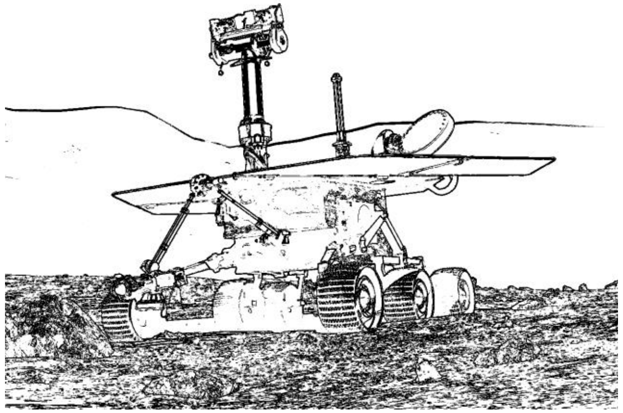


CSC477
Introduction to Mobile Robotics

Florian Shkurti

Week #1: Introduction, Sensors & Actuators

New robotics faculty in CS

Jessica Burgner-Kahrs

Animesh Garg

Myself

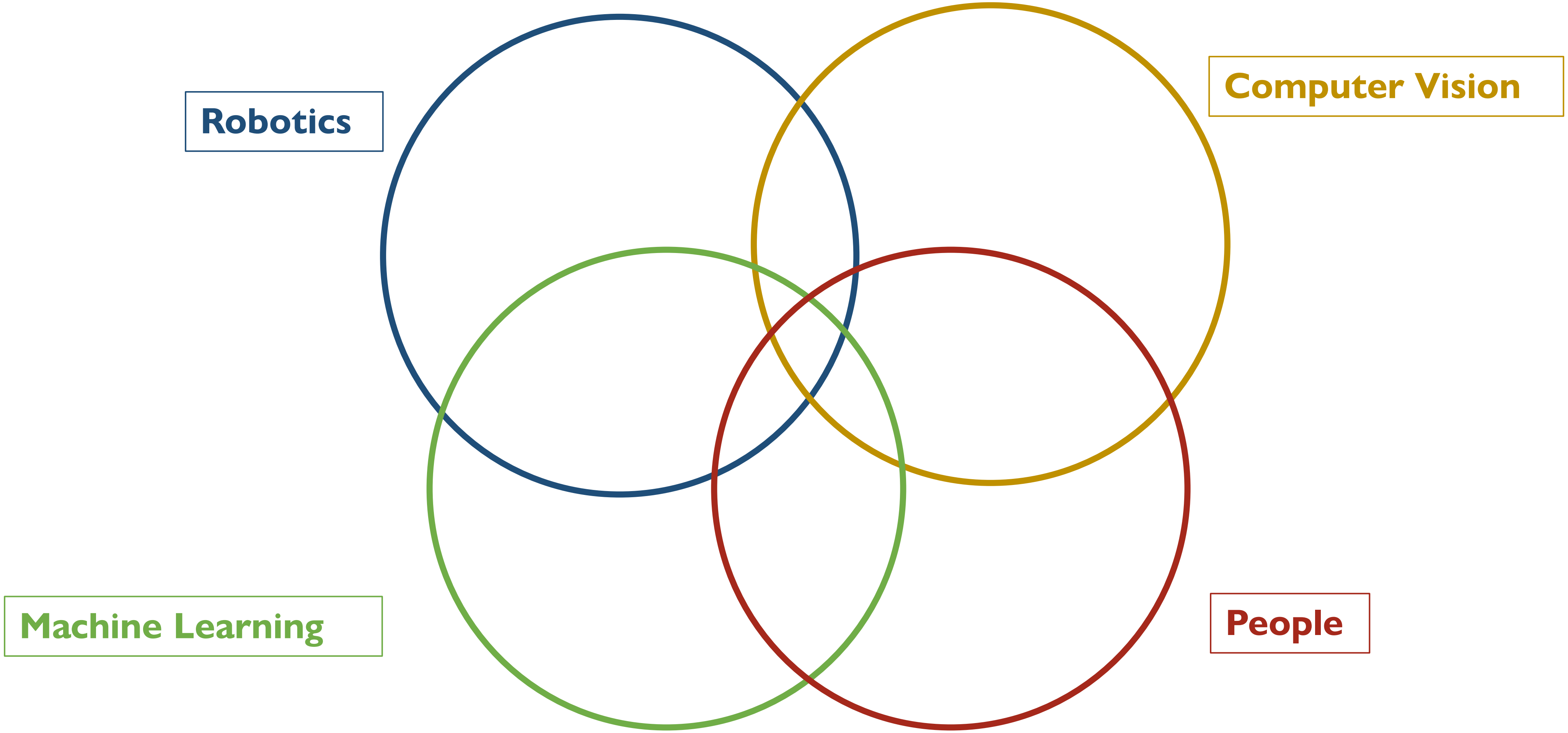
Today’s agenda

- Introduction
- Administrivia
  - Office hours
  - Tutorials
  - Assignment descriptions
  - Prerequisites
- Topics covered by the course
- Sensors and Actuators
- Quiz about background and interests

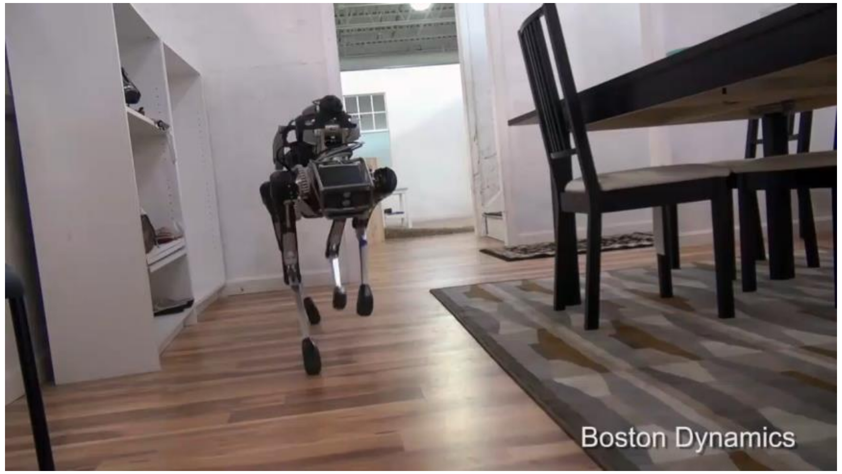
Your TA

Nan Liang
nan.liang@mail.utoronto.ca
Senior undergraduate student
Engineering Science, UofT

How I became interested in robotics

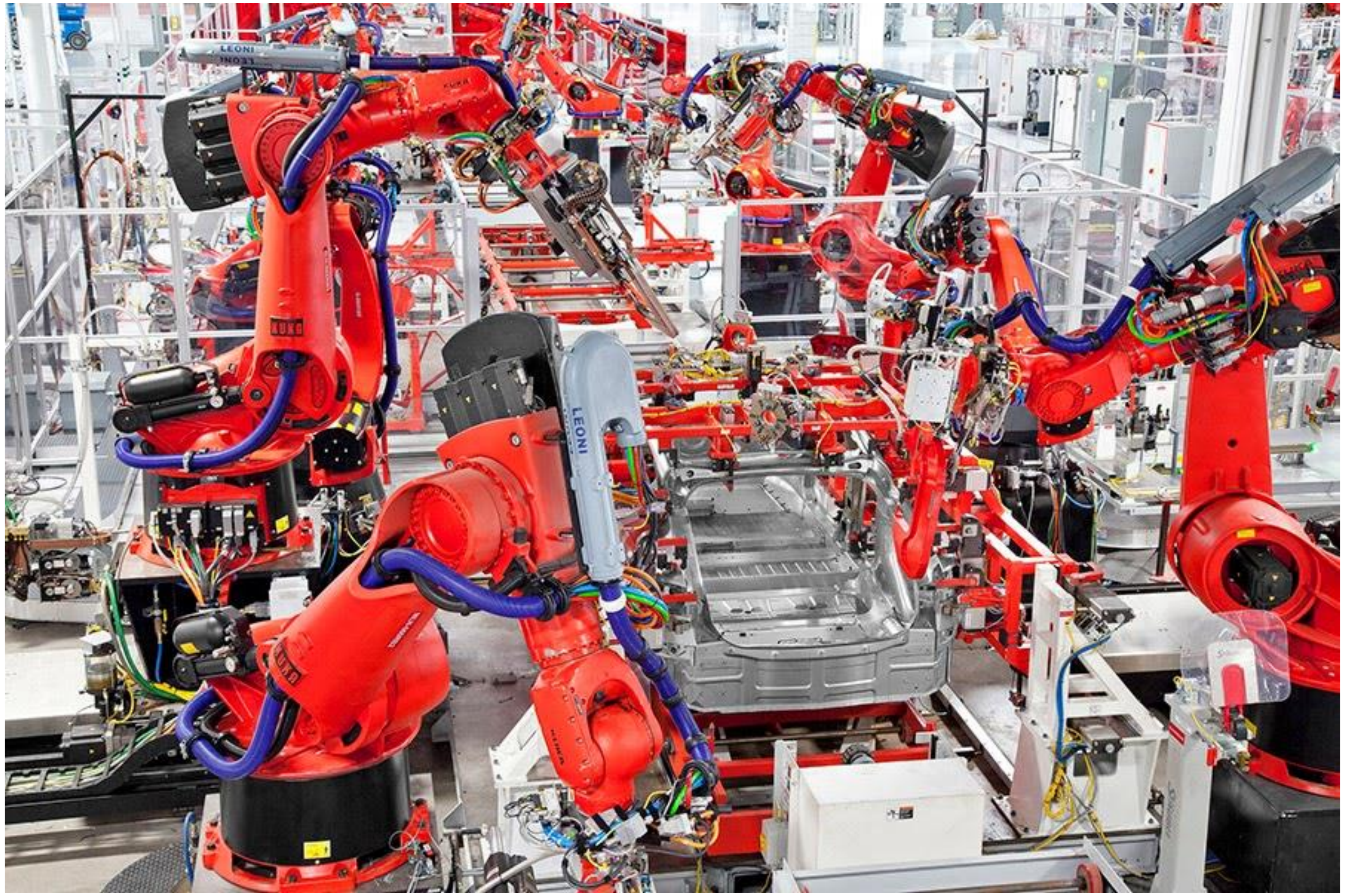


Today you have



Factory Automation

Autonomous warehouse robots at Amazon



Autonomous arms at Tesla

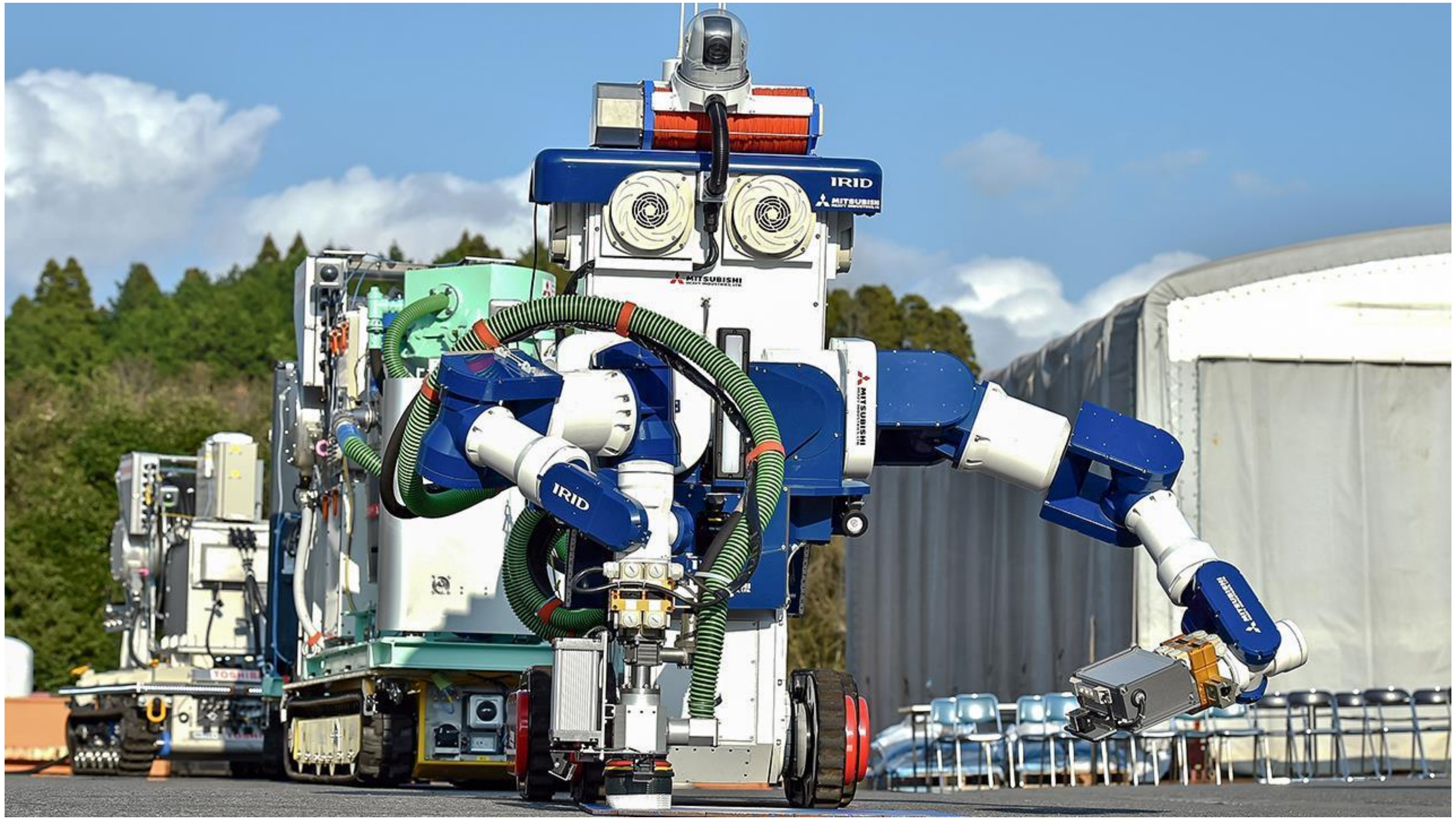
Pipe Inspection

Manually-controlled inspection robots

Nuclear Disaster Cleanup

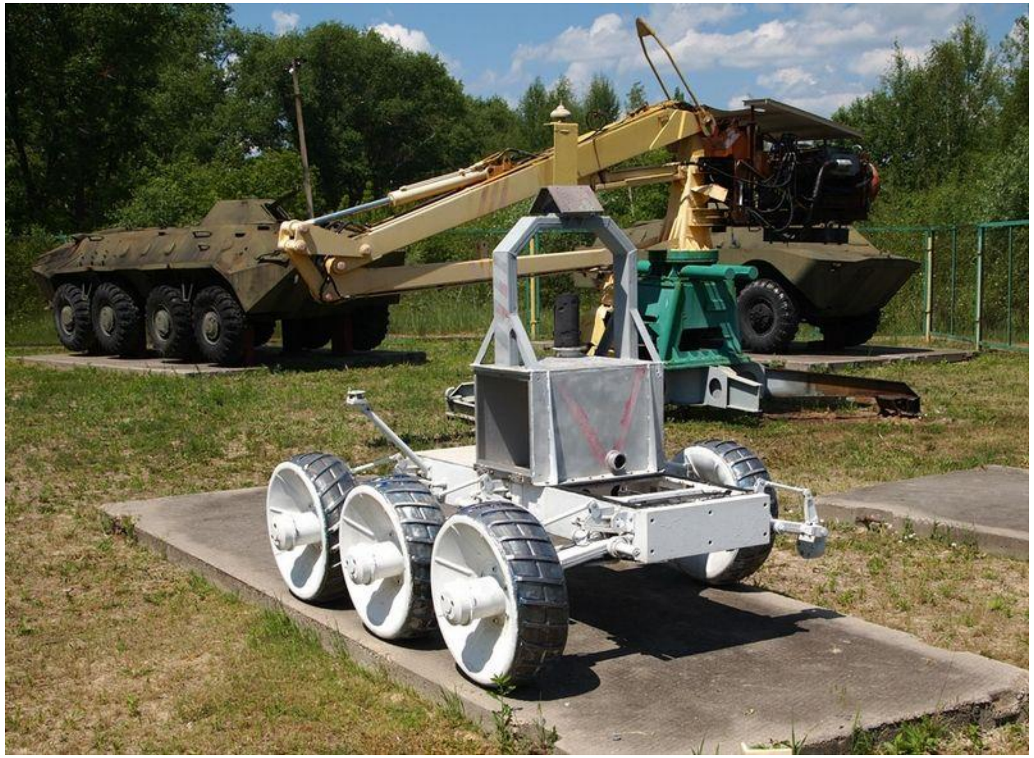
Remote-controlled cleaning robot at Fukushima Daiichi, 2011

Nuclear Disaster Cleanup



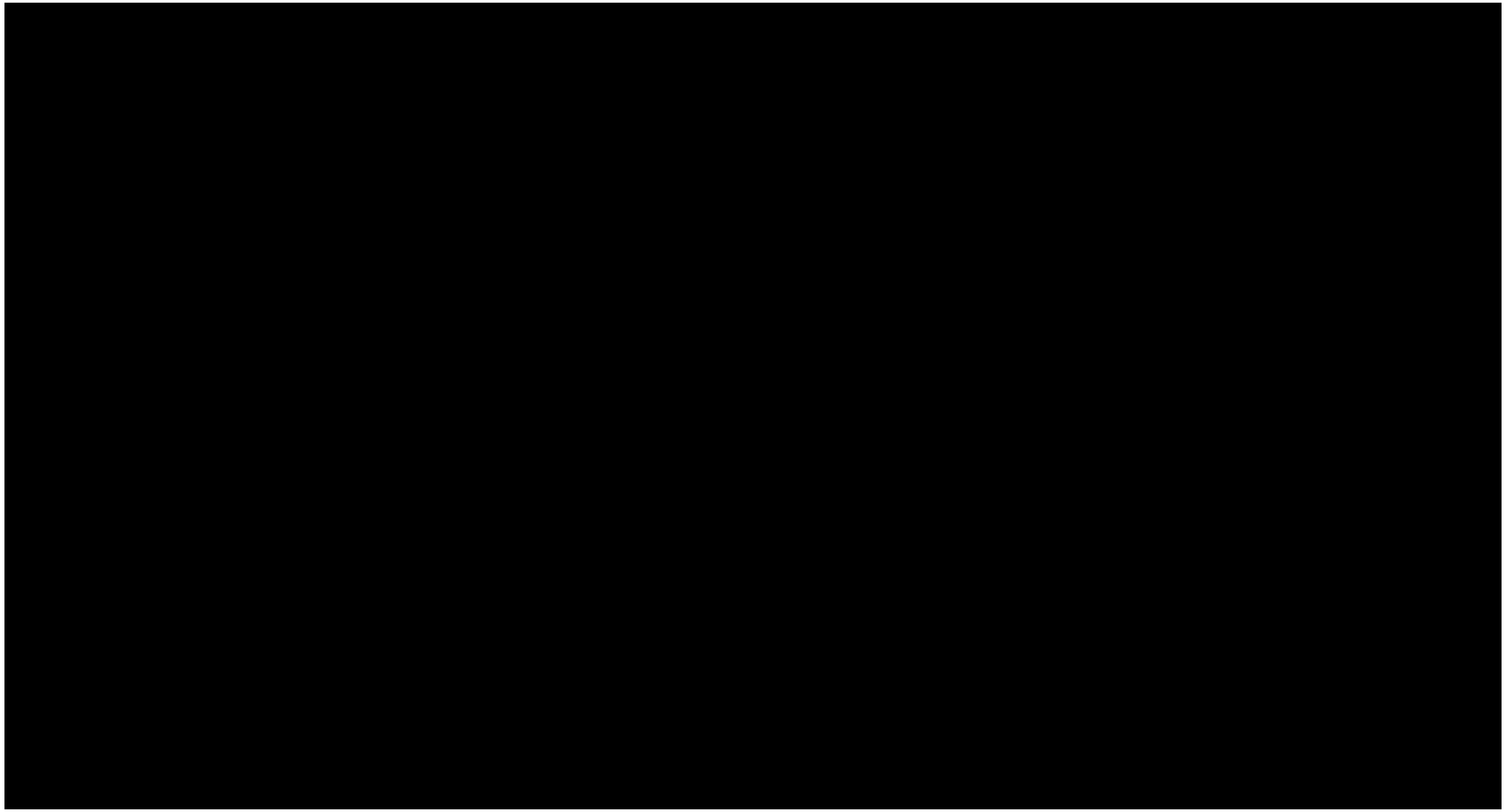
Remote-controlled cleaning robot at Fukushima Daiichi, 2011

Nuclear Disaster Cleanup



Remote-controlled cleaning robot at Chernobyl, 1986

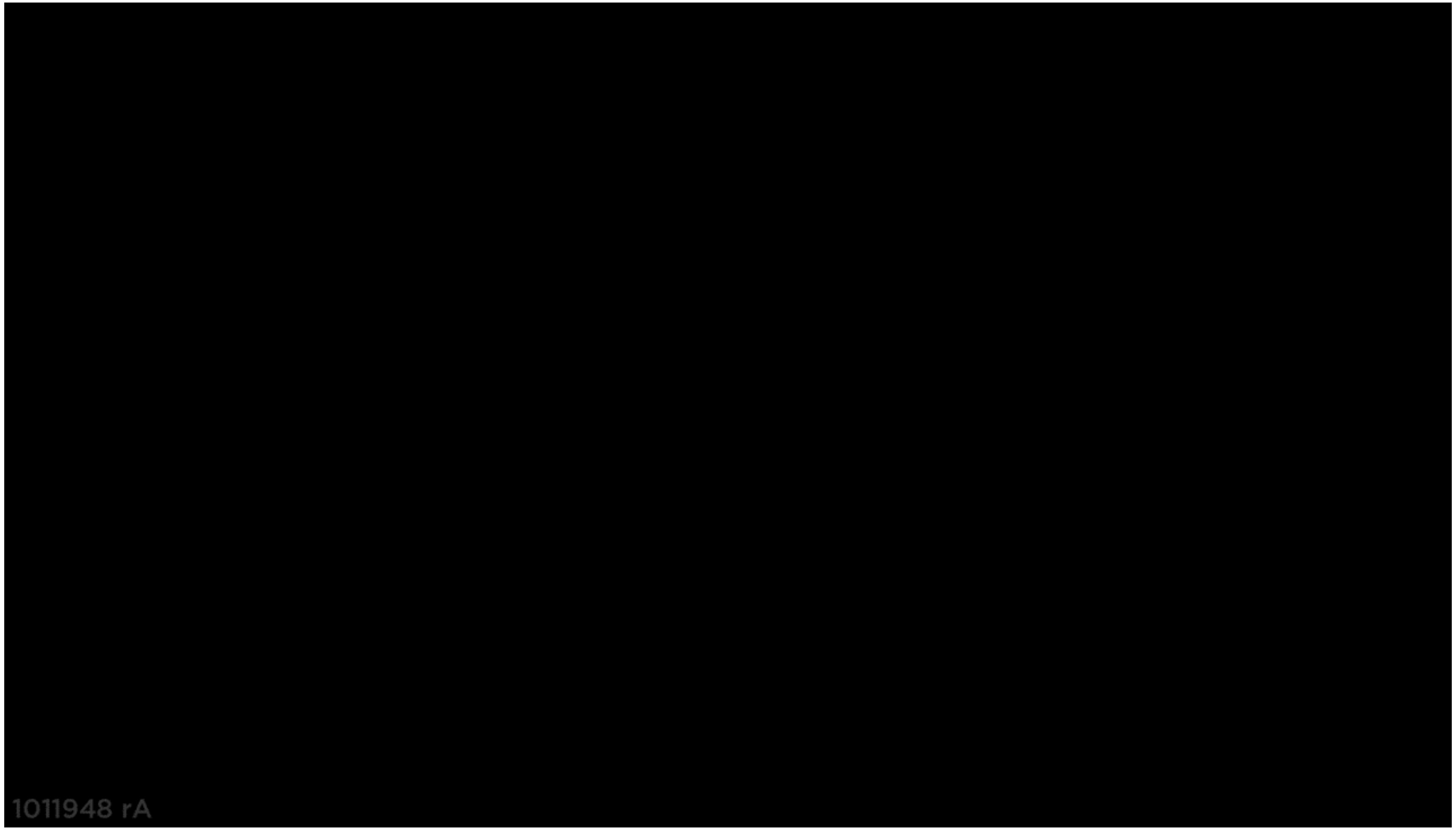
Aerial Package Delivery



Aerial First-Aid Delivery

Smart Wheelchairs

Robot Surgery



daVinci robot-assisted surgery

Precision Agriculture

farmbot.io

Self-driving Trucks

Mining Operations

Oil Spill Containment

BP Deepwater Horizon Spill, Gulf of Mexico, 2010

Autonomy vs. Remote Control

- Q: When is full or partial autonomy necessary?
- Q: When is remote control preferred?

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Prerequisites

- Software Engineering
  - Loops, conditionals, classes, modularity
  - Lists, hash maps/dictionaries, trees
  - Threads, callbacks, remote procedure calls, serialization

- Linear Algebra
  - Matrix multiplication and inversion, determinant
  - Solving systems of equations, Gaussian elimination
  - Matrix decompositions: Cholesky, QR
  - Least squares

- Basic Probability Theory
  - Multivariate distributions, especially Gaussians
  - Conditional probability, Bayes' rule
  - Maximum likelihood estimation

Prerequisites

Currently

Required: CSC209H5; CSC338H5; CSC373H5; MAT244H5; STA256H5
Recommended: CSC375H5; CSC384H5; CSC411H5; MAT224H5/MAT240H5

But actually

Required: CSC209H5; STA256H5; MAT224H5/MAT240H5
Recommended: MAT244H5; CSC384H5; CSC411H5;

4 Assignments

- ~80% coding and the rest theory
- Starter code will be provided
- Bonus questions will be provided
- Accepted languages: Python, C++
- You’re going to learn ROS (Robot Operating System) and use the Gazebo simulator
- You’re also going to learn numpy and scipy
- About 2.5 weeks to work on each

ROS + Gazebo simulation

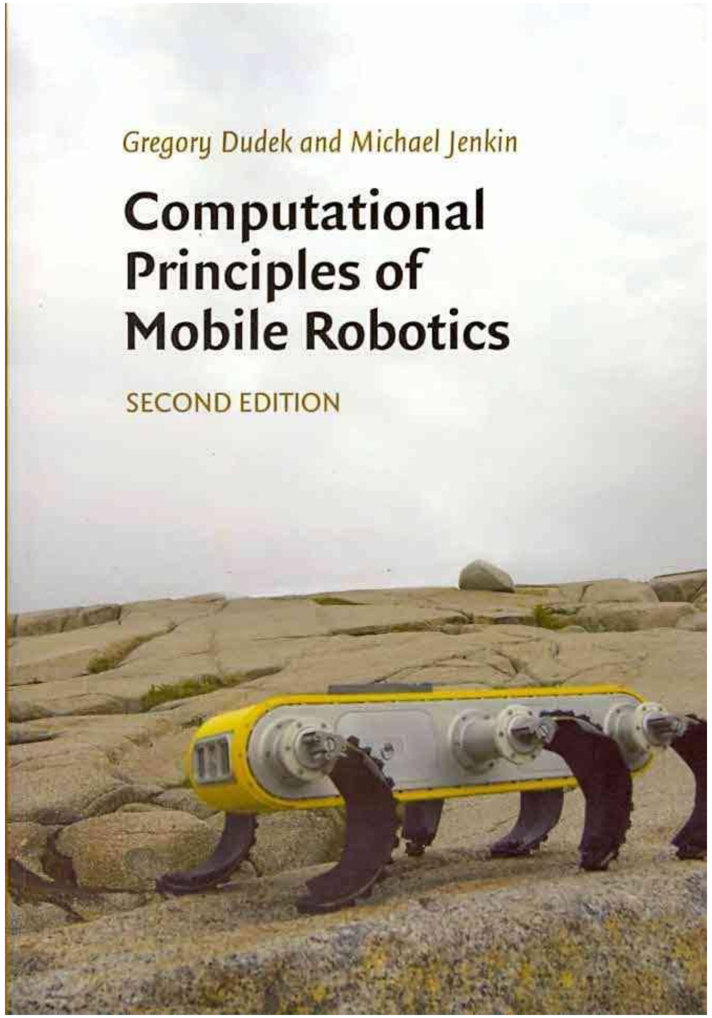
7 Quizzes

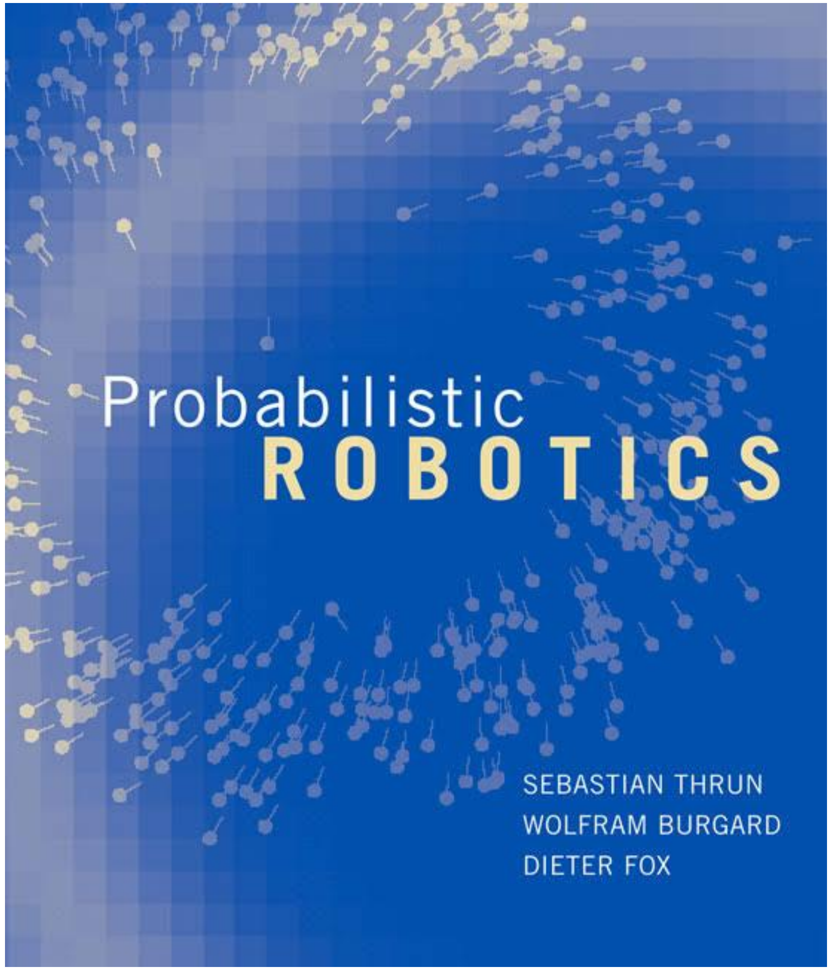
- 5 mins at the end of the class
- Not cumulative in terms of material. They cover only one lecture
- Meant to check whether you have understood basic concepts

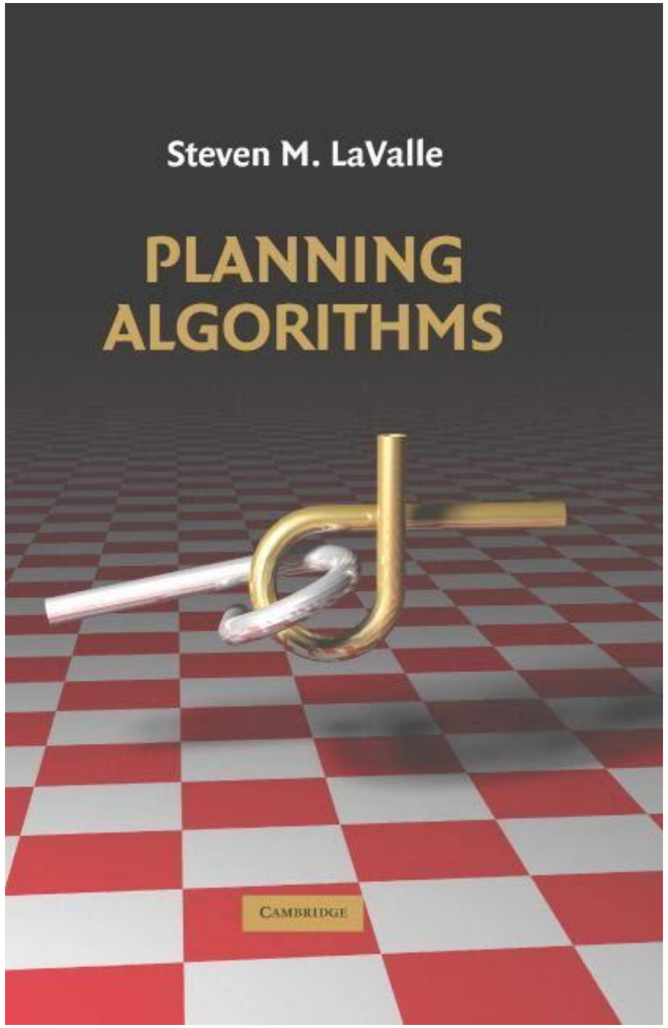
Evaluation

- 4 assignments, 15% each = 60%
- Best 5 out of 7 quizzes, 2% each = 10%
- 1 final exam = 30%

Recommended Textbooks (optional)







Recommended Online Courses (optional)

- Material is related to 477 but not identical
- I will post links on Quercus to specific lectures that are relevant

- https://www.coursera.org/learn/mobile-robot
- https://www.udacity.com/course/artificial-intelligence-for-robotics--cs373
- https://www.edx.org/course/autonomous-mobile-robots-ethx-amrx-1
- https://www.edx.org/course/underactuated-robotics-mitx-6-832x-0 (more advanced, little overlap with 477)

Office Hours

- Mine: Thursdays 4-5pm at DH3066
- Nan's: Tuesdays 2-3pm at UTM, location TBA

- <u>Office hours will begin next week</u>

Online communication

- Use Quercus
- Please check your course-related email frequently
- Email me or the TAs with “CSC477” in the subject line
- Anonymous feedback about anything course-related:
  https://www.surveymonkey.com/r/H8QH65F

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Main topics to be covered

Kinematics & Dynamics:
physical models of
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
desired robot motion?

Planning:
path planning in known maps

State Estimation:
designing estimators that incorporate
sensor measurements

Computer Vision:
estimating 3D structure + motion

Covered

Kinematics & Dynamics:
physical models of
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estimating 3D structure + motion

Not Covered

Electrical engineering:
motors, power supplies,
microcontrollers, batteries

Mechanical design

Ethics of AI

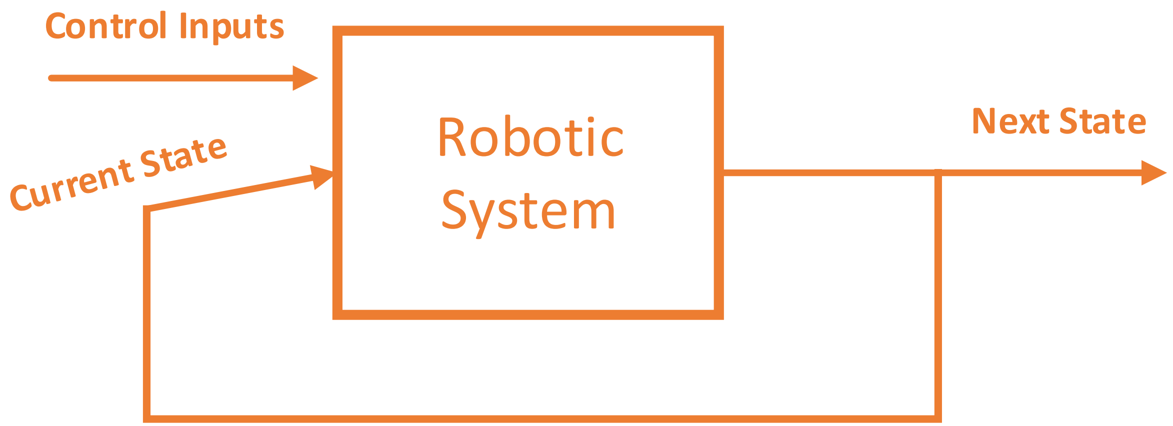
Multi-robot systems

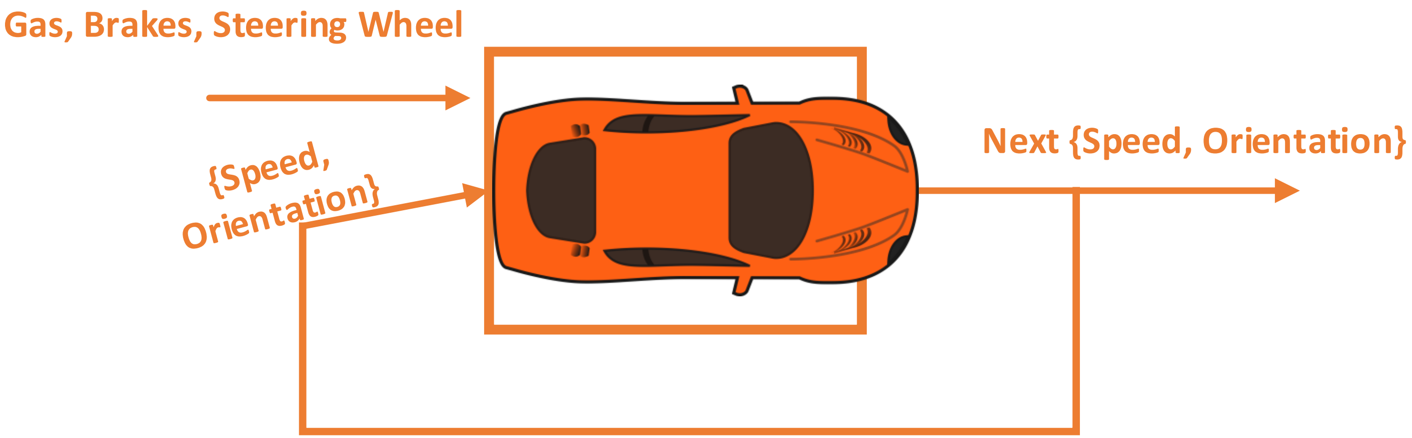
Humanoids and walking

Grasping and manipulation

Main topics to be covered

Kinematics & Dynamics:
physical models of
robotic systems and sensors



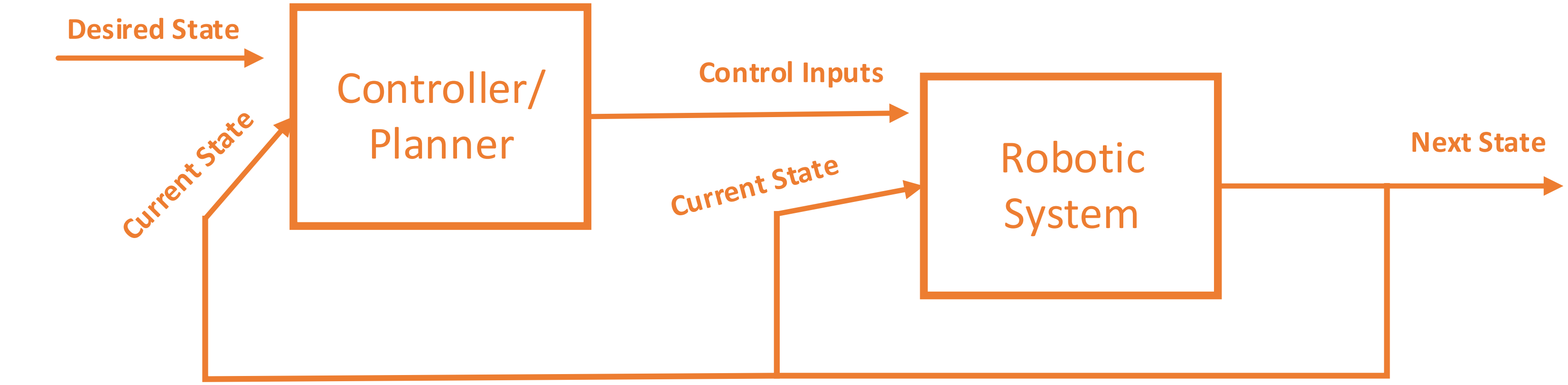


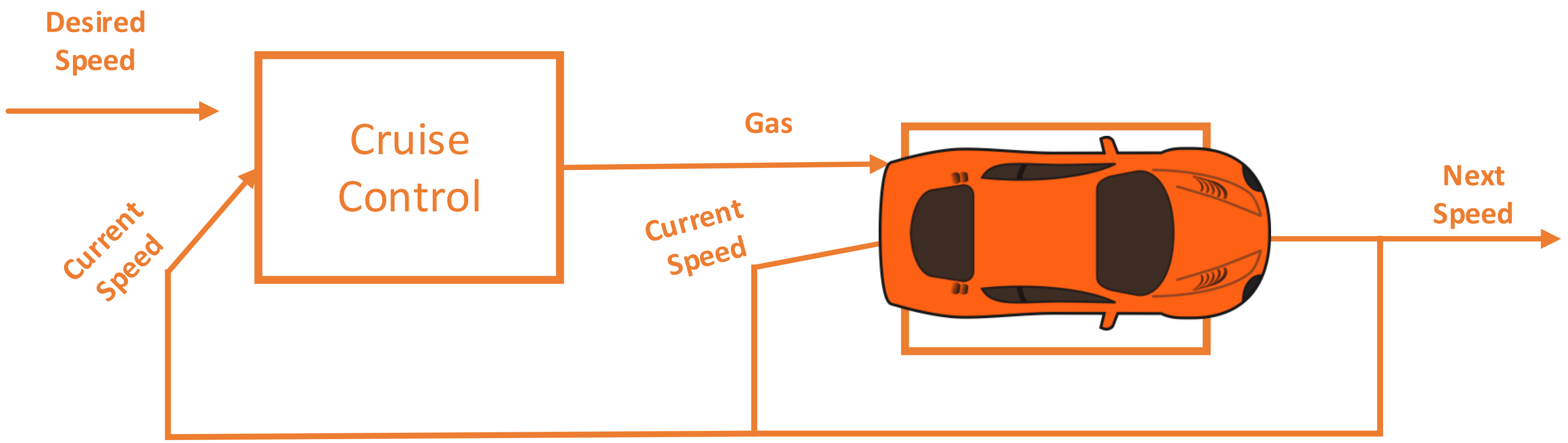
Main question: what is the next state given the current state and controls?

Main topics to be covered

Feedback Control:
which commands will cause the desired robot motion?

Planning:
path planning in known maps





Main question: what are the controls that will take the system from state A to B?

Not covered in CSC477, but related: learning for control

Not covered in CSC477, but related: learning for control

Learning Legged Swimming Gaits from Experience

ICRA 2015 - Best Paper Award Nominee
http://www.cim.mcgill.ca/~dmeger/ICRA2015_GaitLearning/

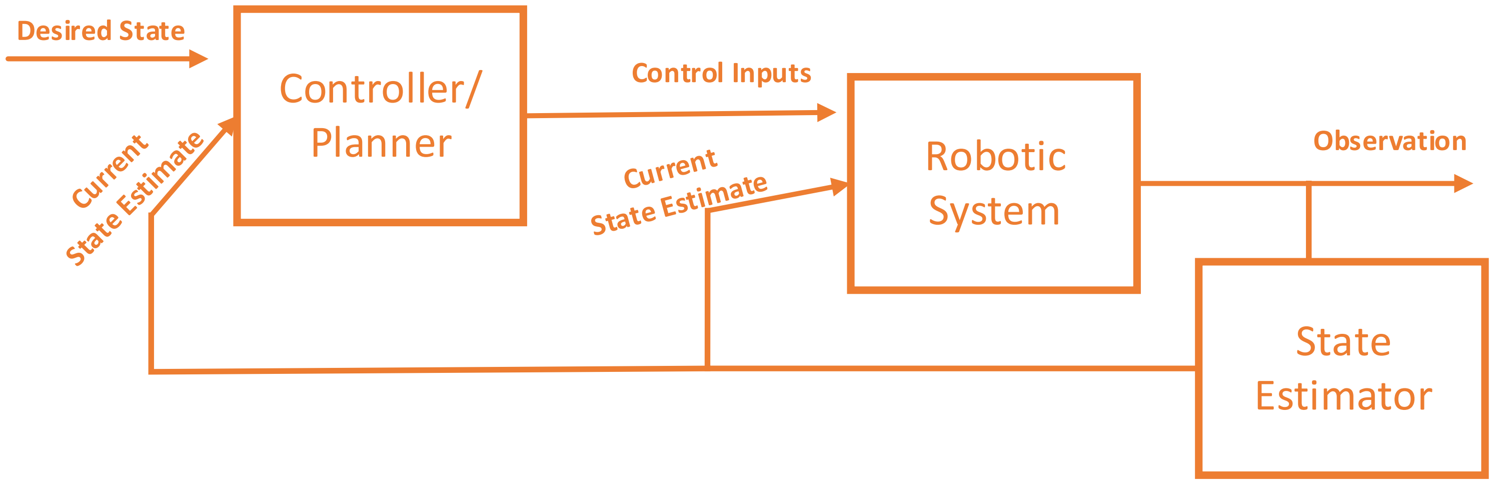
David Meger, Juan Camilo Gamboa Higuera,
Anqi Xu, Philippe Giguere and Gregory Dudek

McGill

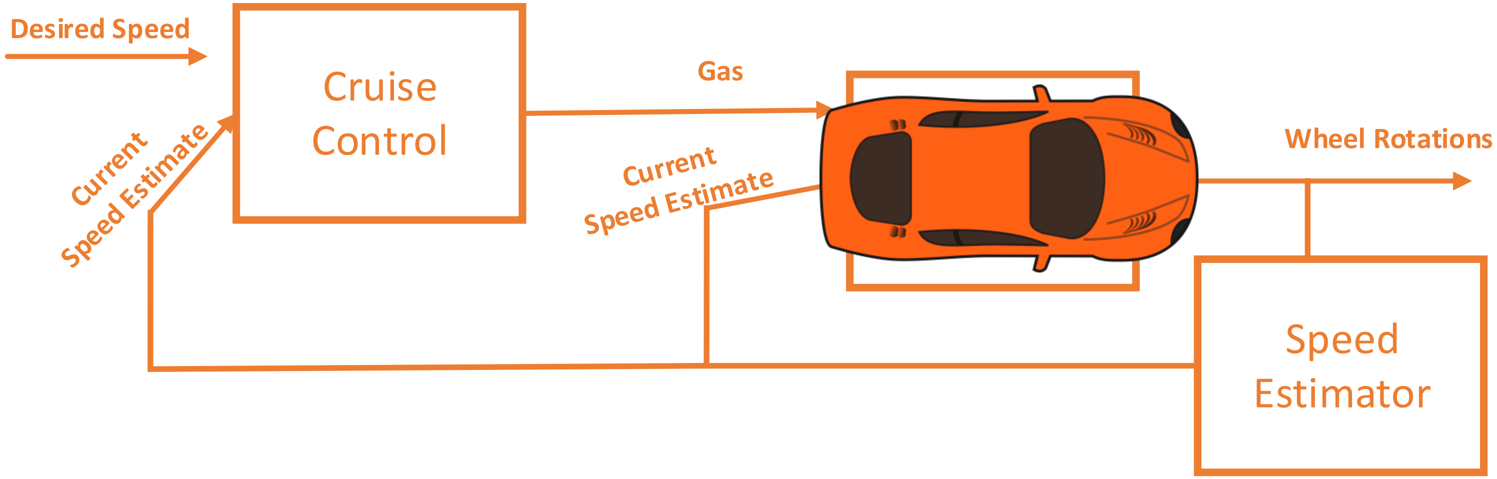
McGill University and Universite Laval

UNIVERSITÉ LAVAL

Main topics to be covered



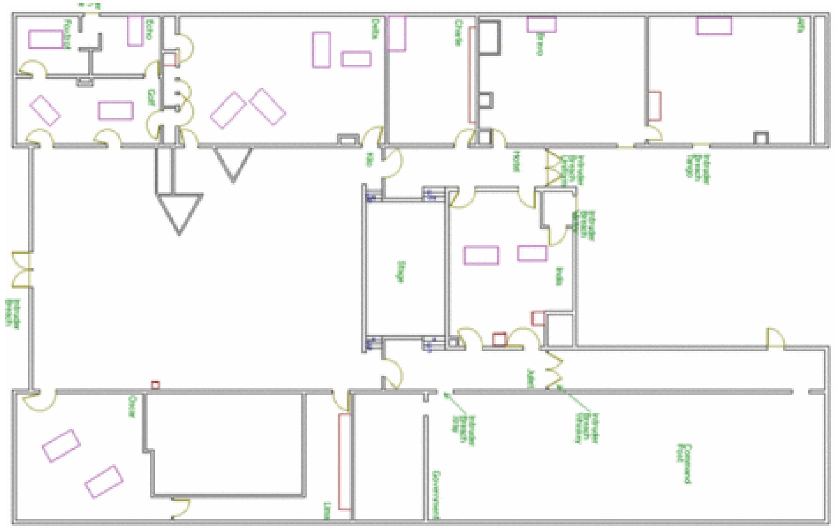
State Estimation:
designing estimators that incorporate
sensor measurements



Main topics to be covered

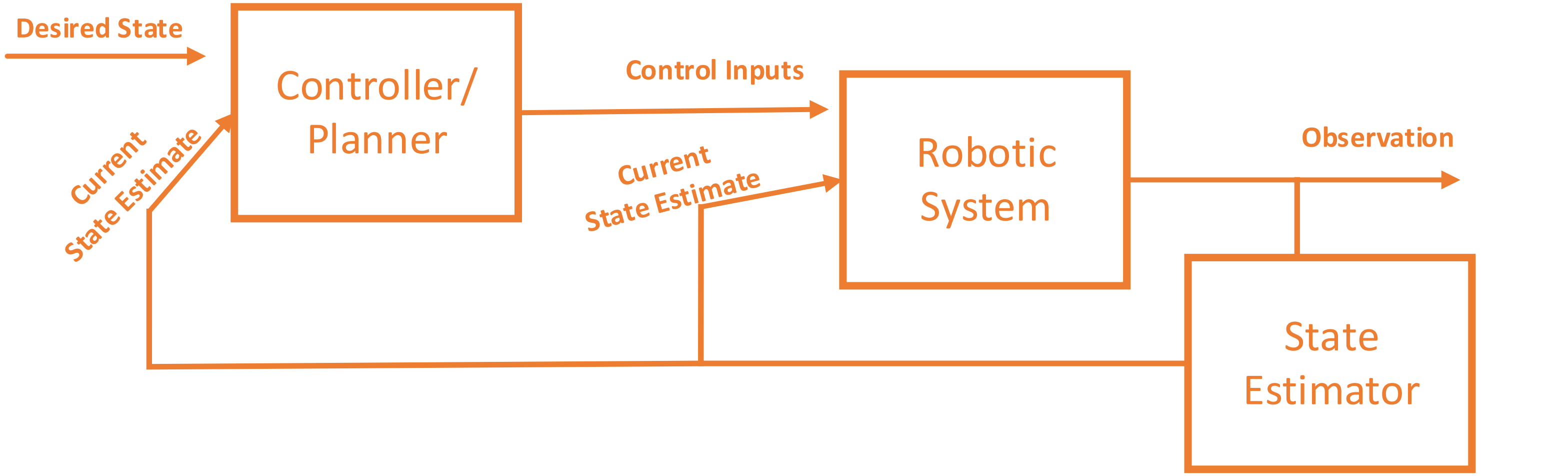
- Known: robot's position and orientation
- Want to estimate: a map of the environment from laser measurements

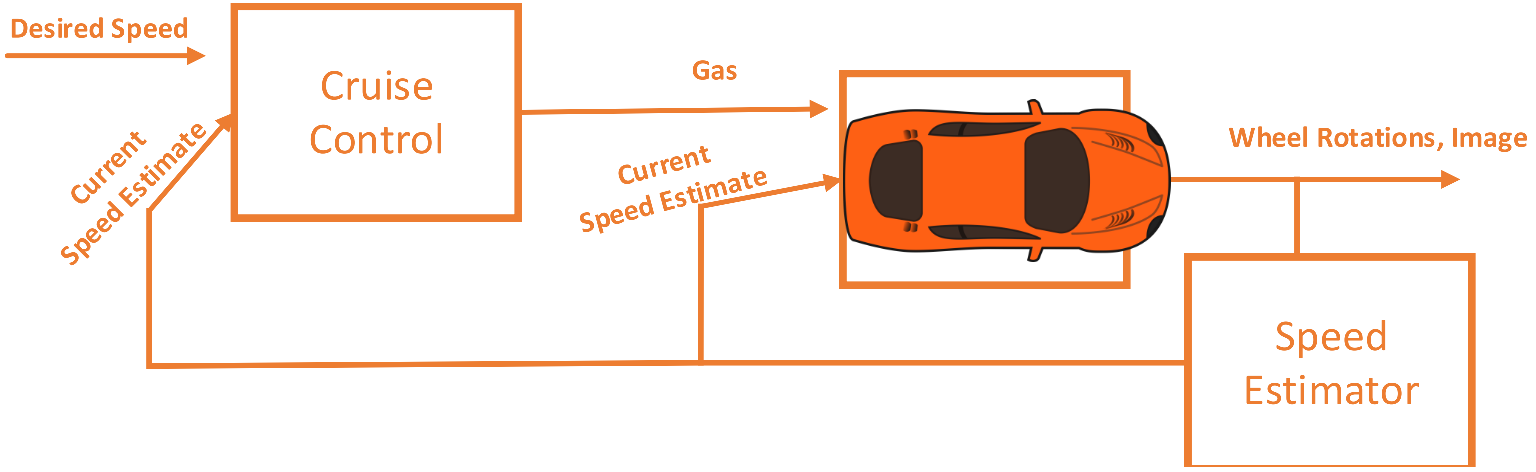
State Estimation:
designing estimators that incorporate
sensor measurements



- Occupancy grid mapping

Main topics to be covered





Computer Vision:
estimating 3D structure + motion

ORB-SLAM

Raúl Mur-Artal, J. M. M. Montiel and Juan D. Tardós

{raulmur, josemari, tardos} @unizar.es

Instituto Universitario de Investigación
en Ingeniería de Aragón
Universidad Zaragoza

Universidad
Zaragoza
1542

Lecture Topics

Kinematics & Dynamics:
physical models of
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
desired robot motion?

Planning:
path planning in known maps

State Estimation:
designing estimators that incorporate
sensor measurements

Computer Vision:
estimating 3D structure + motion

Tutorials

Intro to the Robot Operating System (ROS)

Refresher on linear algebra and least squares

Refresher on basic probability and continuous distributions

How to align 3D pointclouds. Demo of the PCL library

How to implement a Kalman Filter

How to implement a Particle Filter

How to approximate functions

Assignments

Kinematics & Dynamics:
physical models of
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
desired robot motion?

Planning:
path planning in known maps

State Estimation:
designing estimators that incorporate
sensor measurements

Computer Vision:
estimating 3D structure + motion

A1: Designing a feedback controller for wall-following

Assignments

Kinematics & Dynamics:
physical models of
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
desired robot motion?

Planning:
path planning in known maps

State Estimation:
designing estimators that incorporate
sensor measurements

Computer Vision:
estimating 3D structure + motion

A1: Designing a feedback controller for wall-following

A2: Implementing path-planning and feedback control algorithms

Assignments

Kinematics & Dynamics:
physical models of
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
desired robot motion?

A1: Designing a feedback controller for wall-following

Planning:
path planning in known maps

A2: Implementing two path-planning algorithms

State Estimation:
designing estimators that incorporate
sensor measurements

Computer Vision:
estimating 3D structure + motion

A3: Occupancy grid mapping with known robot location

A4: Localization in a known map using particle filters

UTM Robotics Club

- Think about how to get this student club started, and what support you would need

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Sensors and Actuators

- Sensors:
  - Characteristics and types
  - Measurement noise
  - Required bandwidth
- Actuators:
  - Types of motors
  - Pulse-Width Modulation

Sensors

- Devices that can sense and measure physical properties of the environment.

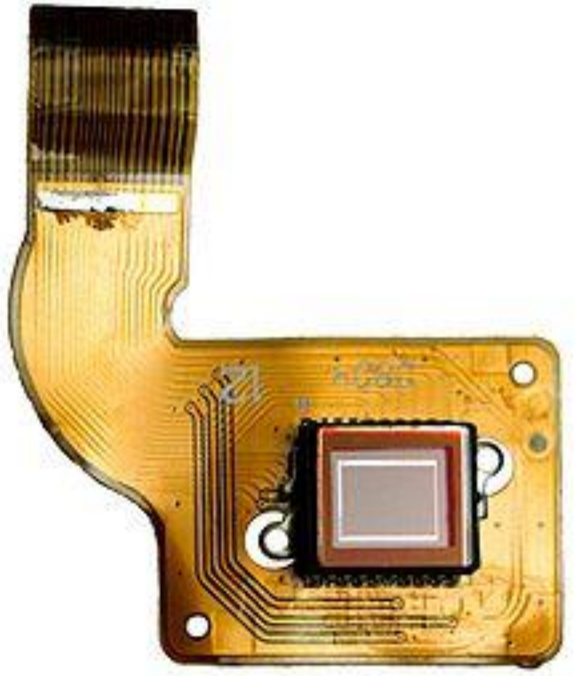
- Key phenomenon is **transduction** (conversion of energy from one form to another). E.g.:
  - Imaging sensors: light to pixel voltages
  - Depth sensors: mechanical pressure to voltage

- Measurements are **noisy**, and difficult to interpret

Sensors: general characteristics

- Sensitivity: (change of output) ÷ (change of input)
- Linearity: constancy of (output ÷ input)
- Measurement range: [min, max] or {min, max}
- Response time: time required for input change to cause output change
- Accuracy: difference between measurement and actual
- Repeatability/Drift: difference between repeated measures
- Resolution: smallest observable increment
- Bandwidth: required rate of data transfer
- SNR: signal-to-noise ratio

Sensors: vision



CCD image sensor

CCD (charge-coupled device) imaging sensors:

- Capacitor array accumulates electric charge proportional to light intensity.
- Each capacitor's charge is transferred to its neighbor.
- Last capacitor's charge gets amplified and output as voltage.
- (+) High-quality, low-noise images
- (-) Higher power consumption
- (-) Slow readout
- (-) Specialized fabrication

voltage → analog-to-digital converter → pixel value in {0, 255}

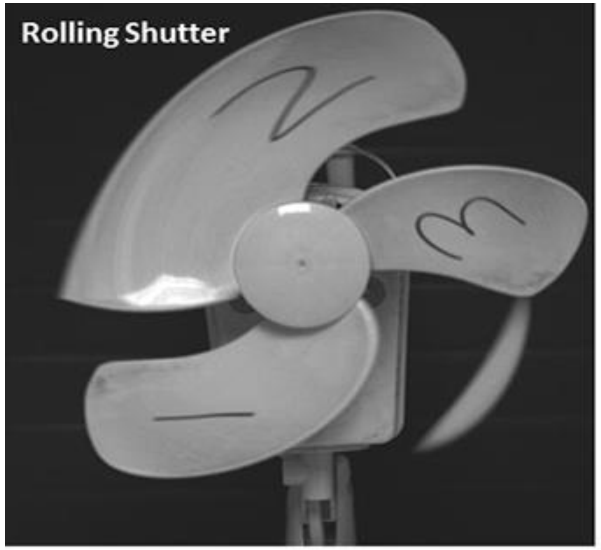
CMOS (complementary metal-oxide semi-conductor) imaging sensors:

- One amplifier per pixel
- (+) Low power
- (+) Fast readout
- (+) Easier to fabricate
- (-) Poor low-light sensitivity
- (-) Higher noise

Global vs. Rolling Shutter

Shutter = mechanism that allows light to hit the imaging sensor

Shutter “speed” = Exposure time = time duration in which the sensor is exposed to light



Rolling shutter

Reading RGB images from a camera

Each pixel contains an intensity value from 0…255

600 x 1000 pixels

600 x 1000 pixels

600 x 1000 pixels

Reading RGB images from a camera

A matrix of

600 x 1000 x 3 =

~ 1.8 million numbers

Each pixel contains an intensity value from 0…255

08	02	22	97	38	15	00	40	00	75	04	05	07	78	52	12	50	77	91	08
49	49	99	40	17	81	18	57	60	87	17	40	98	43	69	48	04	56	62	00
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600 x 1000 pixels

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01	70	54	71	83	51	54	69	16	92	33	48	61	43	52	01	89	19	67	48

600 x 1000 pixels

Computer/robot vision

08	02	22	97	38	15	00	40	00	75	04	05	07	78	52	12	50	77	91	08
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52	70	95	23	04	60	11	42	69	24	68	56	01	32	56	71	37	02	36	91
22	31	16	71	51	67	63	89	41	92	36	54	22	40	40	28	66	33	13	80
24	47	32	60	99	03	45	02	44	75	33	53	78	36	84	20	35	17	12	50
32	98	81	28	64	23	67	10	26	38	40	67	59	54	70	66	18	38	64	70
67	26	20	68	02	62	12	20	95	63	94	39	63	08	40	91	66	49	94	21
24	55	58	05	66	73	99	26	97	17	78	78	96	83	14	88	34	89	63	72
21	36	23	09	75	00	76	44	20	45	35	14	00	61	33	97	34	31	33	95
78	17	53	28	22	75	31	67	15	94	03	80	04	62	16	14	09	53	56	92
16	39	05	42	96	35	31	47	55	58	88	24	00	17	54	24	36	29	85	57
86	56	00	48	35	71	89	07	05	44	44	37	44	60	21	58	51	54	17	58
19	80	81	68	05	94	47	69	28	73	92	13	86	52	17	77	04	89	55	40
04	52	08	83	97	35	99	16	07	97	57	32	16	26	26	79	33	27	98	66
88	36	68	87	57	62	20	72	03	46	33	67	46	55	12	32	63	93	53	69
04	42	16	73	38	25	39	11	24	94	72	18	08	46	29	32	40	62	76	36
20	69	36	41	72	30	23	88	34	62	99	69	82	67	59	85	74	04	36	16
20	73	35	29	78	31	90	01	74	31	49	71	48	86	81	16	23	57	05	54
01	70	54	71	83	51	54	69	16	92	33	48	61	43	52	01	89	19	67	48

Structured numbers

?

1. I’m seeing a parrot
2. I’m seeing a toy bicycle
3. The parrot is riding the bicycle
4. The bicycle is on top of a desk
5. Is this physically plausible?
6. Where is the parrot in 3D w.r.t. the camera?
7. Where will the parrot go next?
8. What is the speed of the parrot?

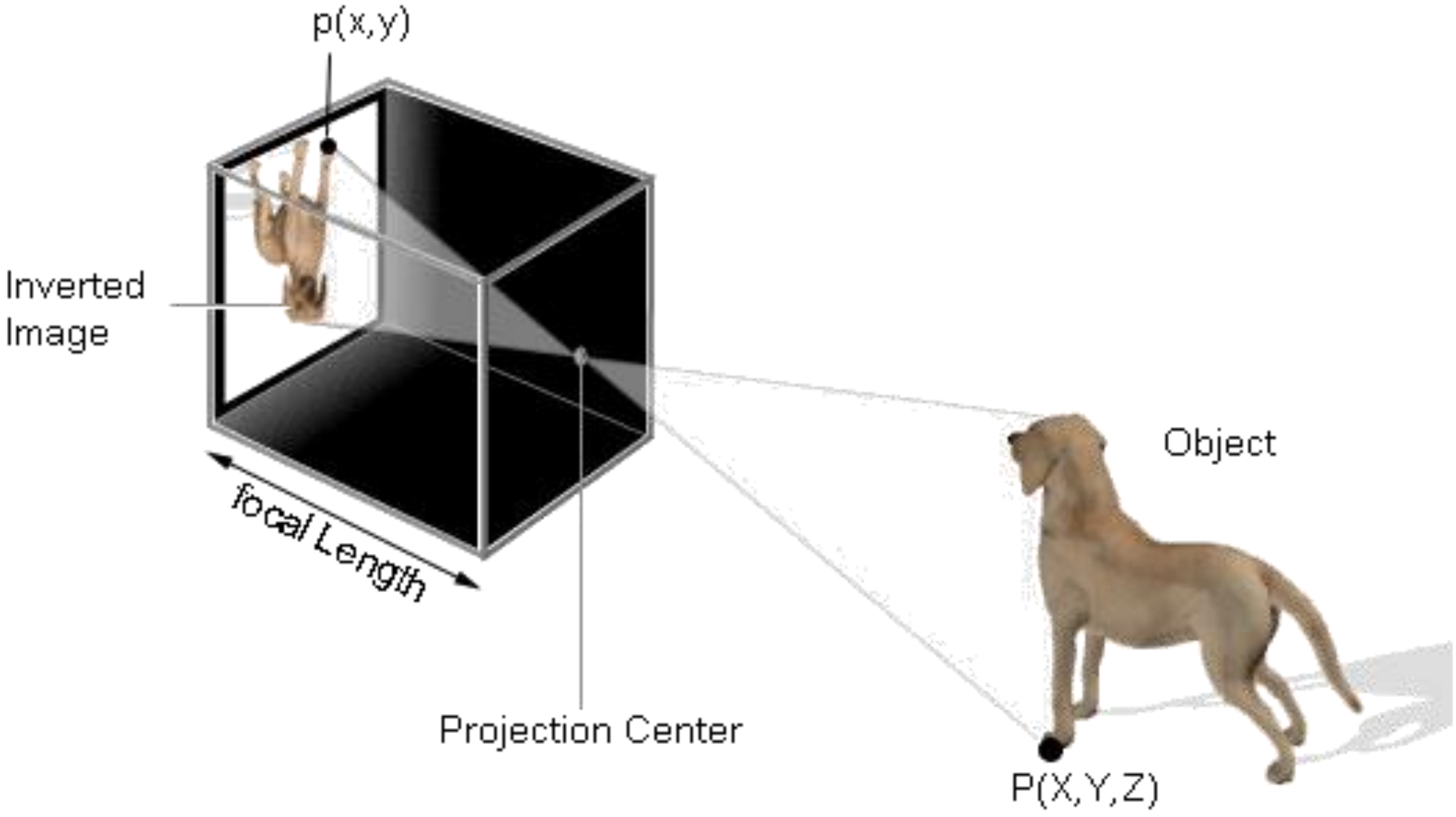
Conclusions/Inference/Deduction/Estimation

Camera lenses

- Lens determines:
  - image distortion
  - focus
  - sharpness or blur

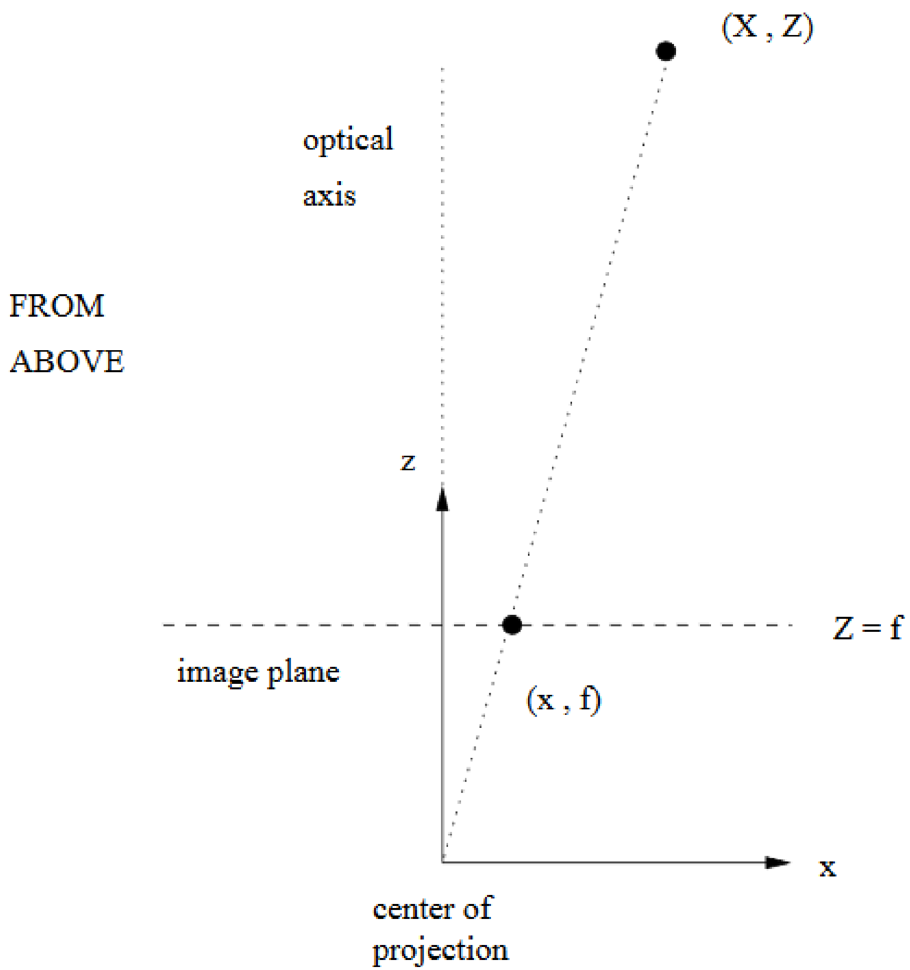
- Lens characteristics:
  - focal length
  - aperture
  - depth-of-field

Pinhole Camera Model



We know **approximately** how a 3D point (X,Y,Z) projects to pixel (x,y)
We call this the ***pinhole projection model***

(1) Perspective projection
$[x,y] = \pi(X,Y,Z)$



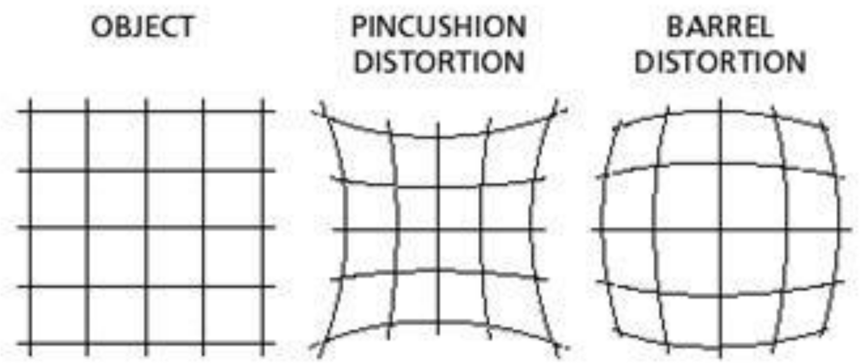
By similar triangles: $x/f = X/Z$

So, $x = f * X/Z$ and similarly $y = f * Y/Z$

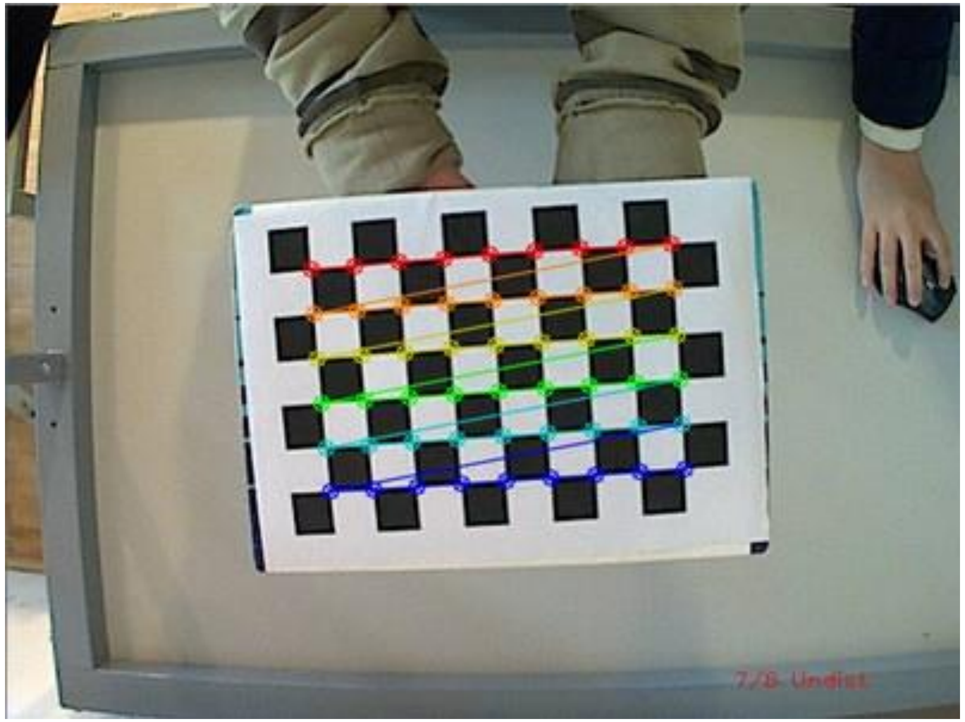
Problem: we just lost depth (Z) information by doing this projection, i.e. depth is now uncertain.

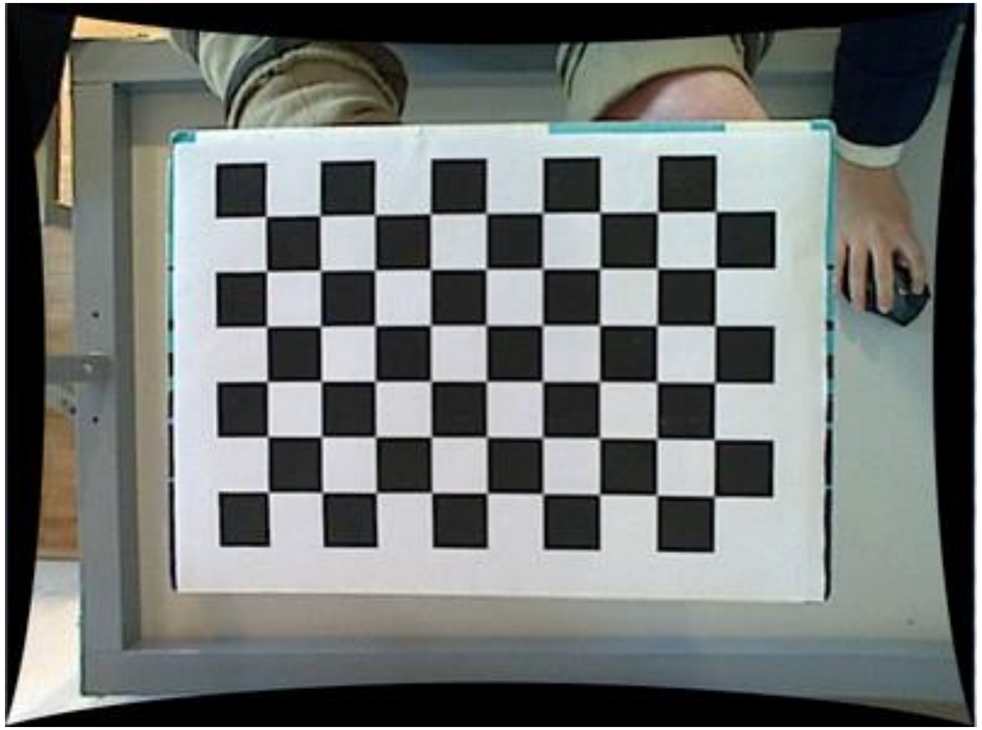
http://www.cim.mcgill.ca/%7Elanger/558.html

(2) Lens distortion

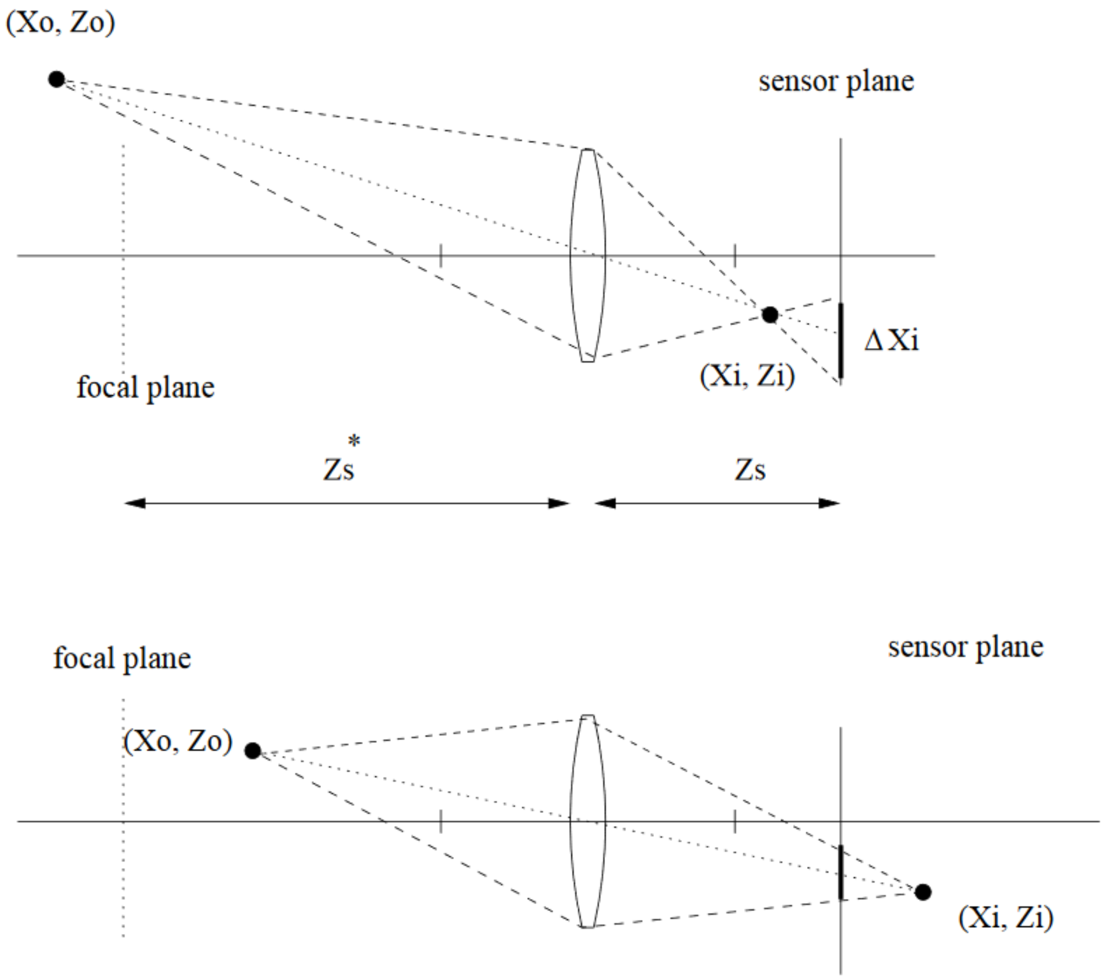


(2) Estimating parameters of lens distortion





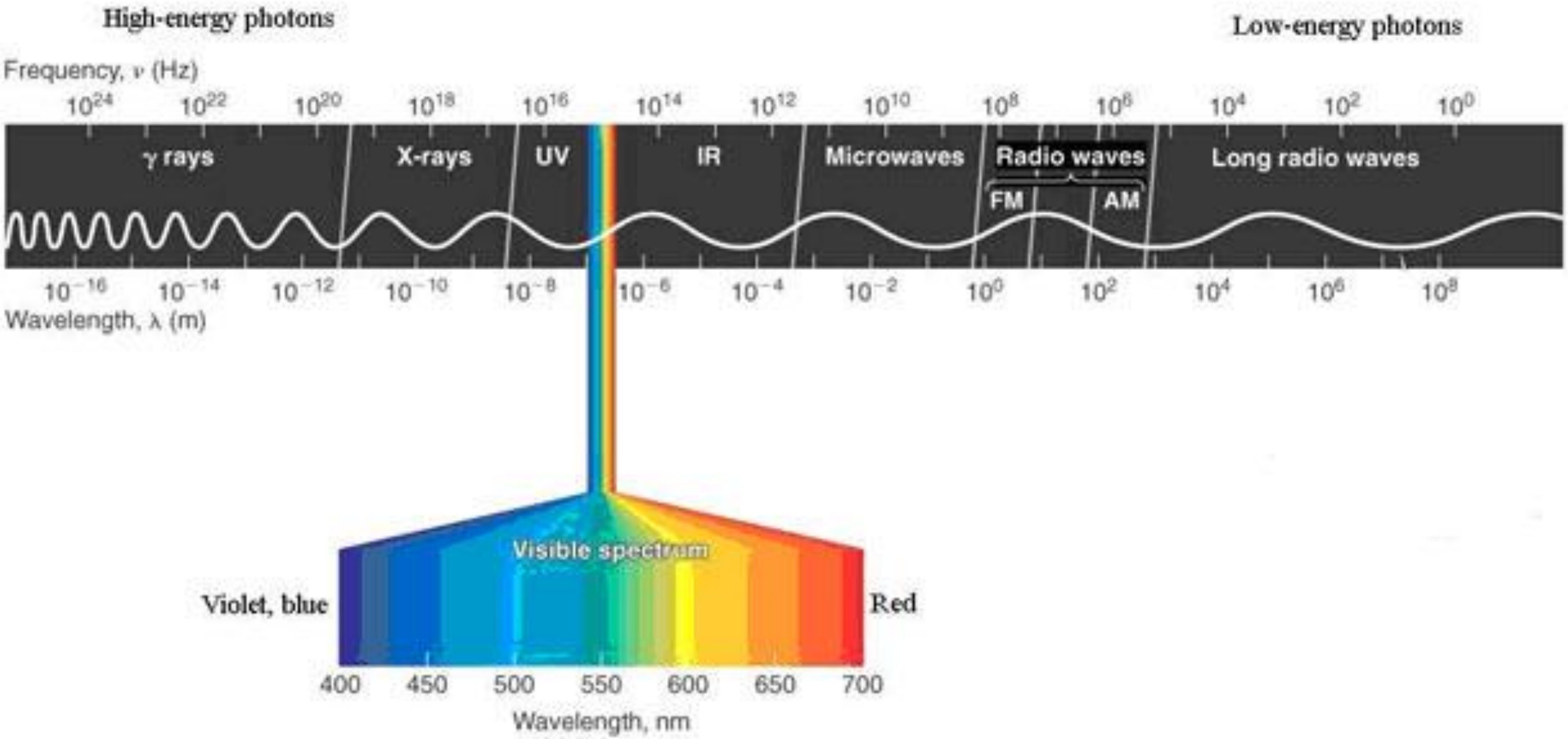
Non-pinhole cameras: thin lens model



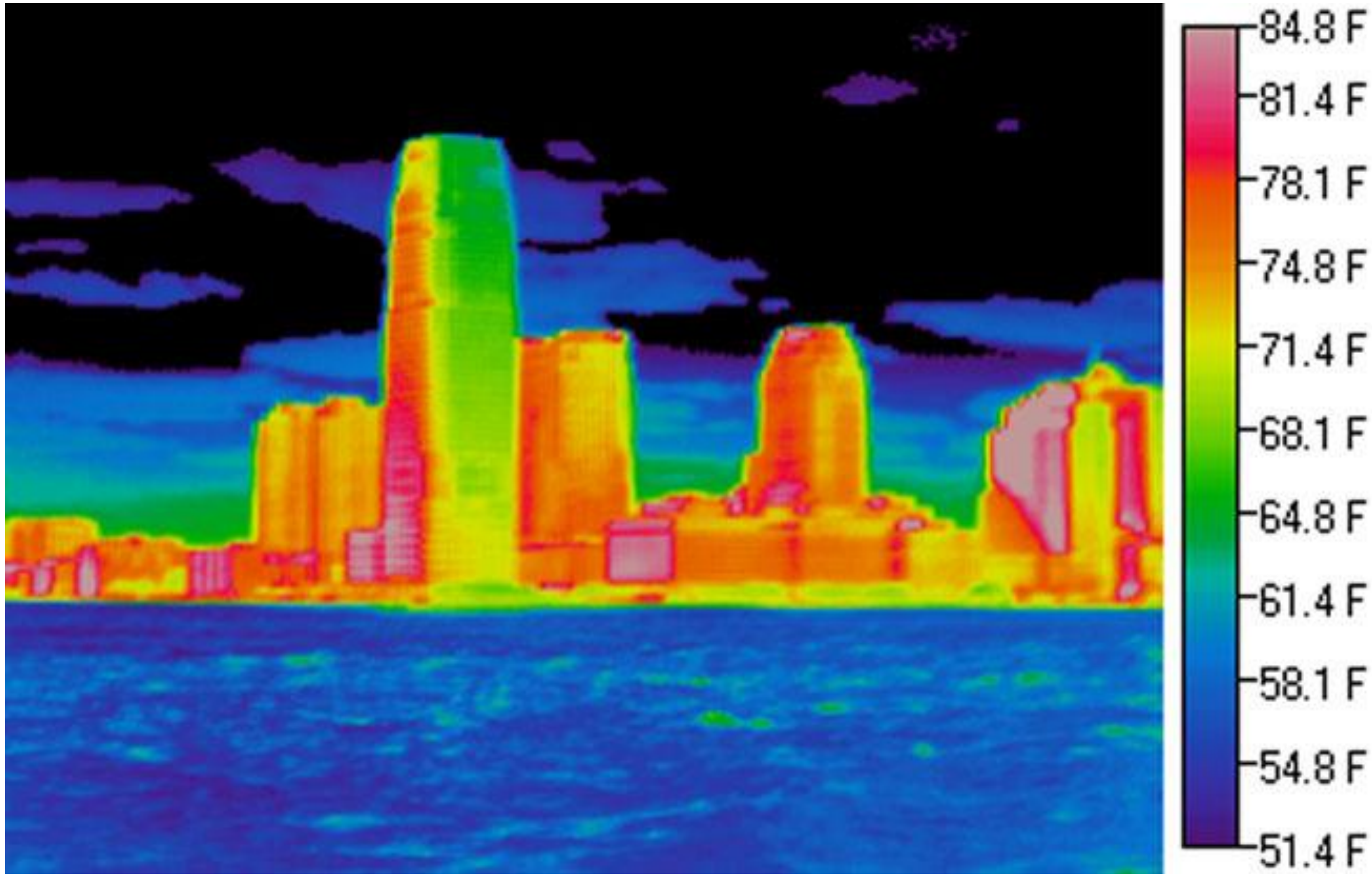
Unlike the pinhole camera, this is able to model blur.

http://www.cim.mcgill.ca/%7Elanger/558.html

Beyond the visible spectrum: infrared cameras



Beyond the visible spectrum: infrared cameras



Drawback:
Doesn’t work underwater

Beyond the visible spectrum: infrared cameras

Beyond the visible spectrum: RGBD cameras

Main ideas:

- Active sensing
- Projector emits infrared light in the scene
- Infrared sensor reads the infrared light
- Deformation of the expected pattern allows computation of the depth

Beyond the visible spectrum: RGBD cameras

Drawbacks:

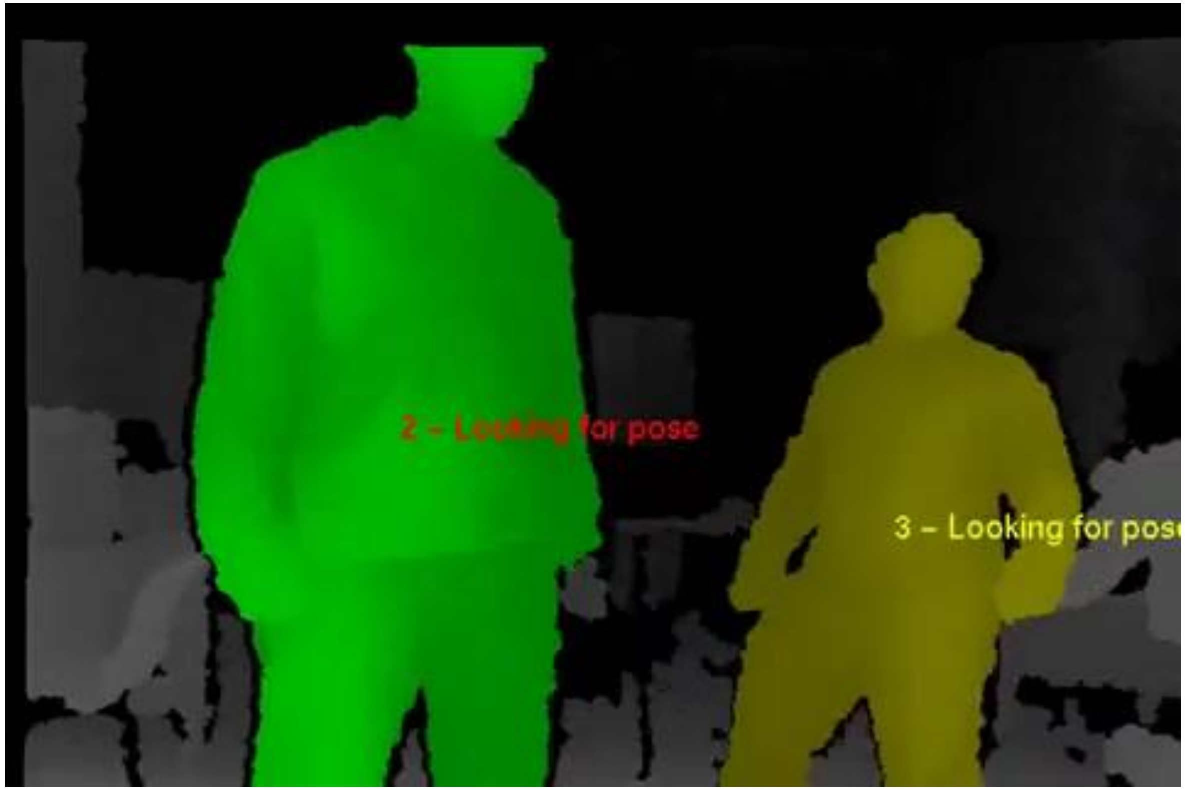
- Does not work well outdoors, sunlight saturates its measurements
- Maximum range is [0.5, 8] meters

Advantages:

- Real-time depth estimation at 30Hz
- Cheap

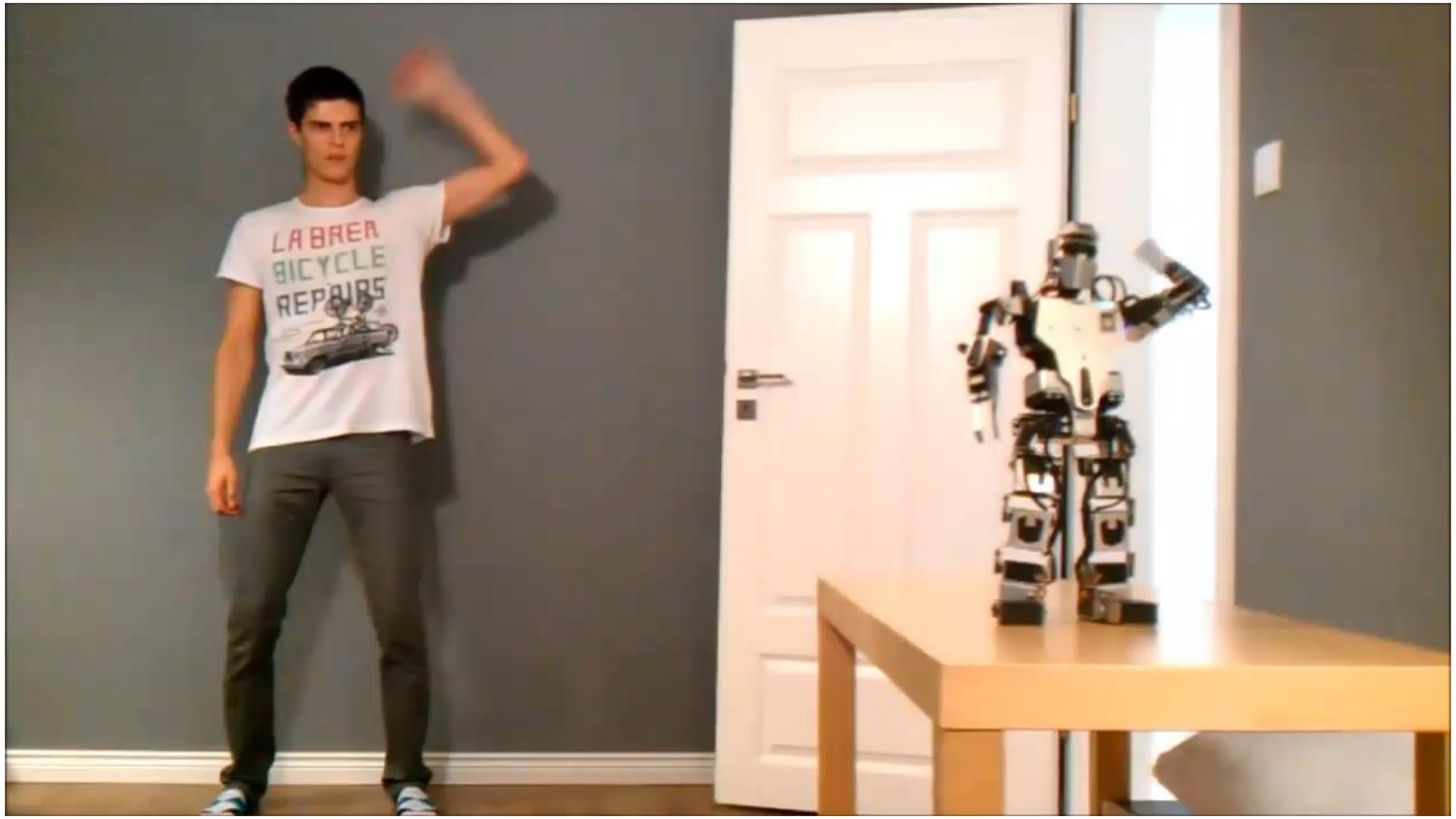
Beyond the visible spectrum: RGBD cameras

Enabled a wave of research, applications, and video games, based on real-time skeleton tracking



Beyond the visible spectrum: RGBD cameras

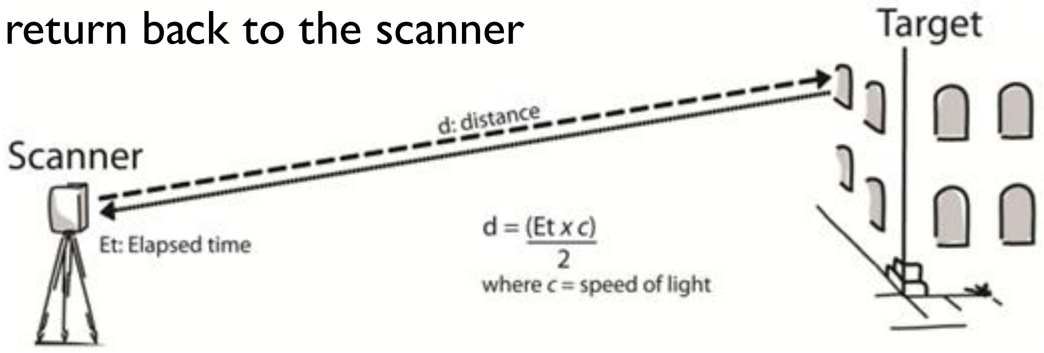
Despite their drawbacks RGBD sensors have been extensively used in robotics.



3D LIDAR (Light detection and ranging)

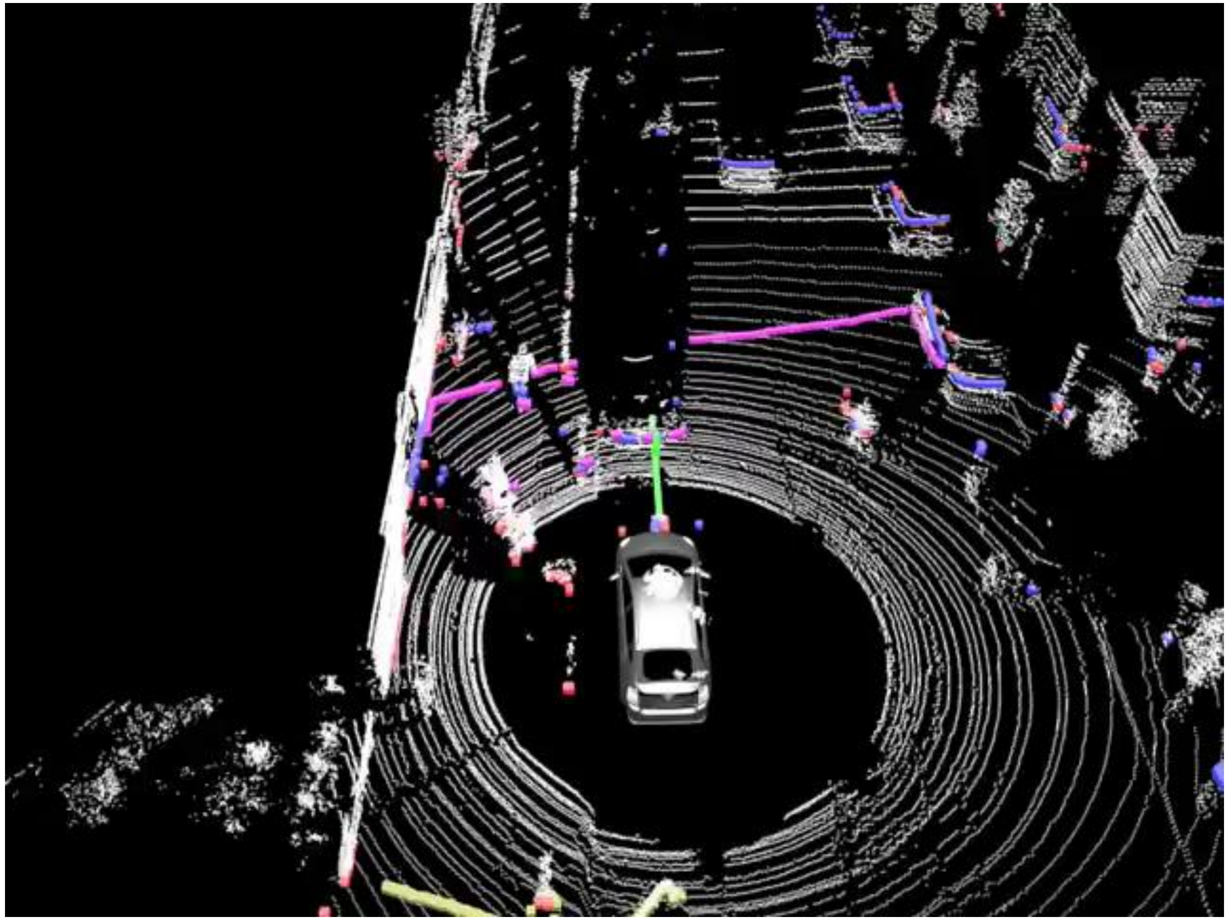
Produces a pointcloud of 3D points and intensities
- (x,y,z) in the laser's frame of reference
- Intensity is related to the material of the object that reflects the light

Works based on time-of-flight for each beam to return back to the scanner



Not very robust to adverse weather conditions: rain, snow, smoke, fog etc.

Used in most self-driving cars today for obstacle detection. Range < 100m.

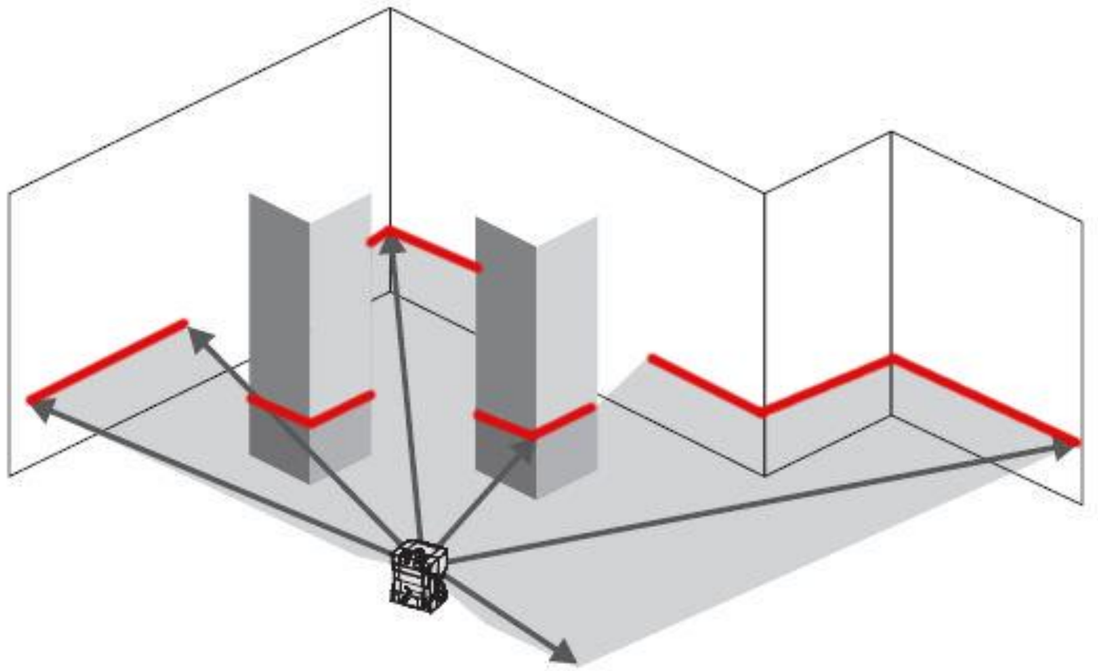


Usually around 1million points in a single pointcloud

2D LIDAR (Light detection and ranging)

Produces a scan of 2D points and intensities
- (x,y) in the laser's frame of reference
- Intensity is related to the material of the object that reflects the light

Certain surfaces are problematic for LIDAR: e.g. glass



2D LIDAR (Light detection and ranging)

Produces a scan of 2D points and intensities

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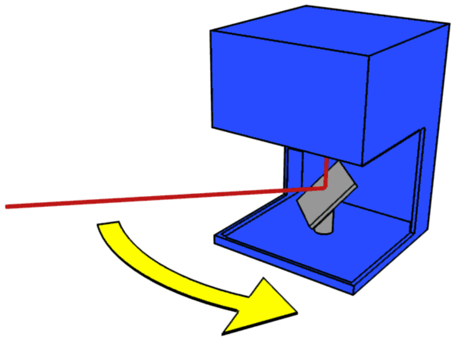
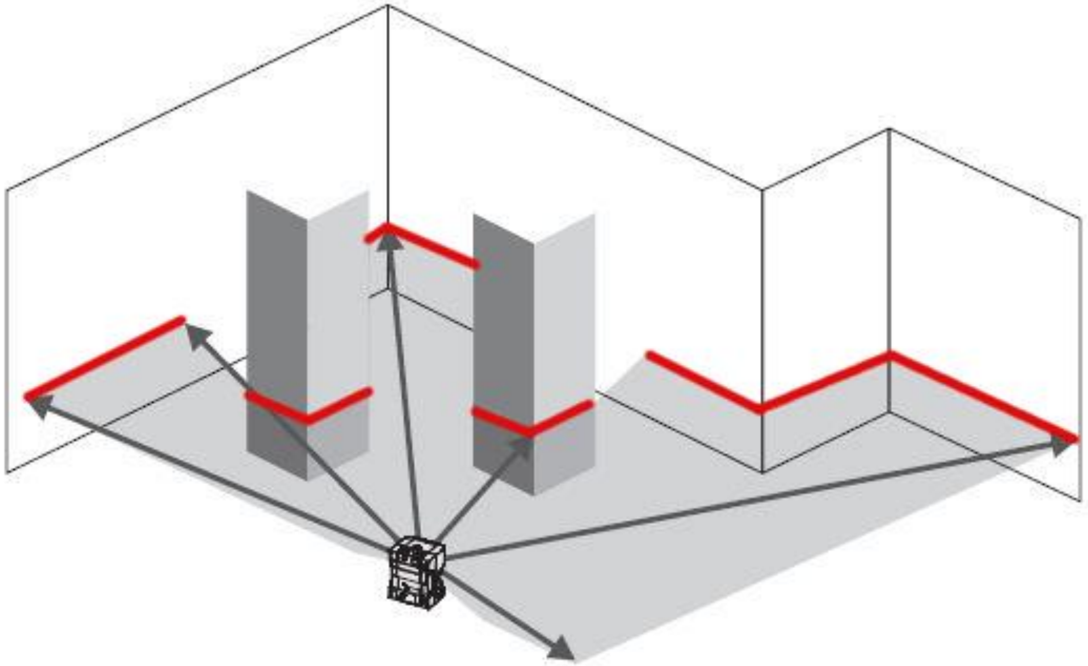


Lots of moving parts: motors quickly rotate the laser beam and once complete (angle bound reached) a scan is returned. I.e. points are not strictly speaking time-synchronized, even though we usually treat them as such.



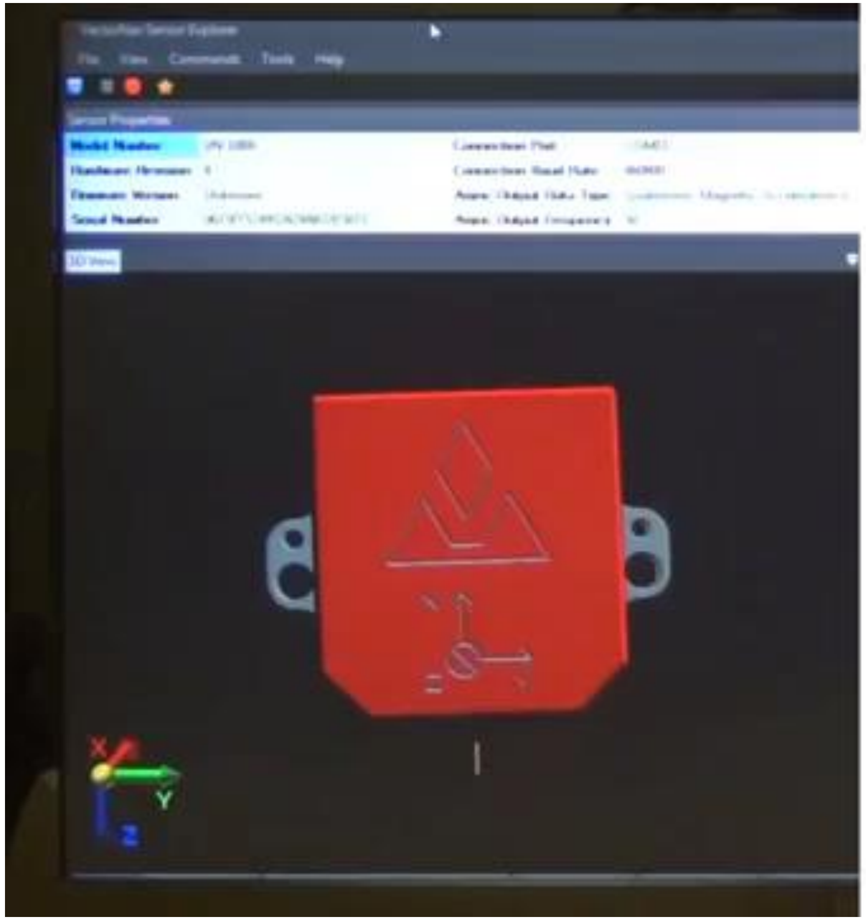
Usually around 1024 points in a single scan.

Inertial Sensors

- Gyroscopes, Accelerometers, Magnetometers
- Inertial Measurement Unit (IMU)

- Perhaps the most important sensor for 3D navigation, along with the GPS

- Without IMUs, plane autopilots would be much harder, if not impossible, to build


File View Commands Tools Help
X
Y
Z

Gyroscopes

- Measure angular velocity in the body frame
- Often affected by noise and bias

$$\omega_{\text{measured}}(t) = \omega_{\text{true}}(t) + b_g(t) + n_g(t)$$

- We integrate it to get 3D orientation (Euler angles, quaternions rotation matrices), but there is drift due to noise and bias

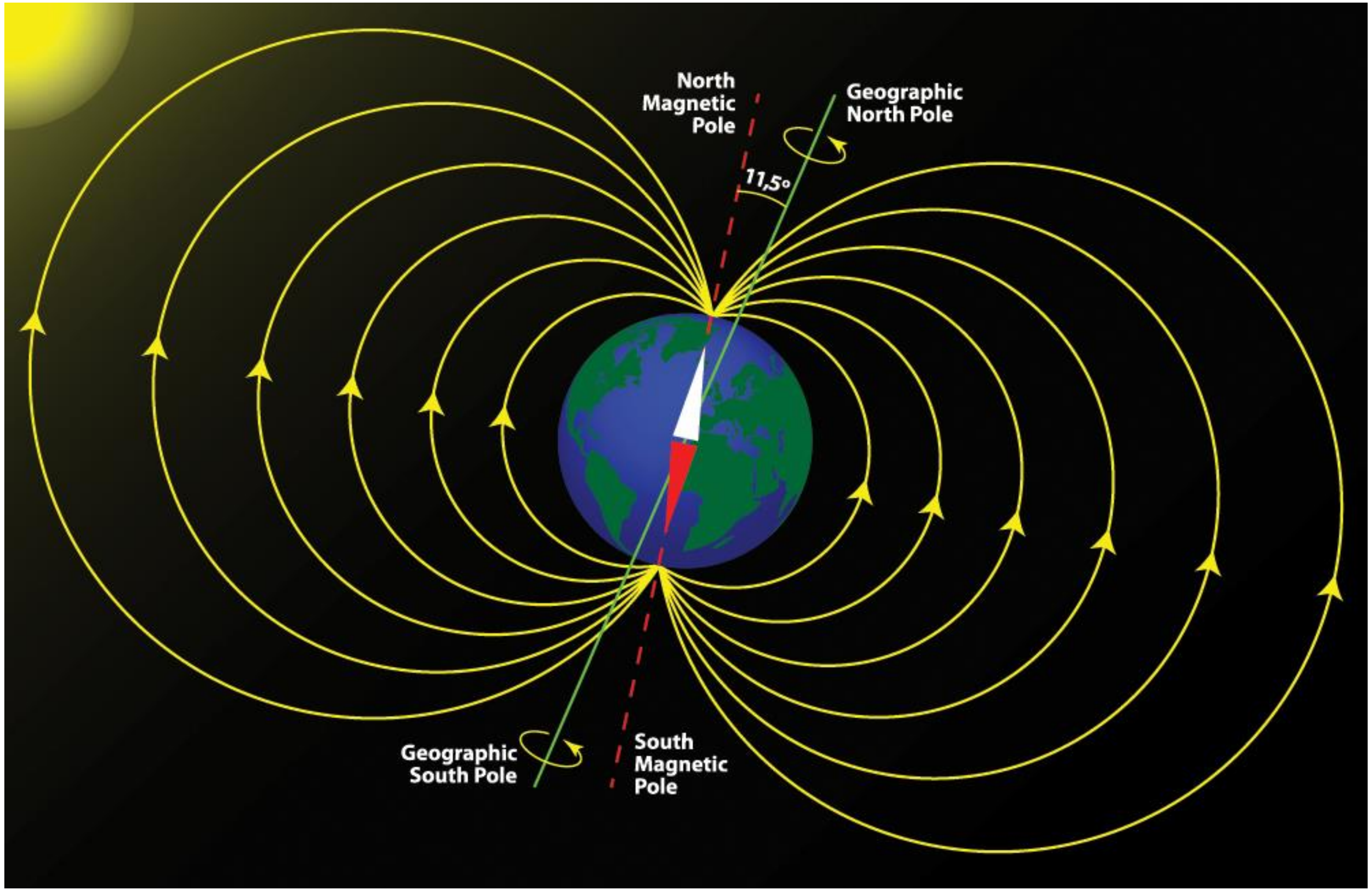
Accelerometers

- Measure linear acceleration relative to freefall (measured in g)
- A free-falling accelerometer in a vacuum would measure zero g
- An accelerometer resting on the surface of the earth would measure 1g
- Also affected by bias and noise.
- Double integration to get position is very noisy. Errors grow quadratically with time.

Magnetometers

Drawbacks:
- Needs careful calibration
- Needs to be placed away from moving metal parts, motors

Advantages:
- Can be used as a compass for absolute heading



Inertial Measurement Unit

- Combines measurements from accelerometer, gyroscope, and magnetometer to output an estimate of orientation with reduced drift.
- Does not typically provide a position estimate, due to double integration.
- Runs at 100-1000Hz
- Expect yaw drift of 5-10 deg/hour on most modern low-end IMUs

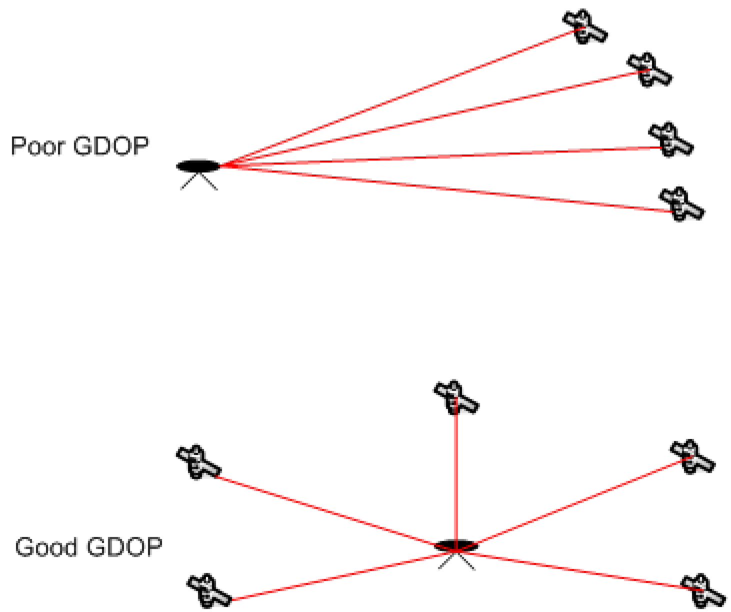
Global Positioning System: Satellites

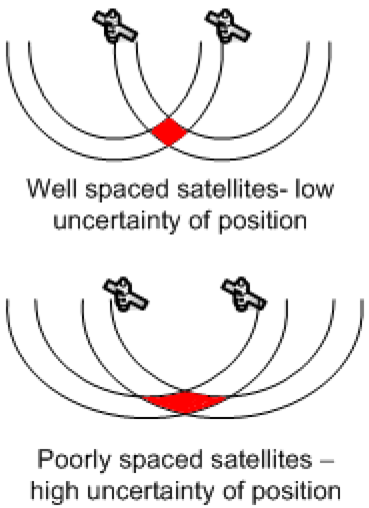
- Each GPS satellite periodically transmits:
  - [Coarse/Acquisition code] A 1023-bit pseudorandom binary sequence (PRN code), which repeats every 1 ms, unique for each satellite (no correlation with other satellites).
  - [Navigation frame] A 1500-bit packet that contains
    - GPS date, time, satellite health
    - Detailed orbital data for the satellite, accurate for the next ~4hrs
    - PRN codes and status of all satellites in the network
    - Takes 12.5mins to transmit
  - [Precision code] A 6.2-terabit code for military use.
- Carrier frequencies are 1575.42 MHz (L1) and 1227.60 MHz (L2)

Global Positioning System: Receivers

- Each (civilian) GPS receiver:
  - Knows the PRN codes for each satellite in advance
  - Correlates received PRN signal with database PRN signal → time shift → noisy distance to satellite
  - If 4 or more satellite PRN codes are received, it does **trilateration** to compute latitude and longitude

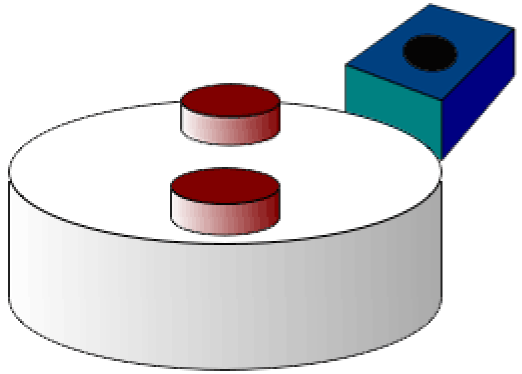
Global Positioning System: Receivers and Dilution of Precision





Geometry in 2-D (GPS Basics, 2000)

Hall Effect Sensor



- Varies its voltage in response to a magnetic field

- Used as a proximity switch, to measure a full rotation of a wheel for example

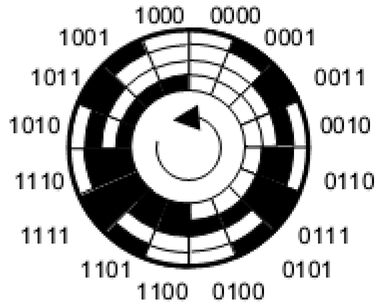
- Used to measure rate of rotation of wheels

Rotary Encoder

- Contains an analog to digital converter for encoding the angle of a shaft/motor/axle

- Usually outputs the discretized absolute angle of the shaft/

- Useful in order to know where different shafts are relative each other.



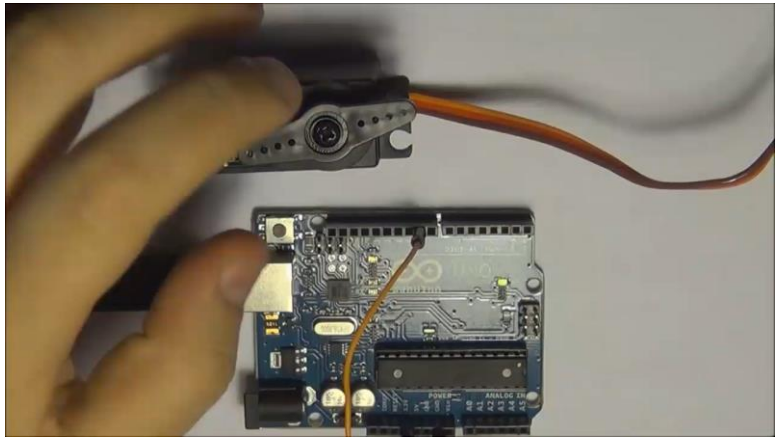
Gray code

Example: flippers on the Aqua robot

Actuators

DC (direct current) motor

They turn continuously at high RPM (revolutions per minute) when voltage is applied. Used in quadrotors and planes, model cars etc.

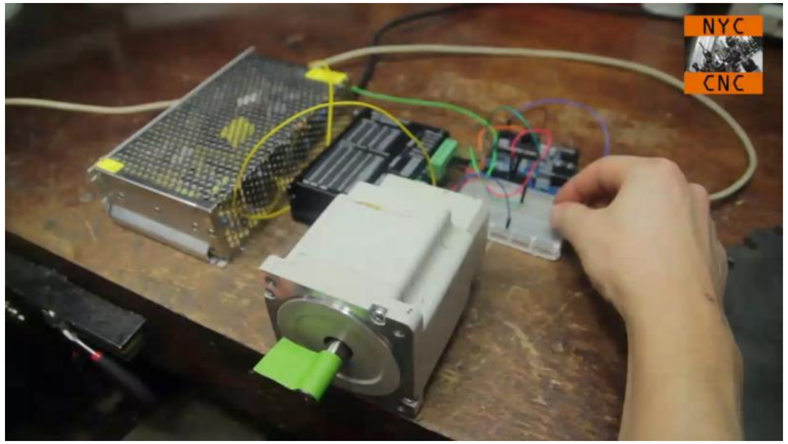


Servo motor

Usually includes: DC motor, gears, control circuit, position feedback

Precise control without free rotation (e.g. robot arms, boat rudders)

Limited turning range: 180 degrees



Stepper motor

Positioning feedback and no positioning errors.

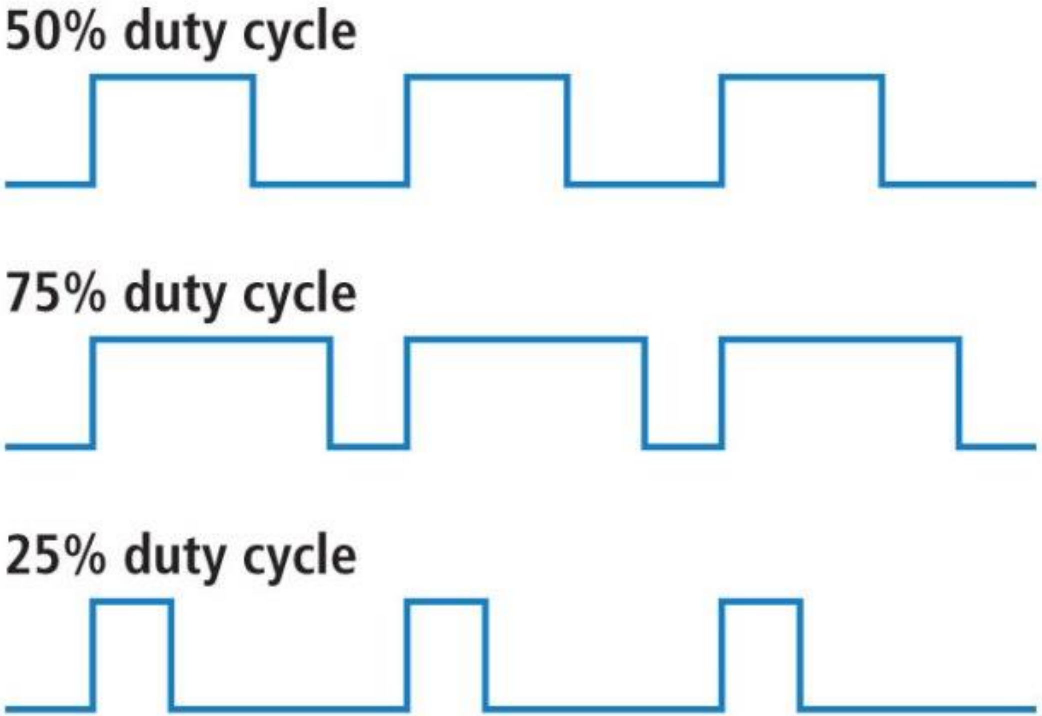
Rotates by a predefined step angle.

Requires external control circuit.

Precise control without free rotation.

Constant holding torque without powering the motor (good for robot arms or weight-carrying systems).

Pulse Width Modulation



Used for creating analog/continuous behavior when voltage applied is discrete.
Main idea: turn on and off the motor fast enough so average voltage is the desired target.
Used in dimming LEDs, controlling the speed of DC motors, controlling the position of servo motors.

Today’s agenda

- Introduction
- Administrivia
  - Office hours
  - Tutorials
  - Assignment descriptions
  - Prerequisites
- Topics covered by the course
- Sensors and Actuators
- Quiz about background and interests