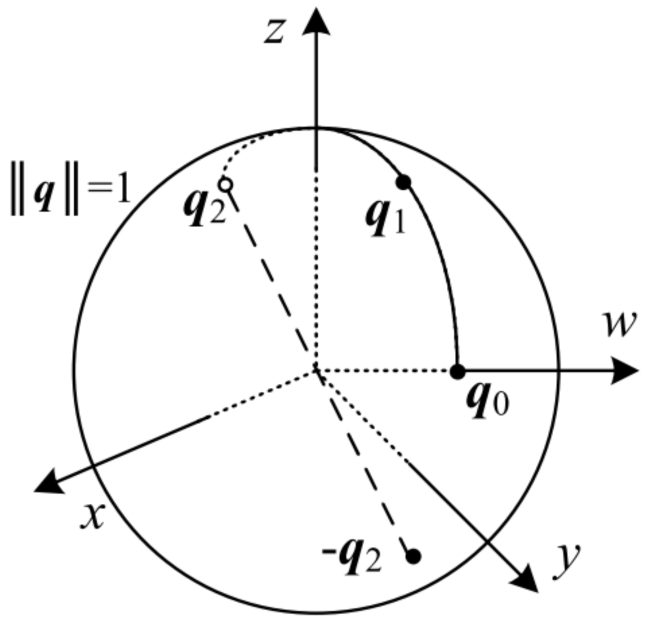
3D Rotation Representation

- Unit quaternion

$$\boldsymbol{q} = (\boldsymbol{v}, w) = (\sin\frac{\theta}{2}\hat{\boldsymbol{n}}, \cos\frac{\theta}{2})$$

$$\boldsymbol{q} = (x, y, z, w)$$

$$\boldsymbol{R}(\boldsymbol{q}) = \begin{bmatrix} 1-2(y^2+z^2) & 2(xy-zw) & 2(xz+yw) \\ 2(xy+zw) & 1-2(x^2+z^2) & 2(yz-xw) \\ 2(xz-yw) & 2(yz+xw) & 1-2(x^2+y^2) \end{bmatrix}$$



3D Rotation Representation/Parameterization

- Euler
  - Minimal
  - Many ambiguities
  - Gimbal Lock
- Axis-angle
  - Minimal
  - Not unique
- Unit quaternion
  - Continuous, almost unique
  - Easy inverse/multiplication
  - Interpolation using *slerp*

procedure *slerp*$(\boldsymbol{q}_0, \boldsymbol{q}_1, \alpha)$:

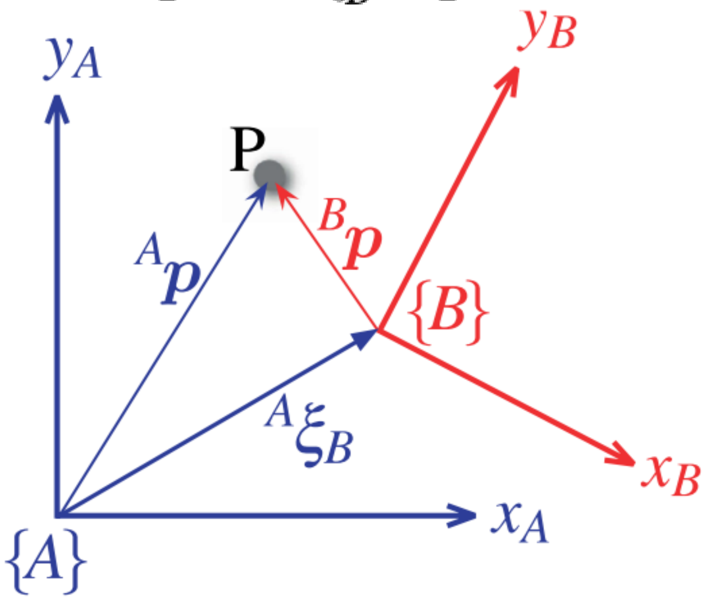
1. $\boldsymbol{q}_r = \boldsymbol{q}_1 / \boldsymbol{q}_0 = (\boldsymbol{v}_r, w_r)$
2. if $w_r < 0$ then $\boldsymbol{q}_r \leftarrow -\boldsymbol{q}_r$
3. $\theta_r = 2\tan^{-1}(\|\boldsymbol{v}_r\| / w_r)$
4. $\hat{\boldsymbol{n}}_r = \mathcal{N}(\boldsymbol{v}_r) = \boldsymbol{v}_r / \|\boldsymbol{v}_r\|$
5. $\theta_\alpha = \alpha\, \theta_r$
6. $\boldsymbol{q}_\alpha = (\sin\frac{\theta_\alpha}{2}\hat{\boldsymbol{n}}_r, \cos\frac{\theta_\alpha}{2})$
7. **return** $\boldsymbol{q}_2 = \boldsymbol{q}_\alpha \boldsymbol{q}_0$

- *Two more new rotation representation with Deep Learning*
  - *RSS'20: https://github.com/utiasSTARS/bingham-rotation-learning*
  - *CVPR'19: https://zhouyisjtu.github.io/project_rotation/rotation.html*

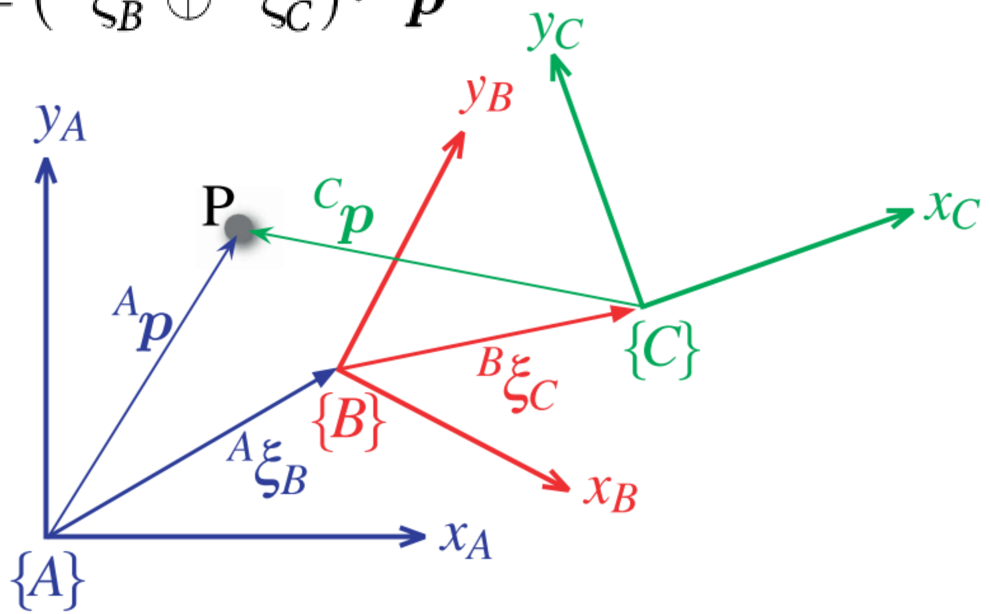
Coordinate Frames and Their Compositions

B's pose in A

$$^{A}\boldsymbol{p} = {}^{A}\xi_{B} \cdot {}^{B}\boldsymbol{p}$$



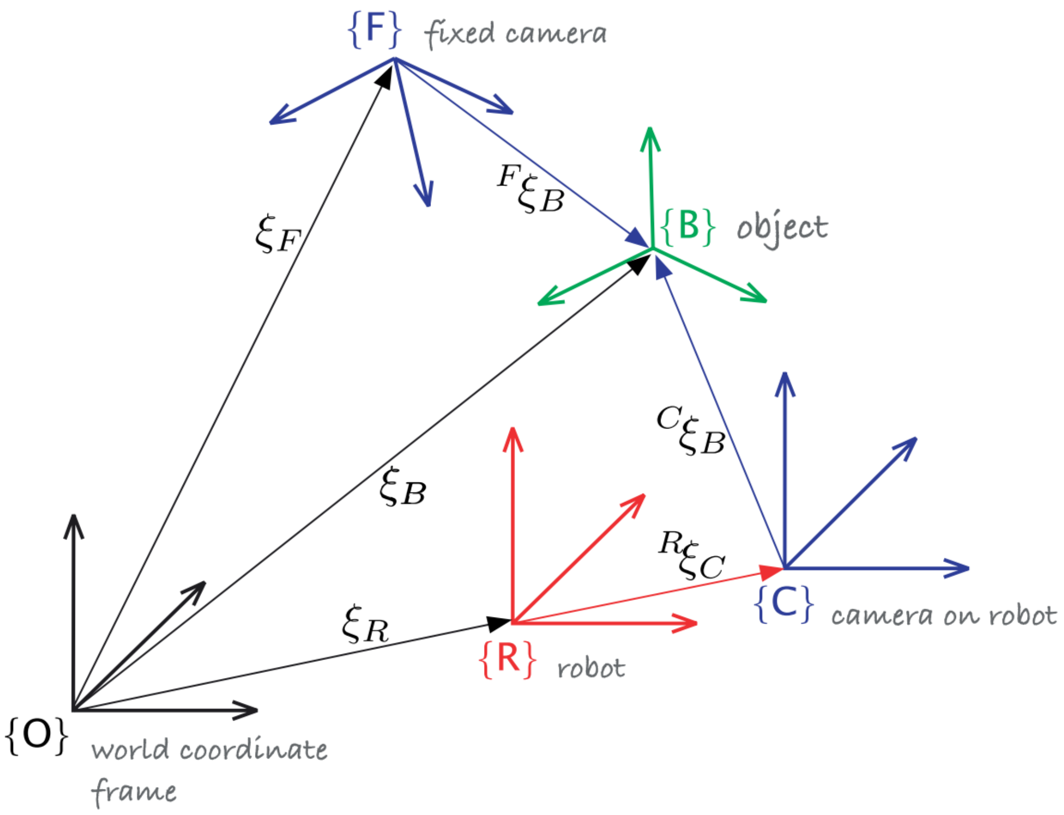
$$^{A}\boldsymbol{p} = ({}^{A}\xi_{B} \oplus {}^{B}\xi_{C}) \cdot {}^{C}\boldsymbol{p}$$



$$^{A}\xi_{C} = {}^{A}\xi_{B} \oplus {}^{B}\xi_{C}$$

Image from Corke 2011

Coordinate Frames and Their Compositions



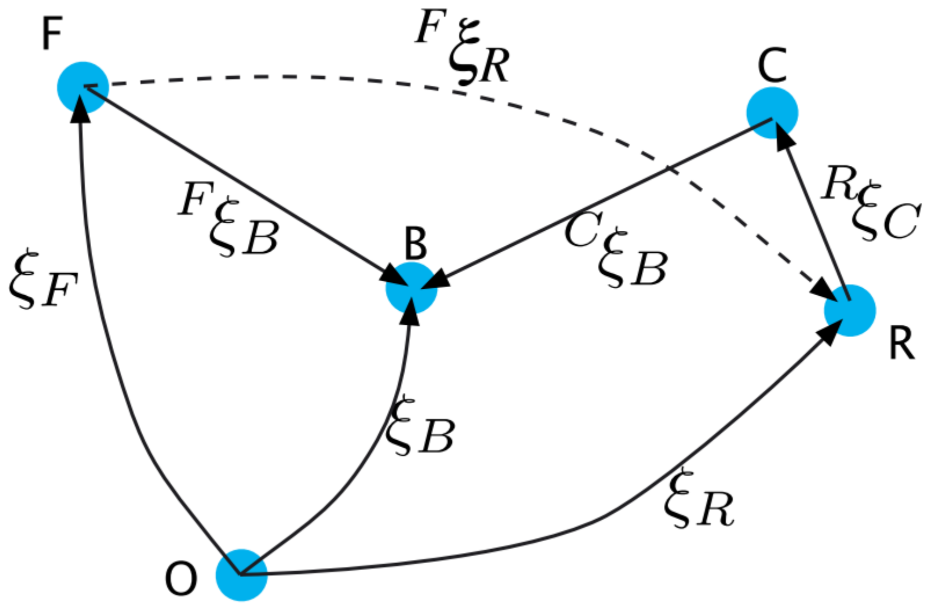
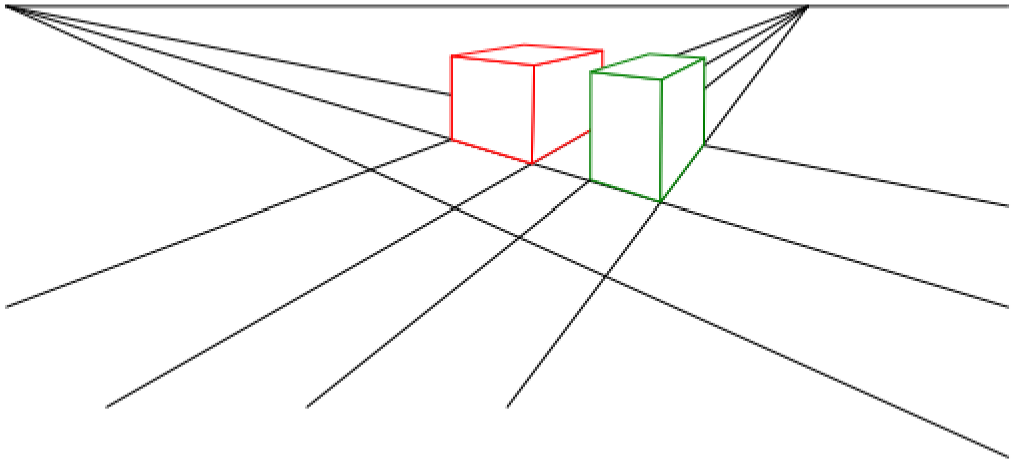


Image from Corke 2011

3D to 2D Projection

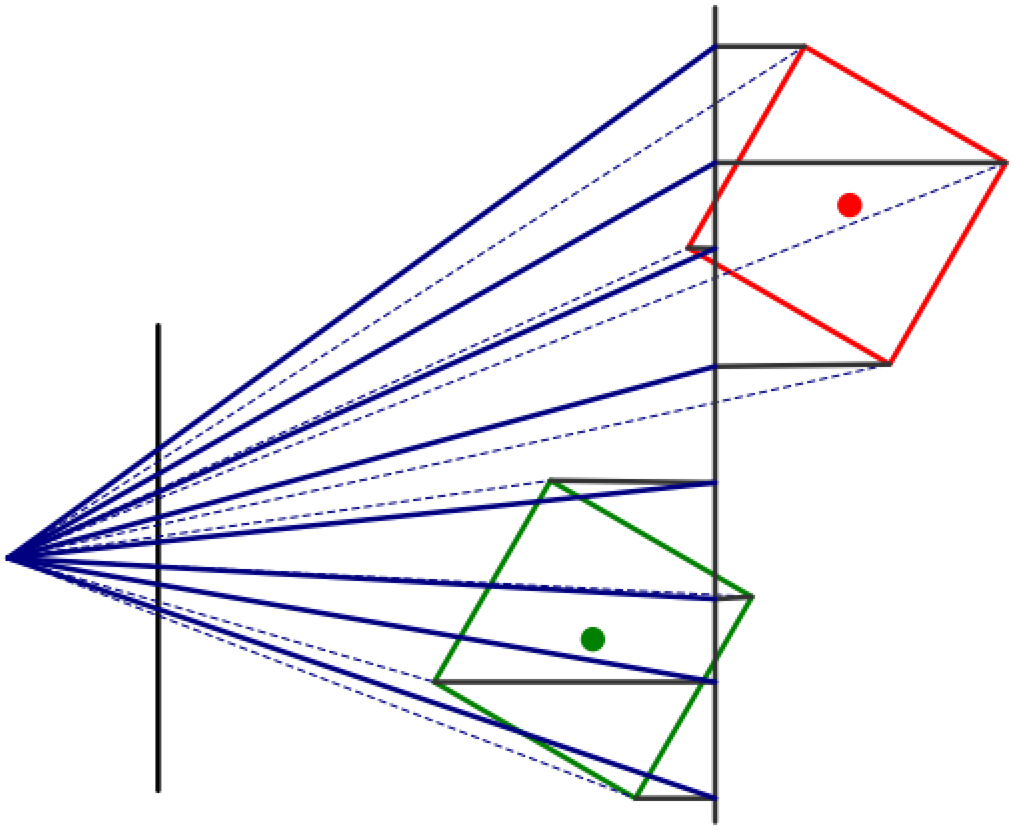


3D to 2D Projection

- Orthographic projection

- Approximation of telephoto

$$\tilde{\boldsymbol{x}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tilde{\boldsymbol{p}}$$



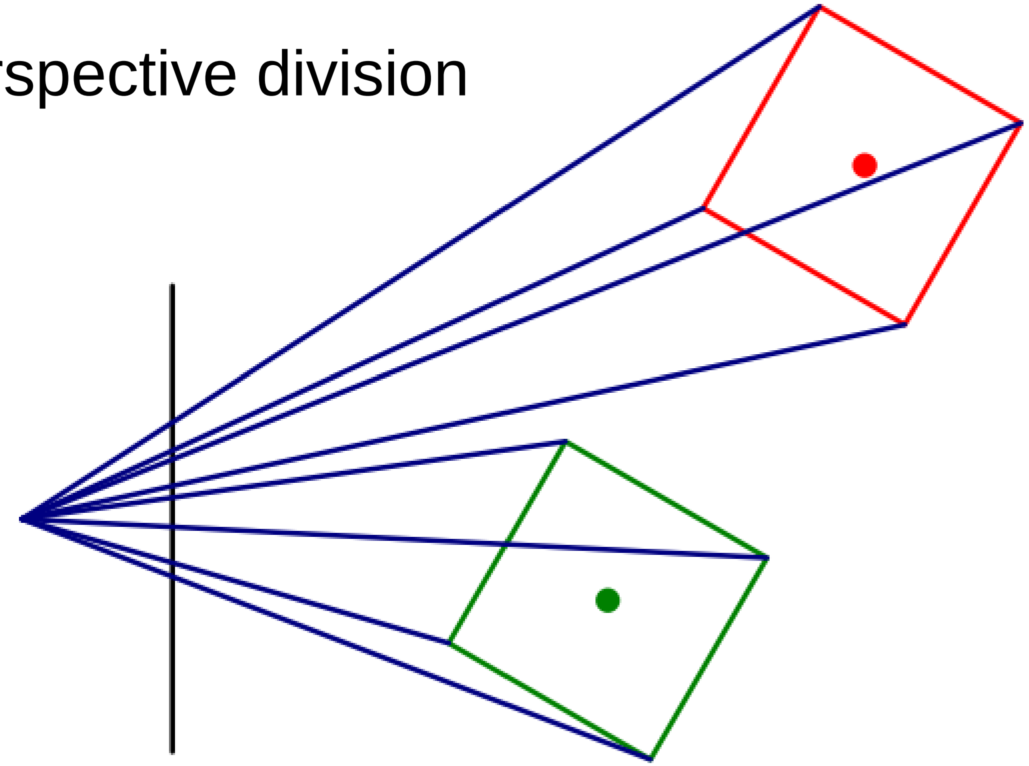
3D to 2D Projection

- **Perspective projection**

Perspective division

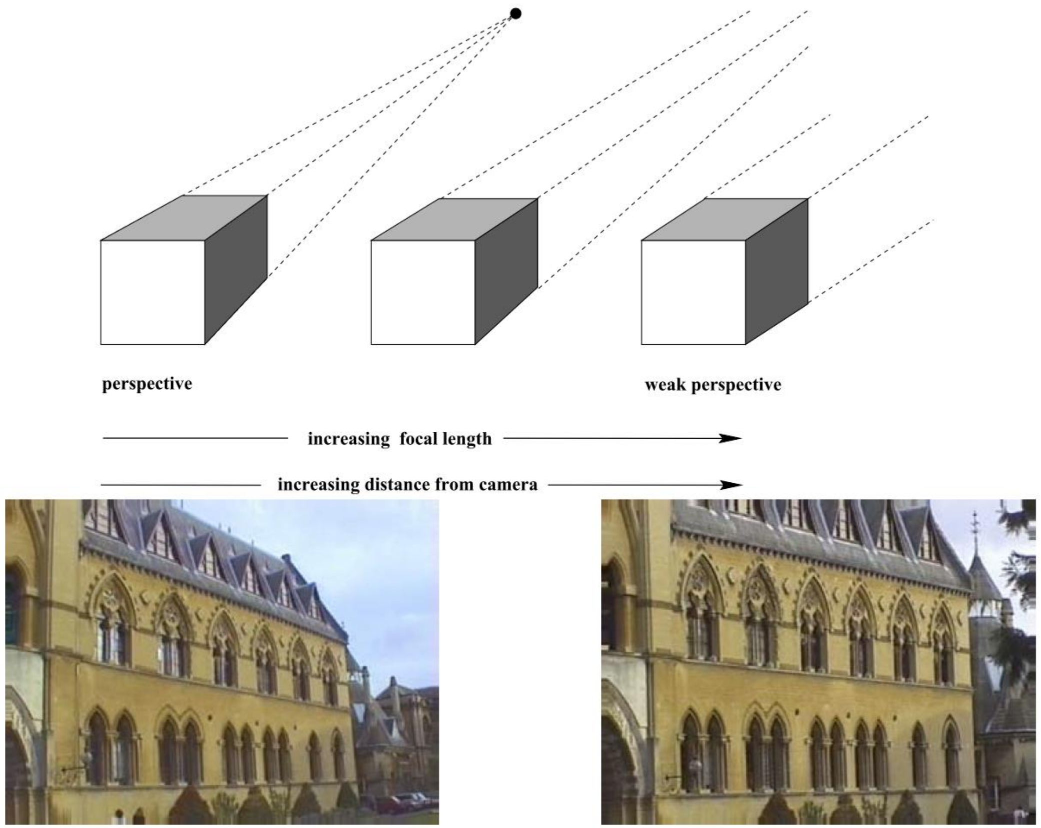
$$\bar{\boldsymbol{x}} = \mathcal{P}_z(\boldsymbol{p}) = \begin{bmatrix} x/z \\ y/z \\ 1 \end{bmatrix}$$

$$\tilde{\boldsymbol{x}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tilde{\boldsymbol{p}}$$



3D to 2D Projection

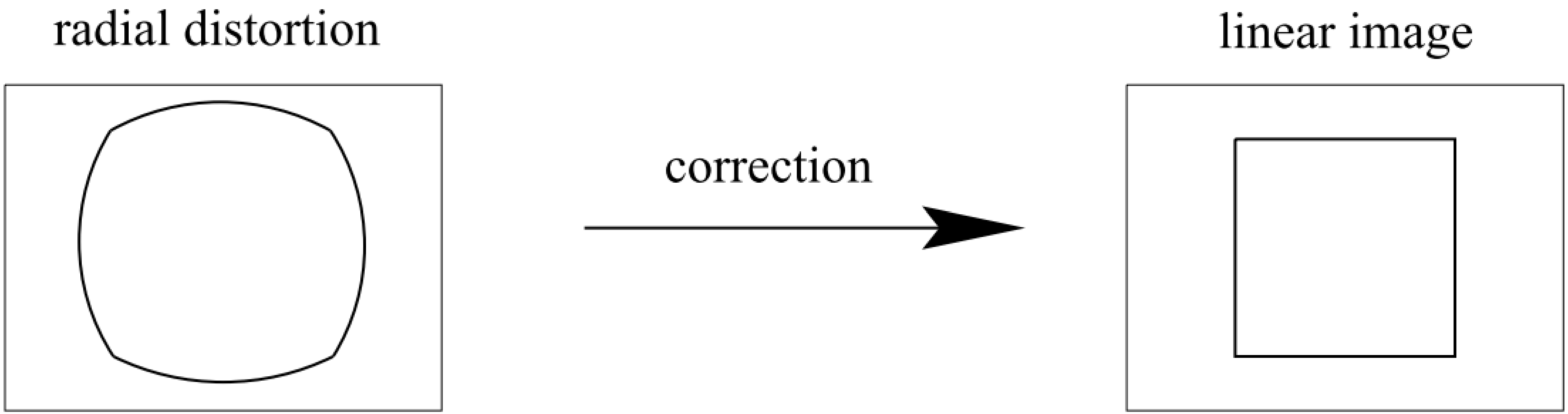
- Weak perspective projection



Lens Distortion

- Radial distortion

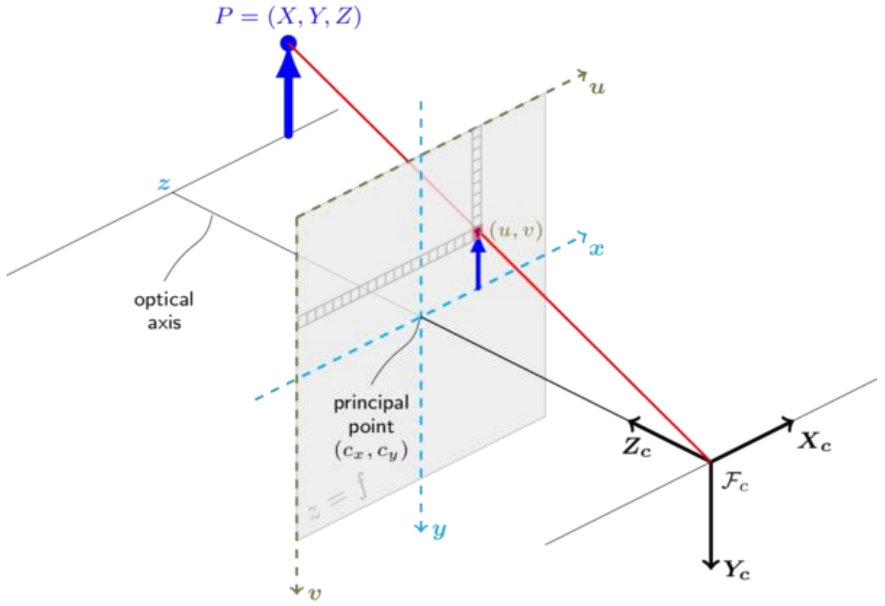
Lens Distortion

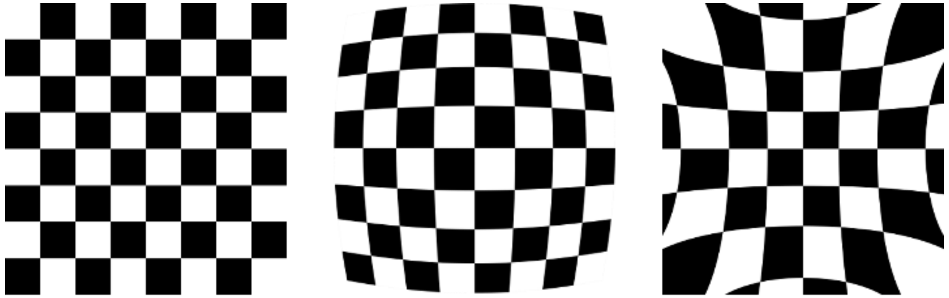


$$x_{\text{corrected}} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$y_{\text{corrected}} = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

https://hal-enpc.archives-ouvertes.fr/hal-01556898/document
https://jo.dreggn.org/home/2016_optics.pdf

Everything Together in OpenCV (Full Model)





No distortion

Positive radial distortion (Barrel distortion)

Negative radial distortion (Pincushion distortion)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + t$$

$$x' = x/z$$

$$y' = y/z$$

$$x'' = x' \frac{1 + k_1 r^2 + k_2 r^4 + k_3 r^6}{1 + k_4 r^2 + k_5 r^4 + k_6 r^6} + 2p_1 x' y' + p_2(r^2 + 2x'^2)$$

$$y'' = y' \frac{1 + k_1 r^2 + k_2 r^4 + k_3 r^6}{1 + k_4 r^2 + k_5 r^4 + k_6 r^6} + p_1(r^2 + 2y'^2) + 2p_2 x' y'$$

$$\text{where} \quad r^2 = x'^2 + y'^2$$

$$u = f_x * x'' + c_x$$

$$v = f_y * y'' + c_y$$

https://docs.opencv.org/2.4/modules/calib3d/doc/camera_calibration_and_3d_reconstruction.html

Next Week

++ Ax=b, Ax=0

* Homography Estimation

+ AprilTags

* Camera Calibration, Zhang's method

+ DLT

+ Vanishing Points & Lines

*: know how to code
++: know how to derive
+: know the concept

References for Next Week

- HZ2003:
  - Section 2.3, 4.1, 4.4, 7.1, 7.2, 7.4, 8.6
- FP2011:
  - Section 1.2, 1.3, 12.1
- Sz2011:
  - Section 6.3.1, 7.4.3
- Co2011:
  - Section 11.2, 11.1
- Linear algebra:
  - Szeliski 2011: section A.1.1, A.1.2, A.1.3, A.2, A.2.1
  - Hartley & Zisserman 2003: A5.1, A5.2, A5.3