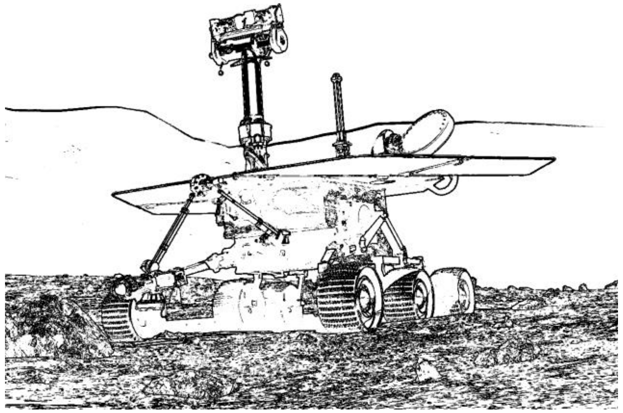


CSC477
Introduction to Mobile Robotics

Florian Shkurti

Week #1: Introduction, Sensors & Actuators

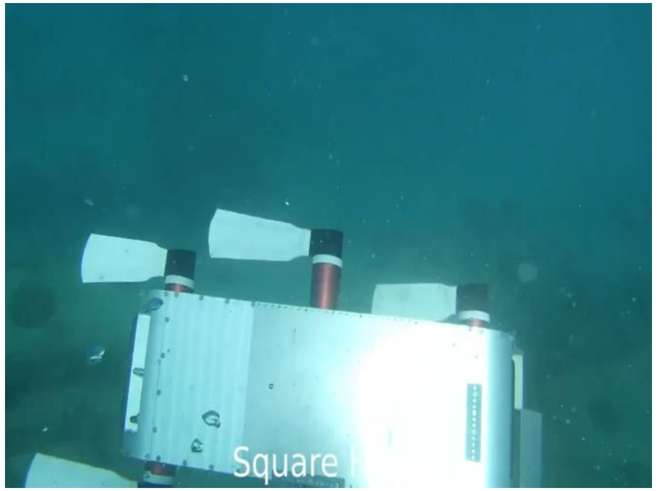
Today’s agenda

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

Your TA

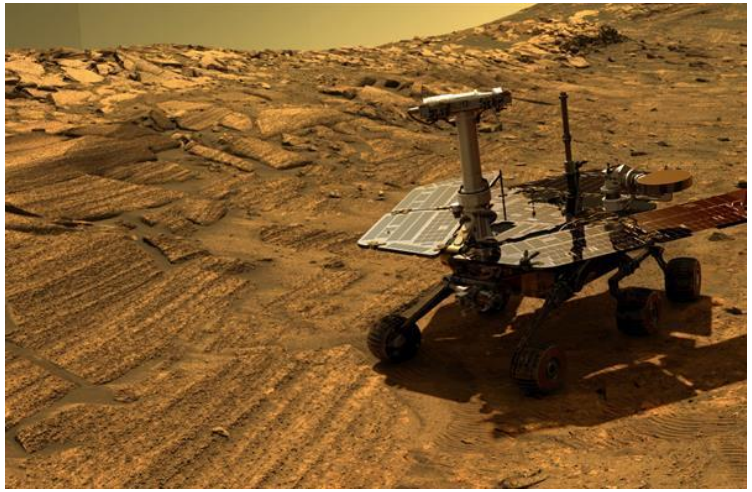
Homanga Bharadhwaj
homanga.bharadhwaj@mail.utoronto.ca
Graduate student
Computer Science, UofT

My lab: Robot Vision and Learning (RVL)



Mission: create algorithms that enable robots to learn to act intelligently in outdoor environments and alongside humans

How I became interested in robotics

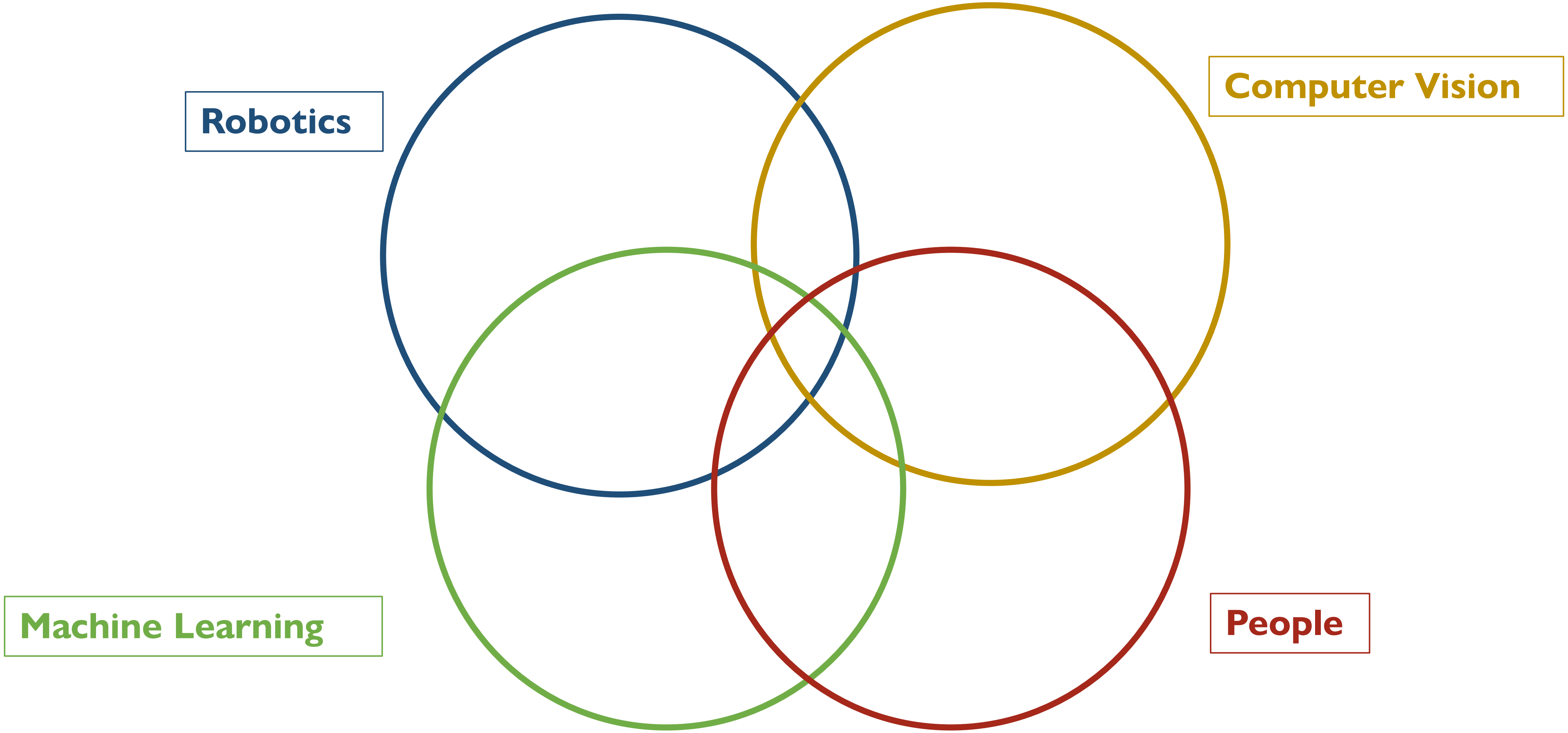


Mars Exploration Rover

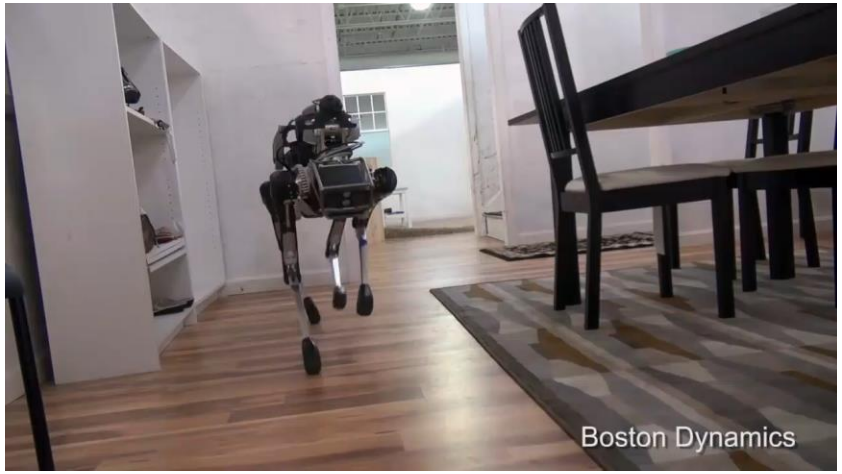
RoboCup, small-sized league

How I became interested in robotics

How I became interested in robotics

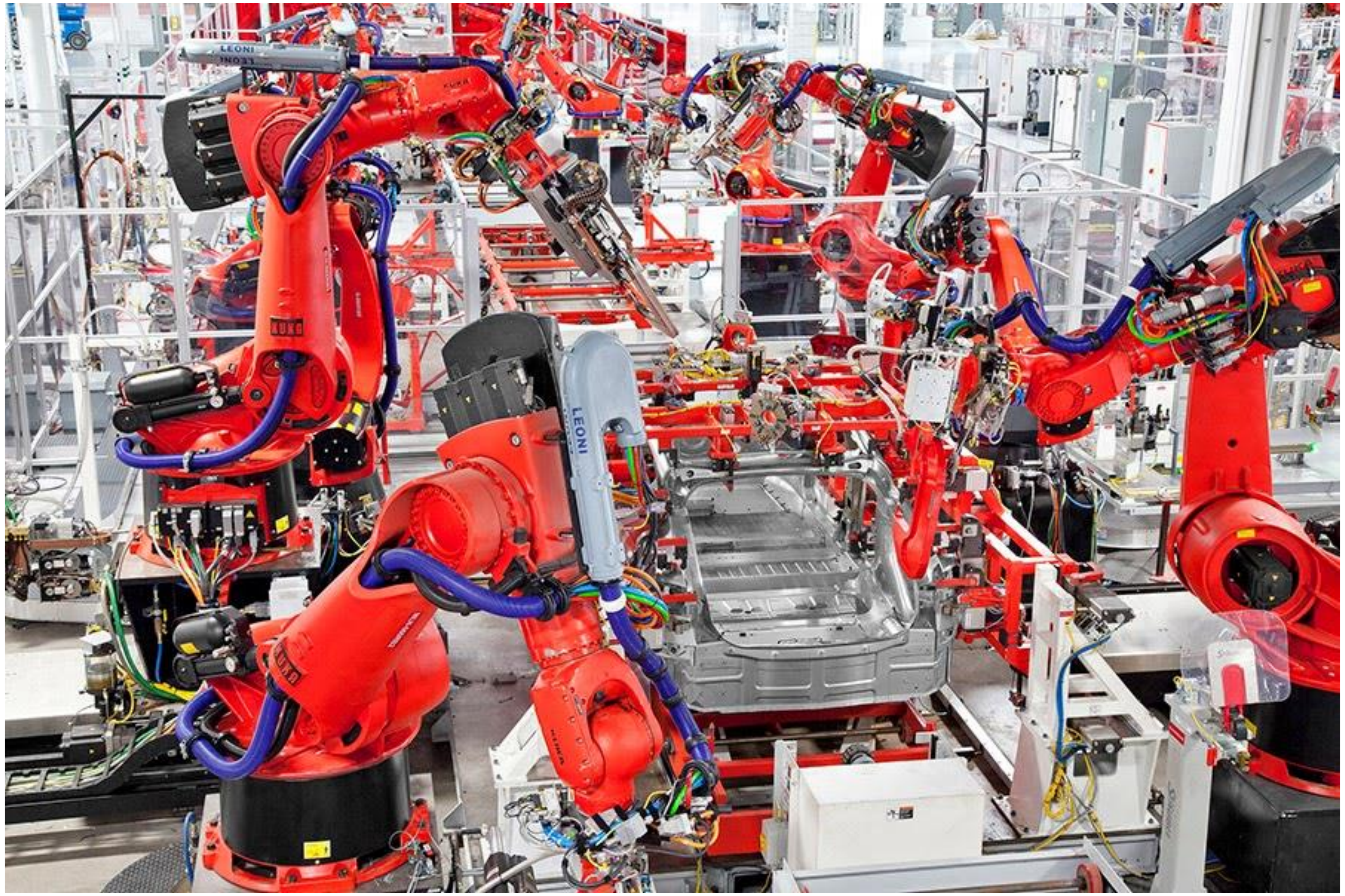


Today you have



Factory Automation

Autonomous warehouse robots at Amazon



Autonomous arms at Tesla

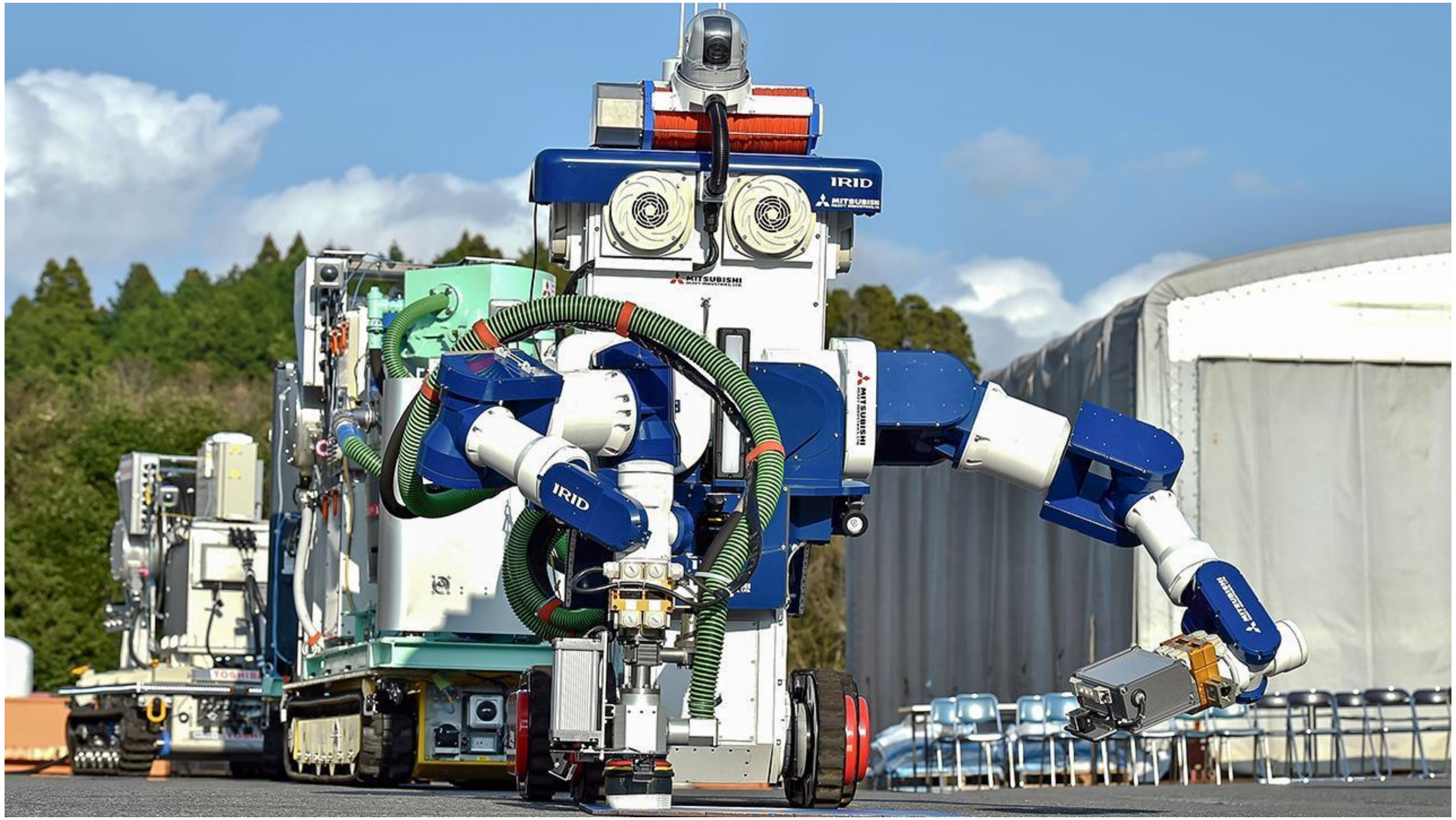
Pipe Inspection

Manually-controlled inspection robots

Nuclear Disaster Cleanup

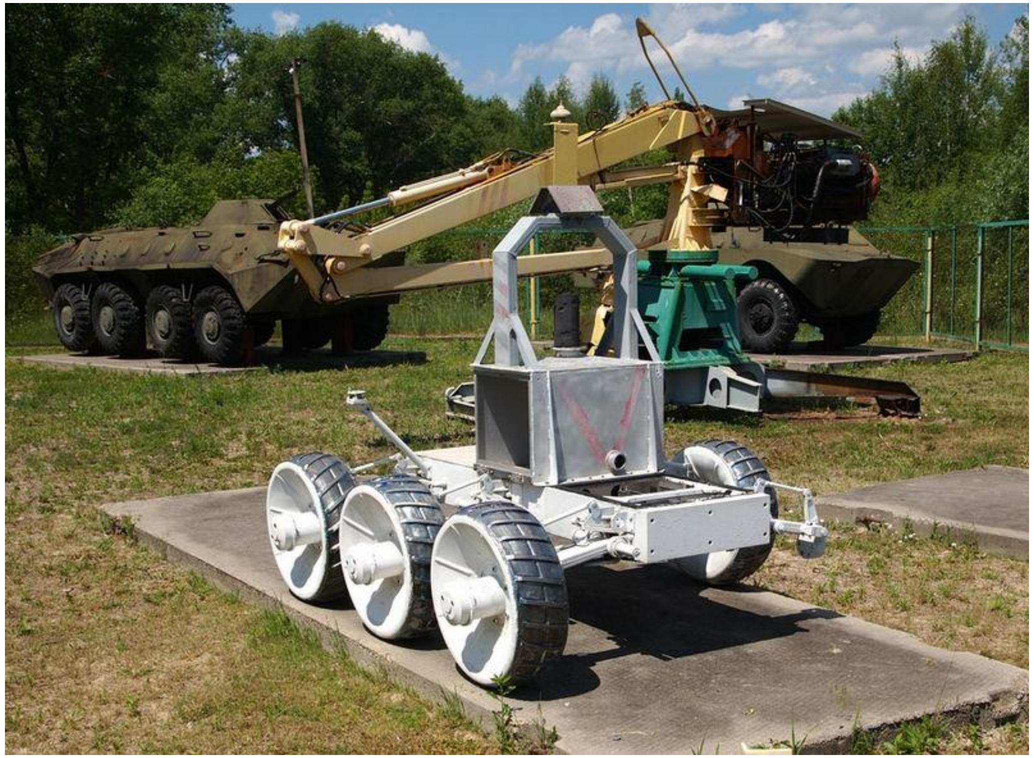
Remote-controlled cleaning robot at Fukushima Daiichi, 2011

Nuclear Disaster Cleanup



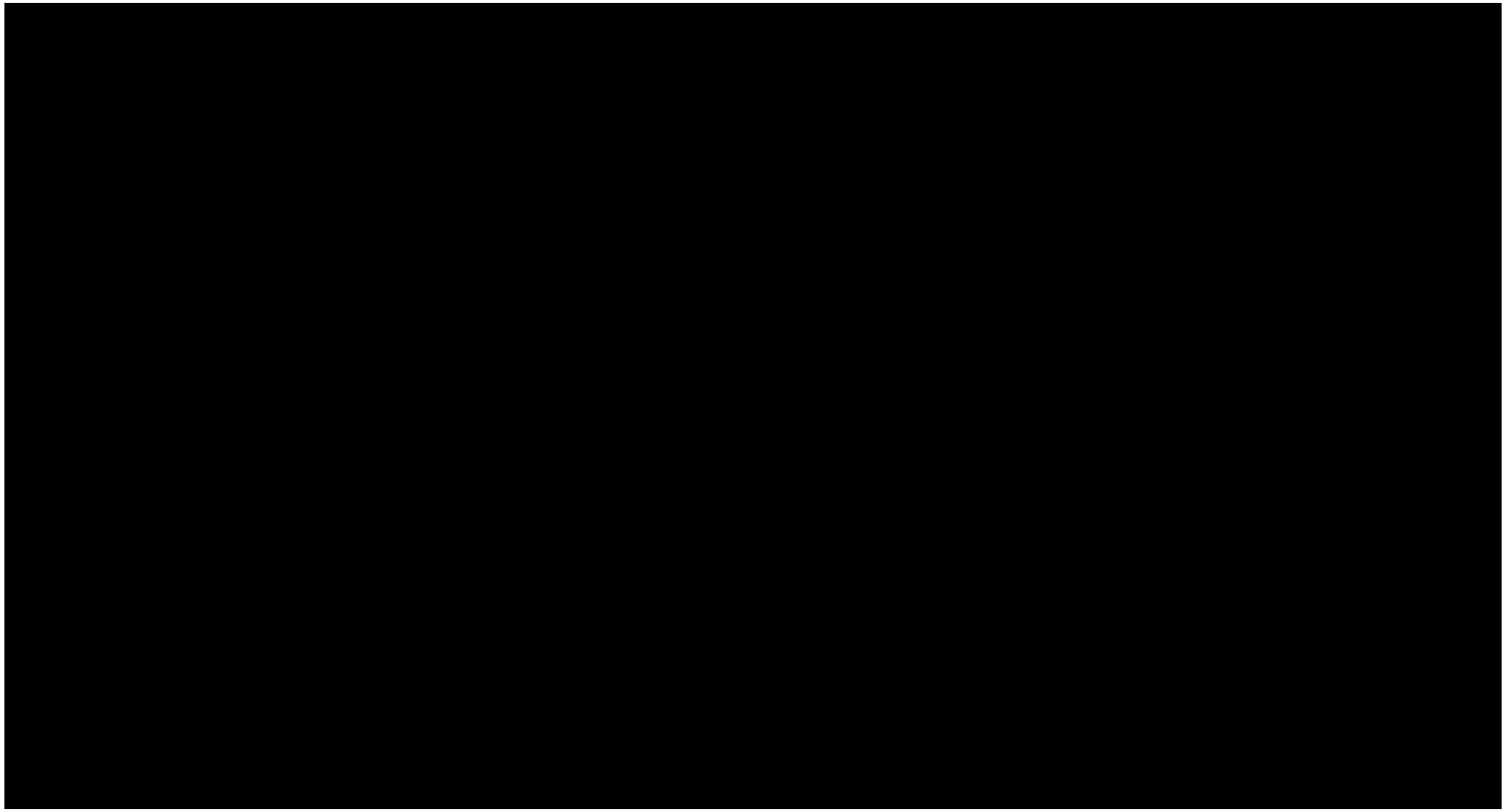
Remote-controlled cleaning robot at Fukushima Daiichi, 2011

Nuclear Disaster Cleanup



Remote-controlled cleaning robot at Chernobyl, 1986

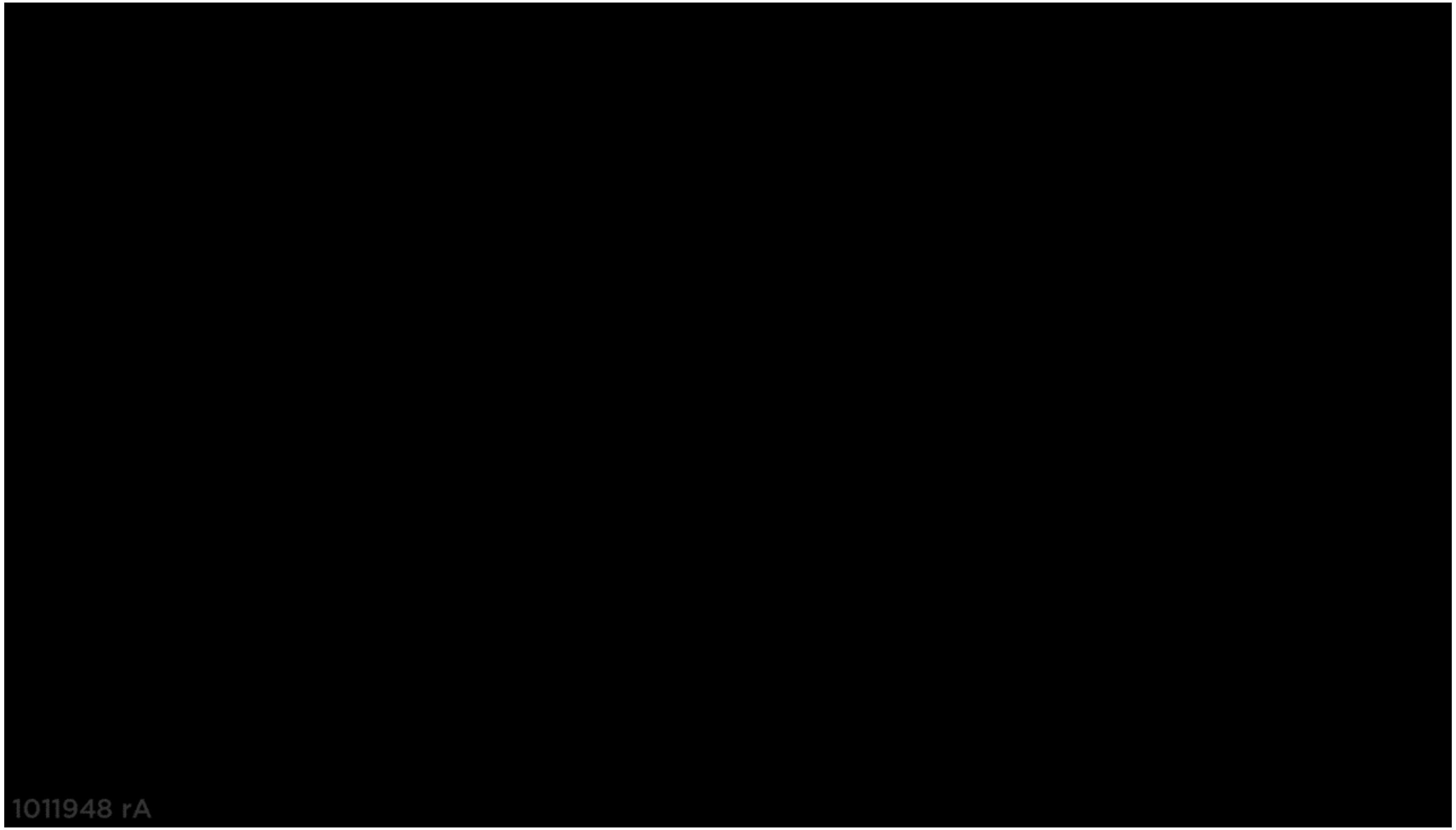
Aerial Package Delivery



Aerial First-Aid Delivery

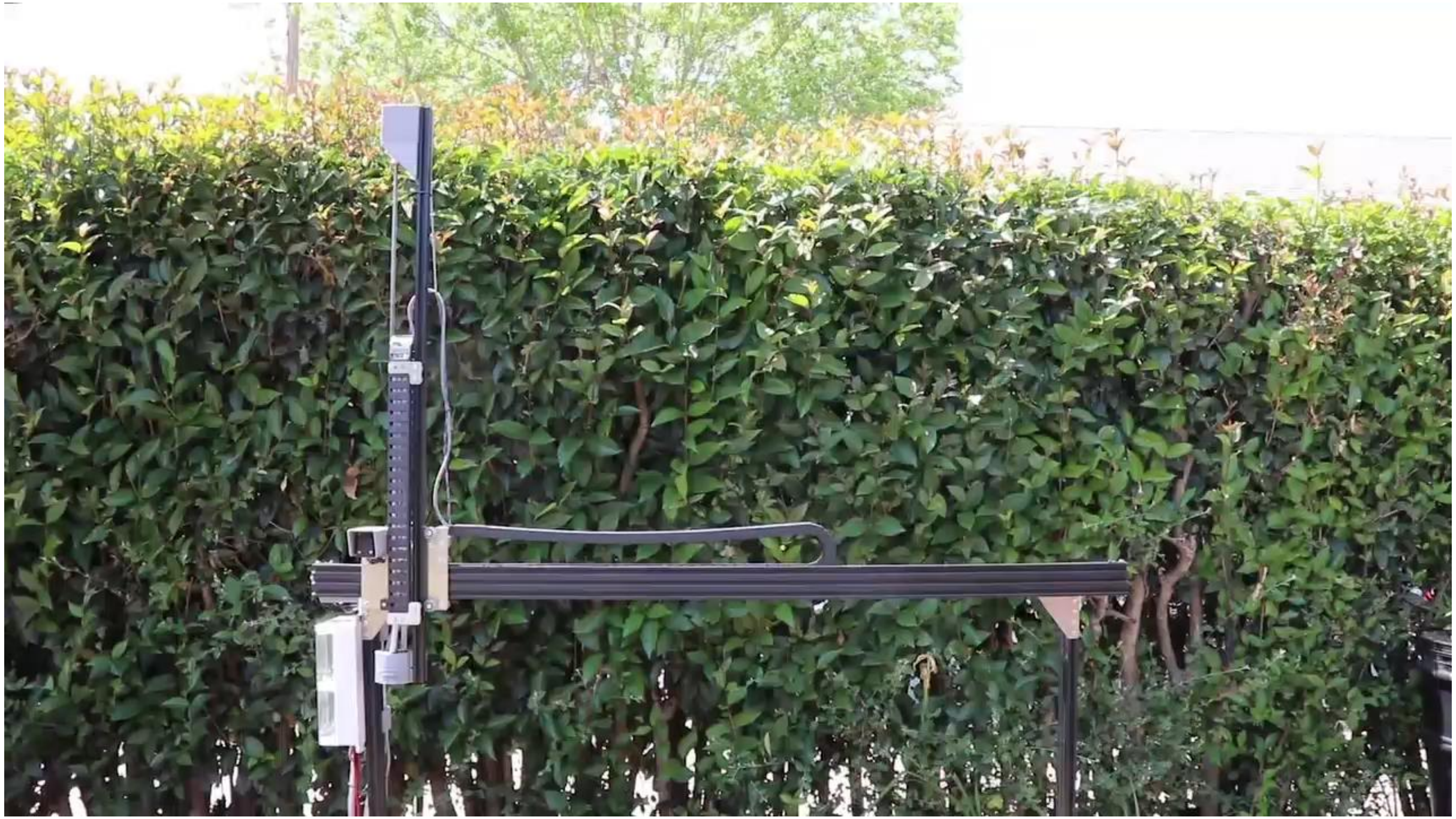
Smart Wheelchairs

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

Required: CSC209H5 and MAT223H5 and MAT232H5 and STA256

Recommended: CSC384H5 and CSC311H5 and CSC376H5 and MAT224H5

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

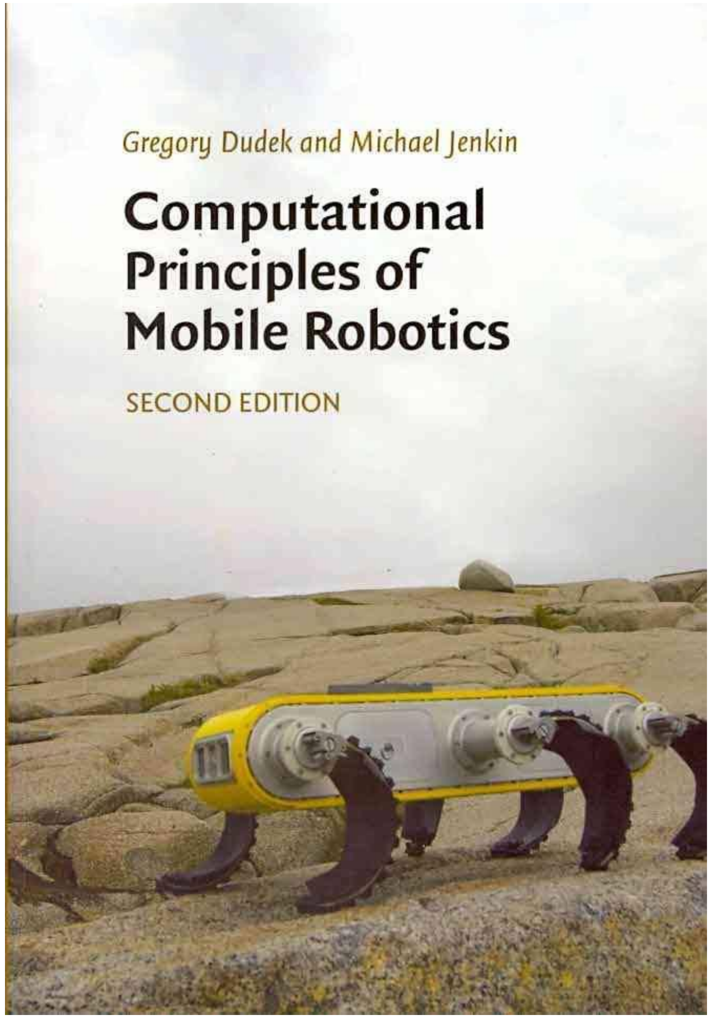
- 5 mins in the middle of class
- Not cumulative in terms of material. They cover only one lecture
- Meant to check whether you have understood basic concepts

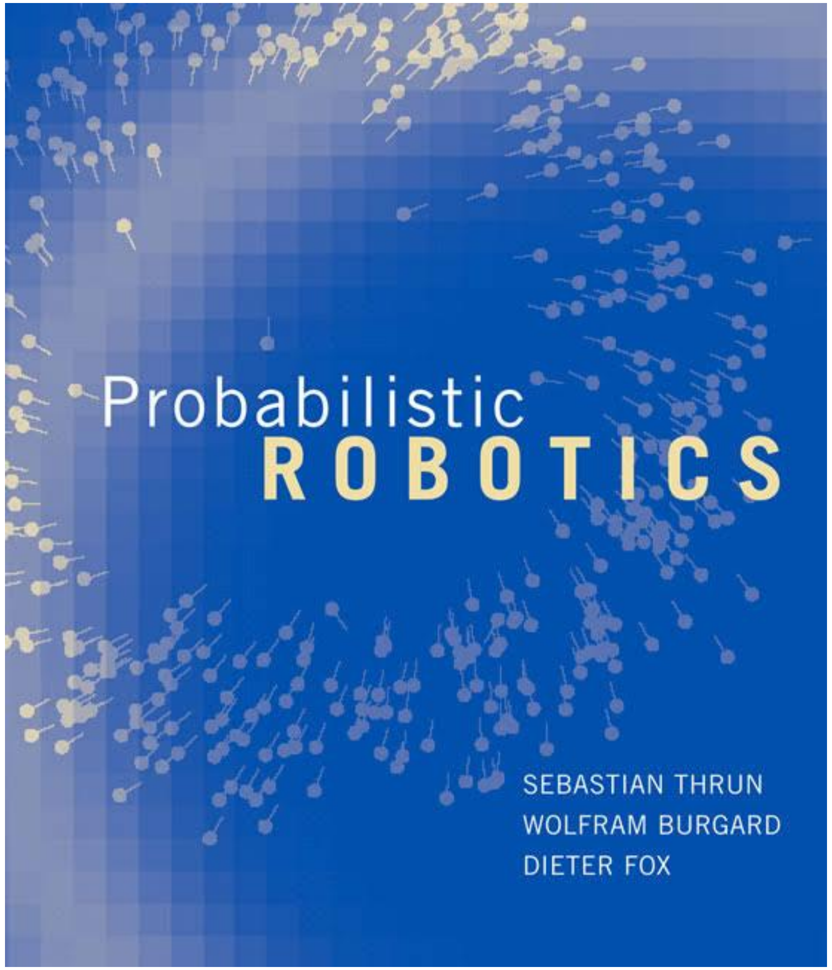
Evaluation

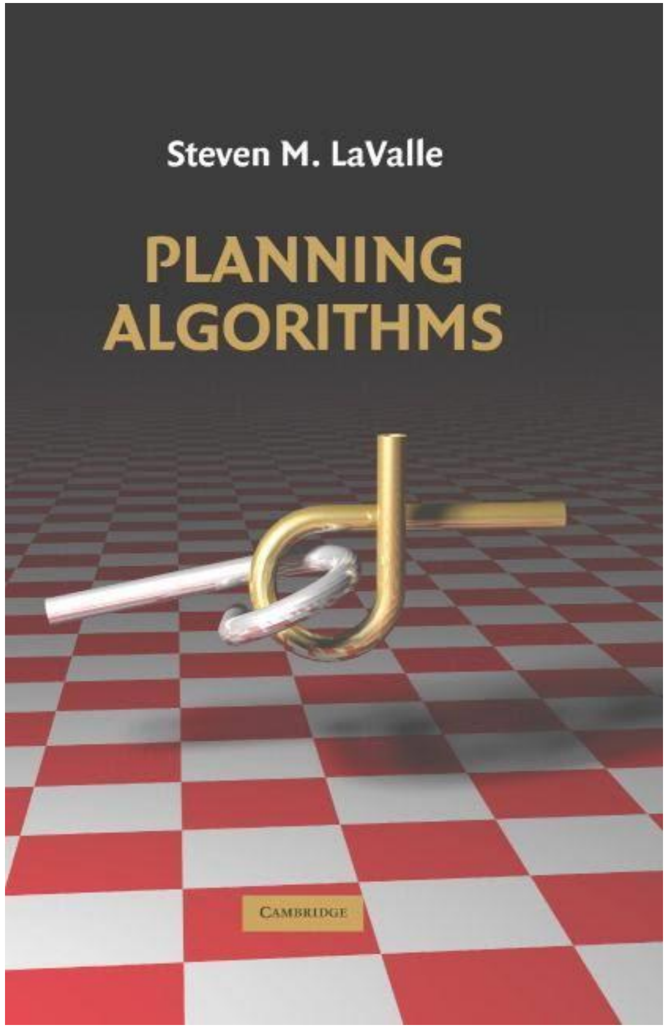
- 4 assignments, 15% each = 60%
- Best 5 out of 7 quizzes, 3% each = 15%
- 1 final exam = 25%

Final exam will be open-book and open notes

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: Mondays 4-5pm ET on Zoom
- TA's: Fridays 2-3pm ET on Zoom

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

- <u>The zoom link has been posted on Quercus</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
vehicles, actuators and sensors

Feedback Control:
which commands will cause the
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designing estimators that incorporate
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Computer Vision:
estimating 3D structure + motion

Not Covered

Electrical engineering:
motors, power supplies,
microcontrollers, batteries

Mechanical design

Ethics of AI

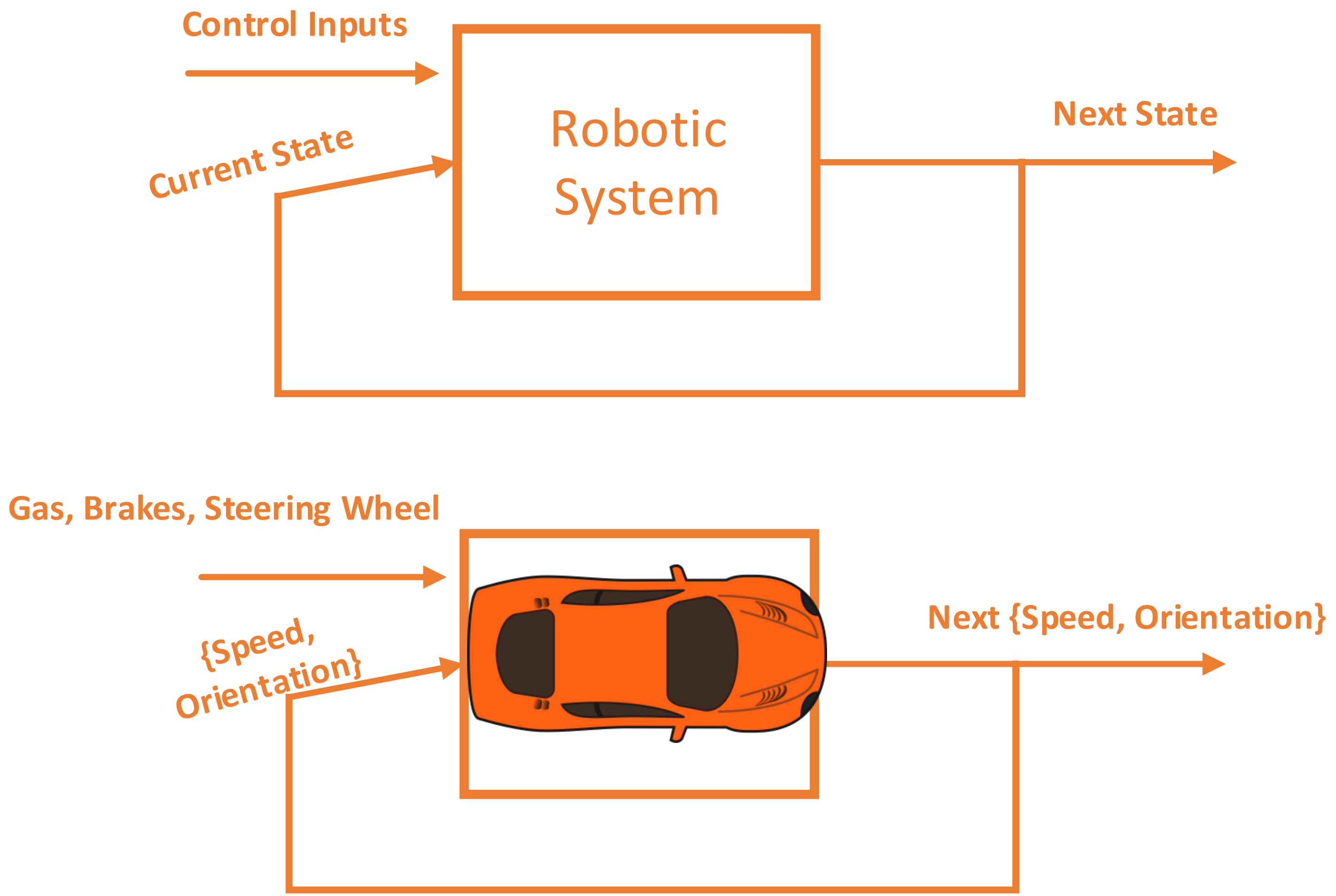
Multi-robot systems

Humanoids and walking

Grasping and manipulation

Main topics to be covered

Kinematics & Dynamics:
physical models of
robotic systems and sensors

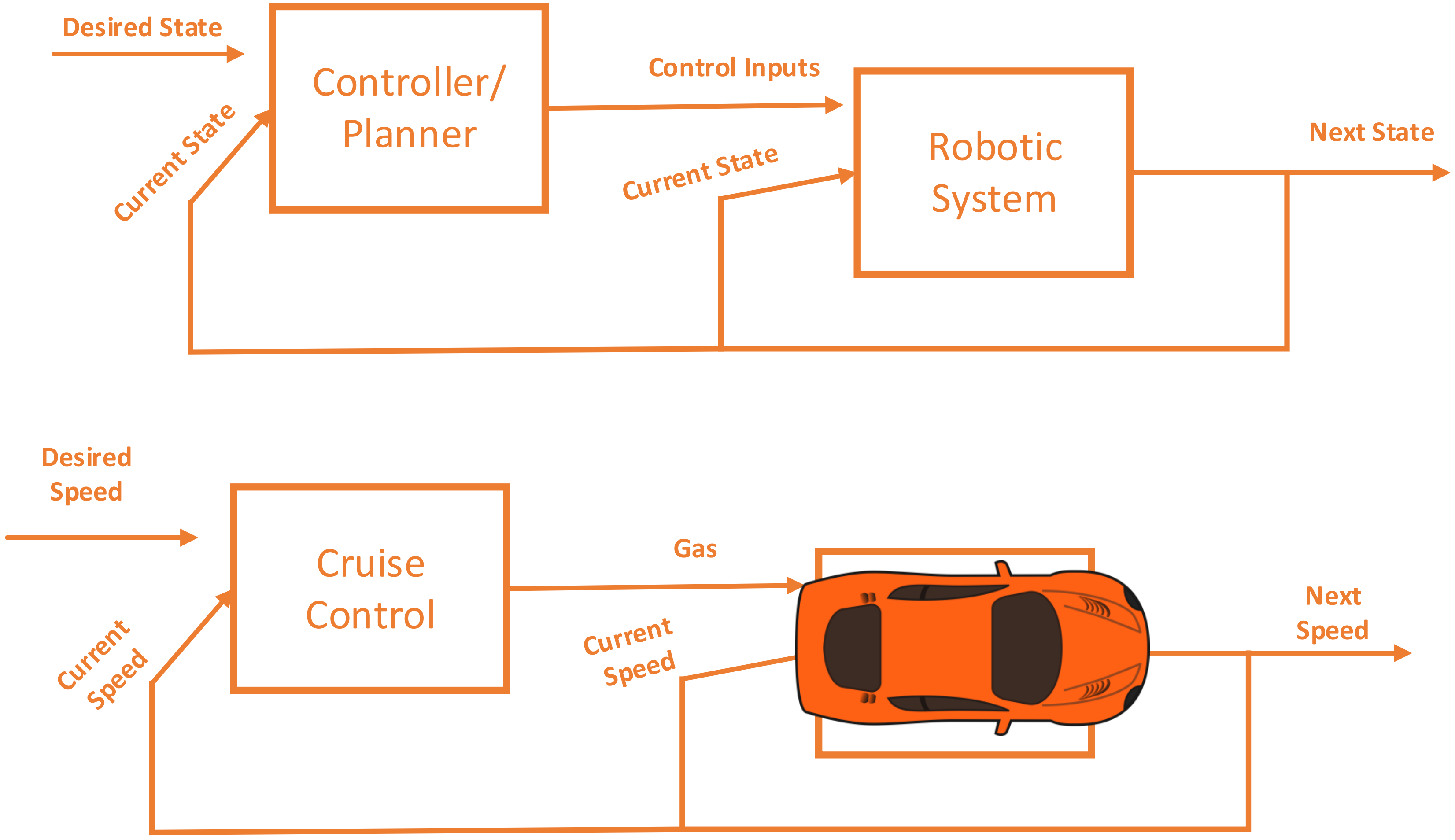


Main question: what is the next state given the current state and controls?

Main topics to be covered

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

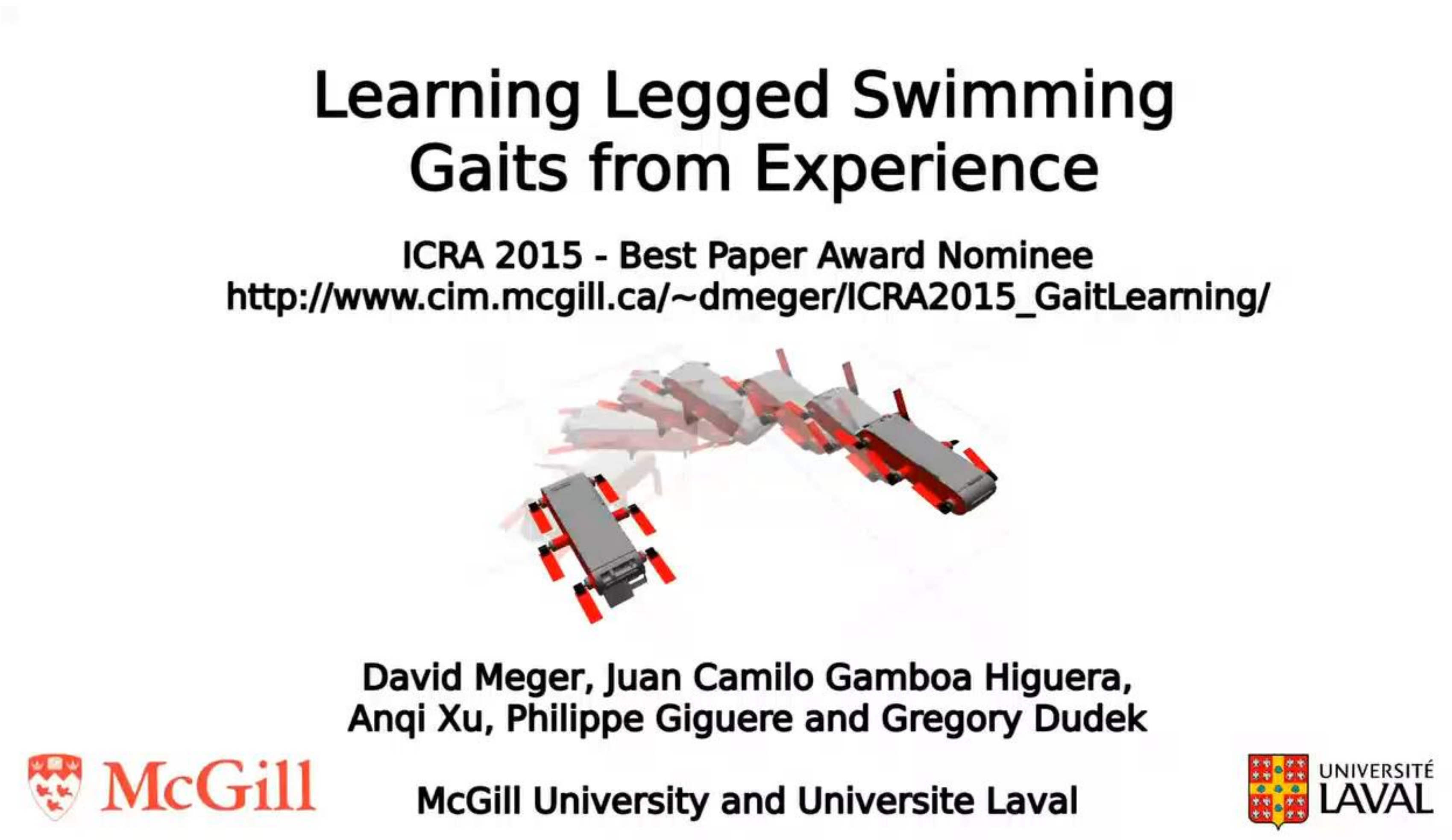
Planning:
path planning in known maps



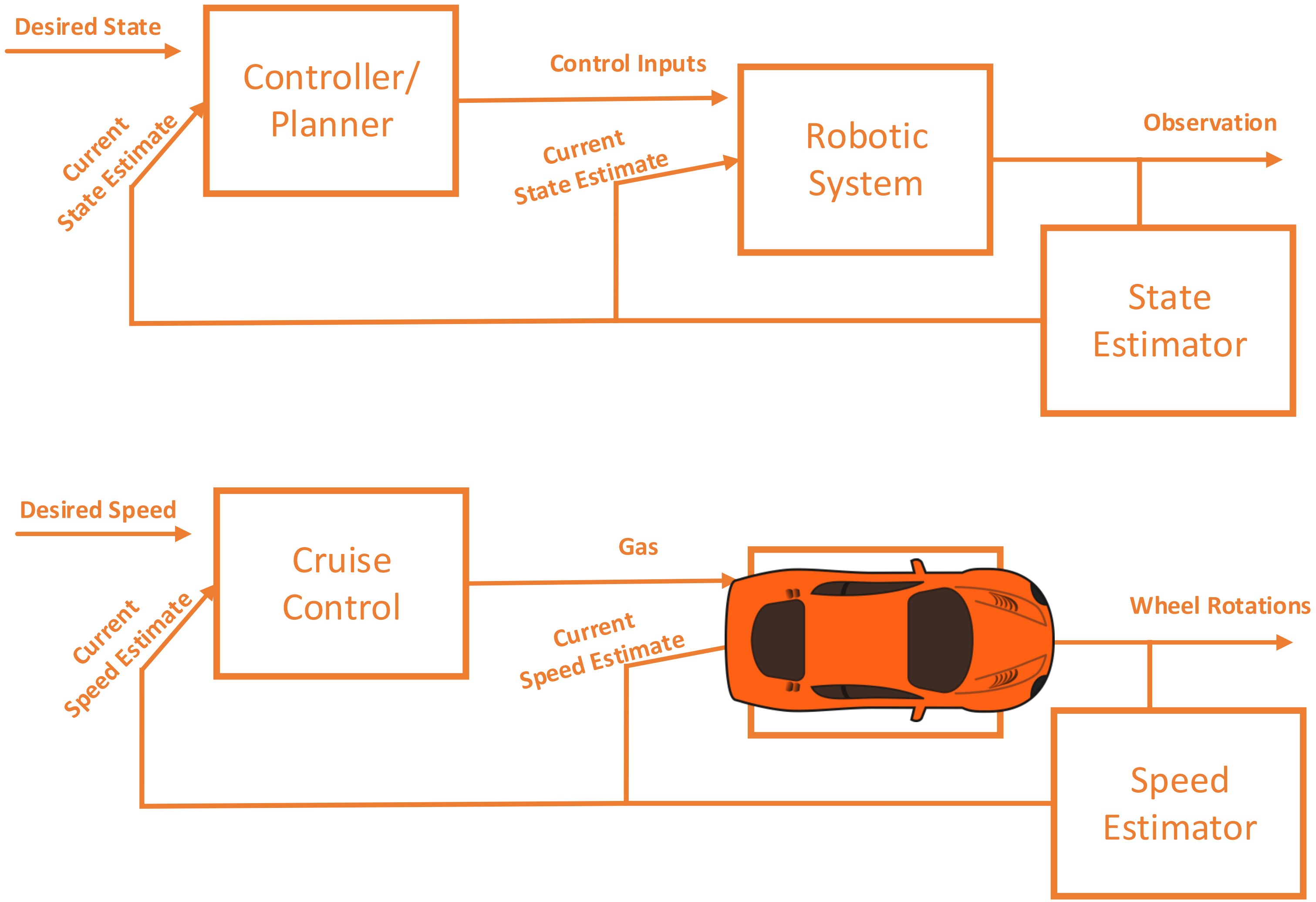
Main question: what are the controls that will take the system from state A to B?

Not covered in CSC477, but related: learning for control

Not covered in CSC477, but related: learning for control



Main topics to be covered

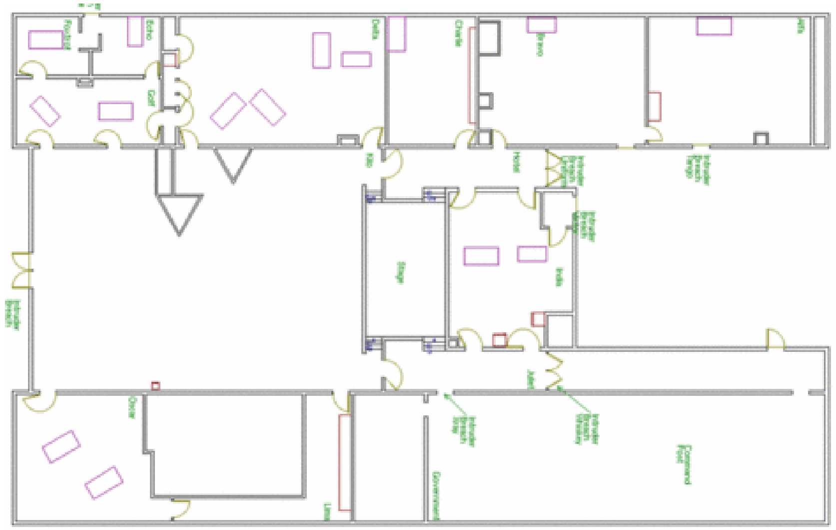


State Estimation:
designing estimators that incorporate sensor measurements

Main topics to be covered

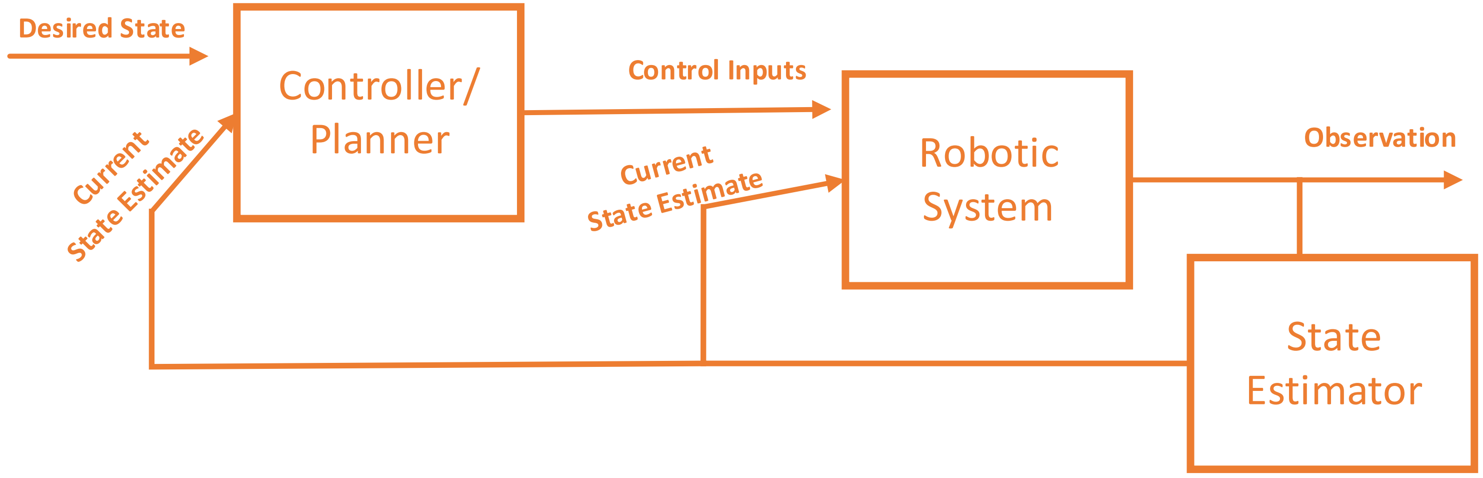
- Known: robot's position and orientation
- Want to estimate: a map of the environment from laser measurements

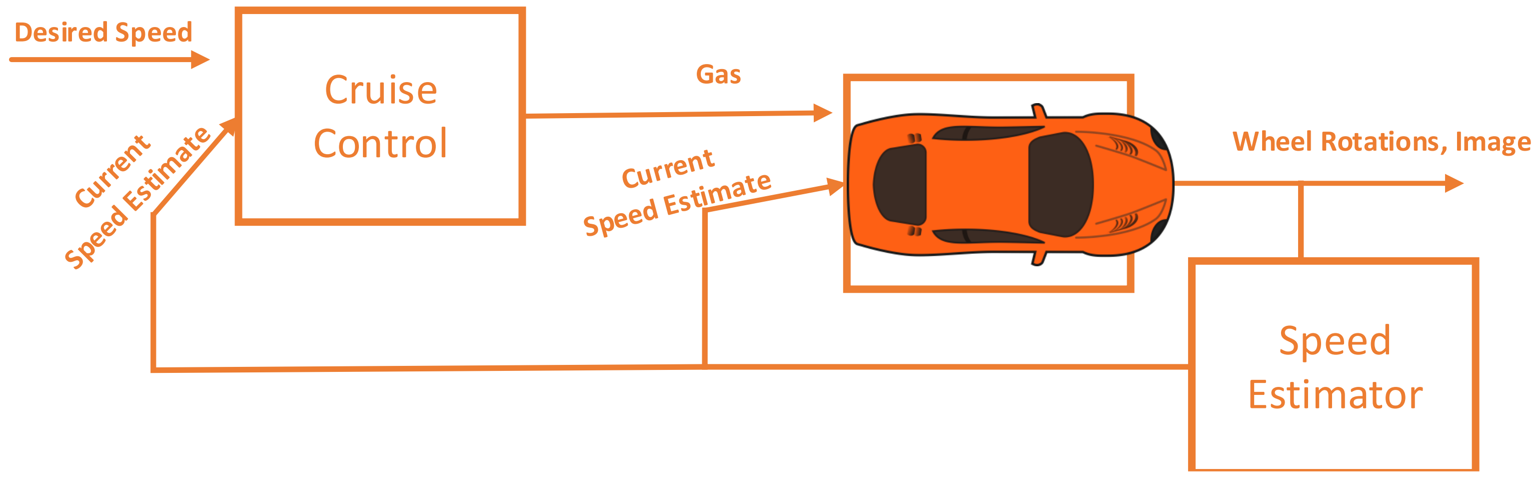
State Estimation:
designing estimators that incorporate
sensor measurements



- 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

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Instituto Universitario de Investigación
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Universidad Zaragoza

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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

- Consider getting involved, it is a fun community!

  https://utmrobotics.com/

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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.

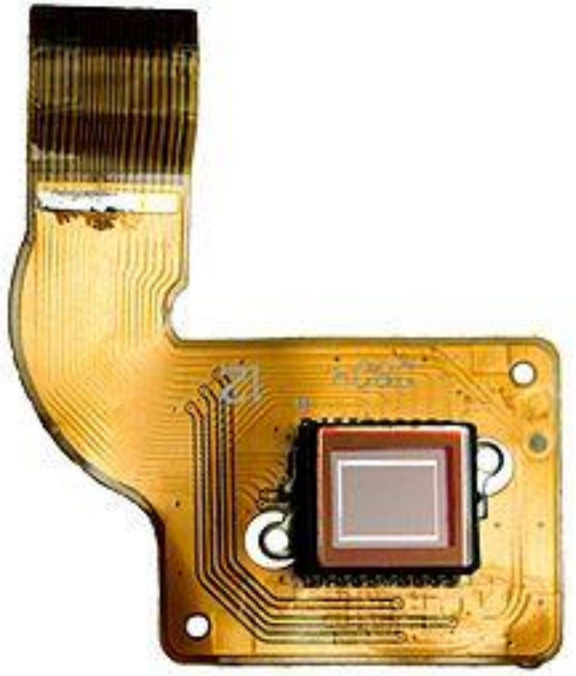
- Key phenomenon is **transduction** (conversion of energy from one form to another). E.g.:
  - Imaging sensors: light to pixel voltages
  - Depth sensors: mechanical pressure to voltage

- 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}

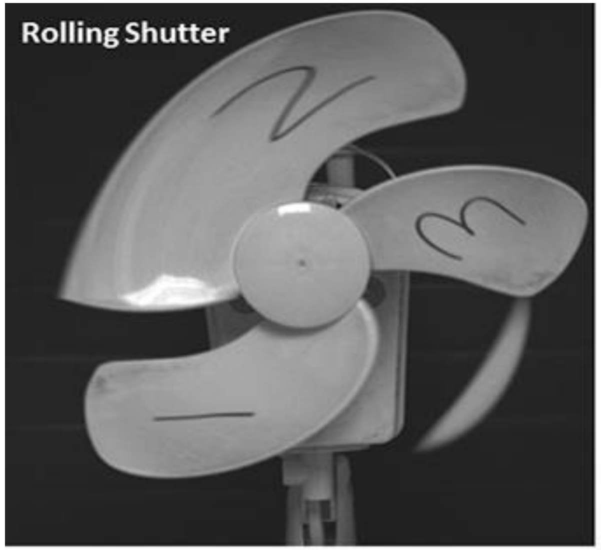
CMOS (complementary metal-oxide semi-conductor) imaging sensors:

- 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
81 49 31 73 55 79 14 29 93 71 40 67 53 88 30 03 49 13 36 65
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
```

600 x 1000 pixels


```
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
81 49 31 73 55 79 14 29 93 71 40 67 53 88 30 03 49 13 36 65
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
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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
```

600 x 1000 pixels

```
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
81 49 31 73 55 79 14 29 93 71 40 67 53 88 30 03 49 13 36 65
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
```

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
49	49	99	40	17	81	18	57	60	87	17	40	98	43	69	48	04	56	62	00
81	49	31	73	55	79	14	29	93	71	40	67	53	88	30	03	49	13	36	65
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?

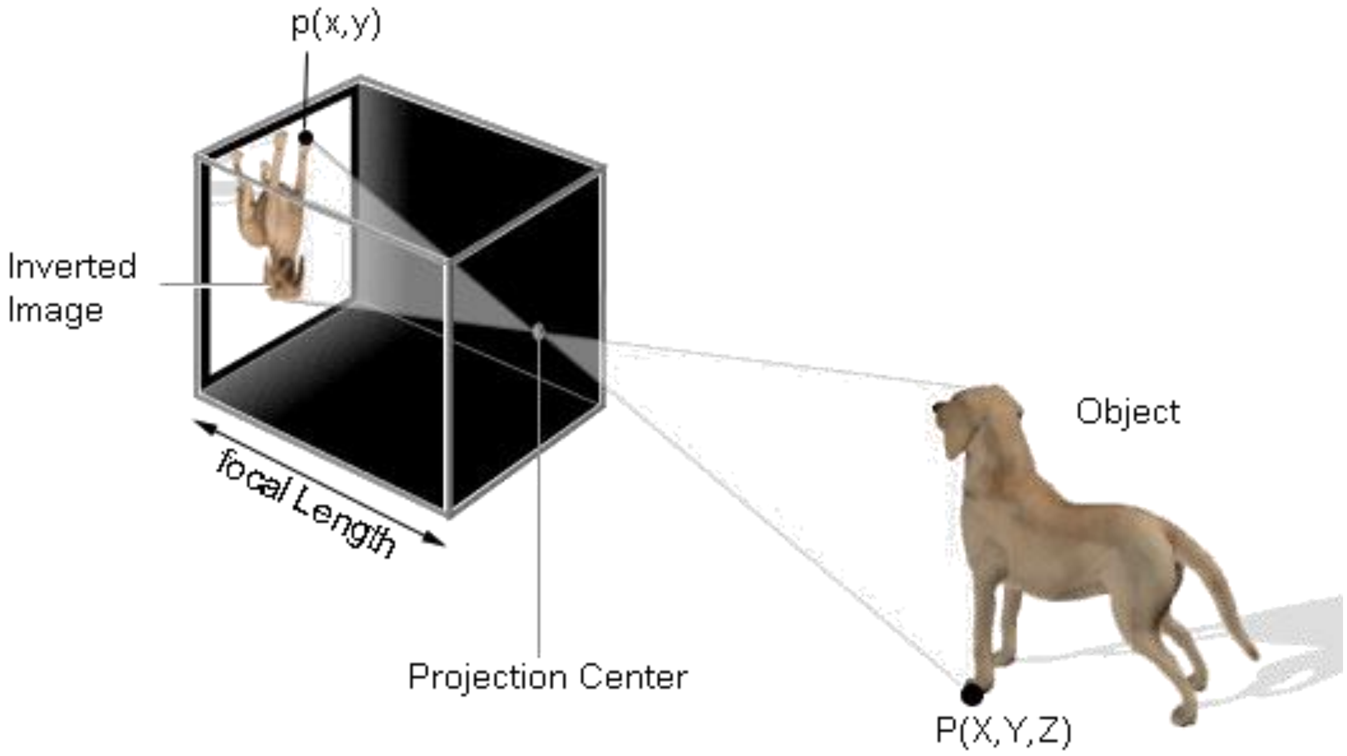
Inference & estimation

Camera lenses

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

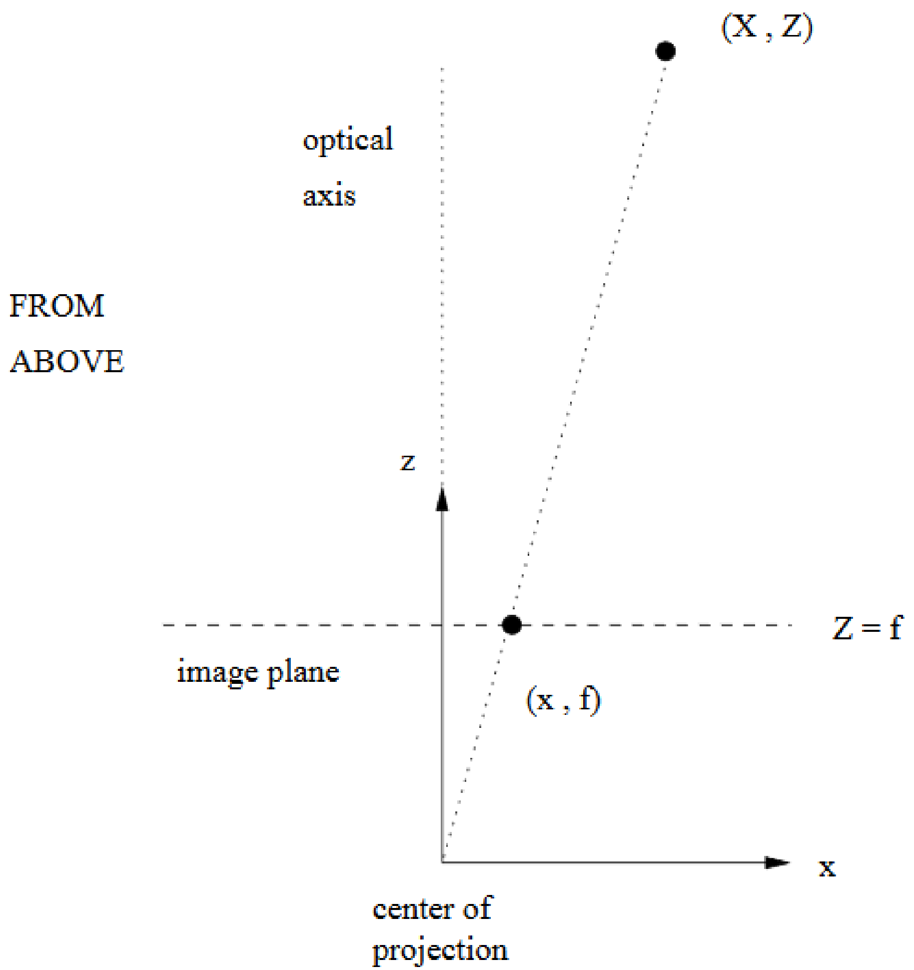
- Lens characteristics:
  - focal length
  - aperture
  - depth-of-field

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



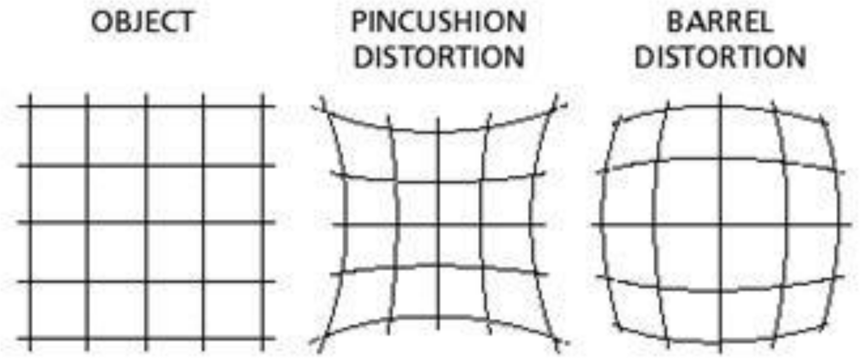
http://www.cim.mcgill.ca/%7Elanger/558.html

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

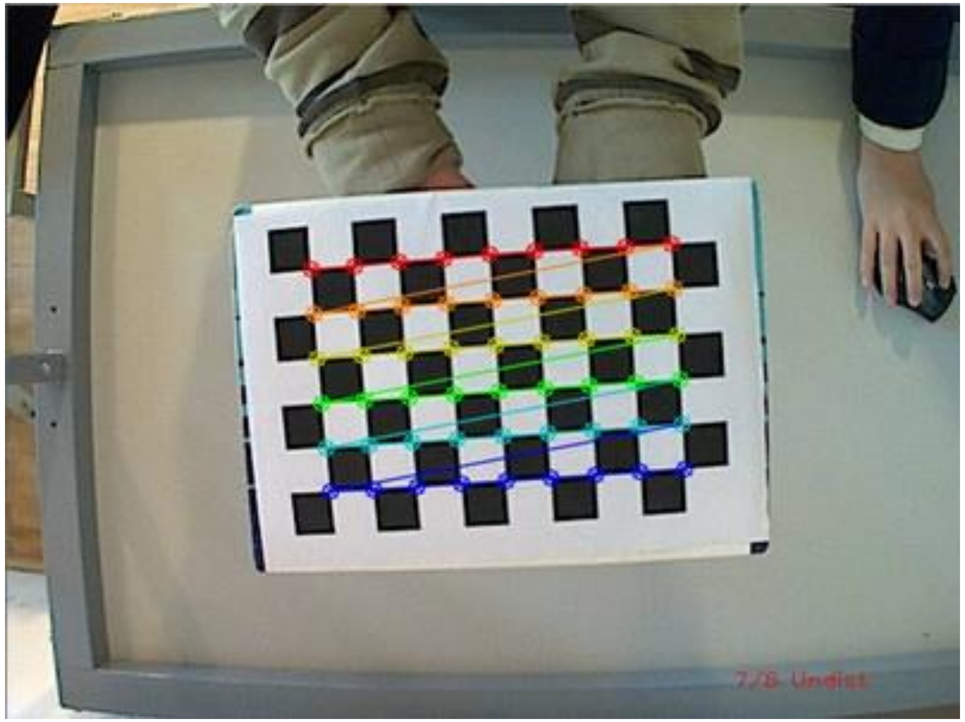
So, $x = f * X/Z$ and similarly $y = f * Y/Z$

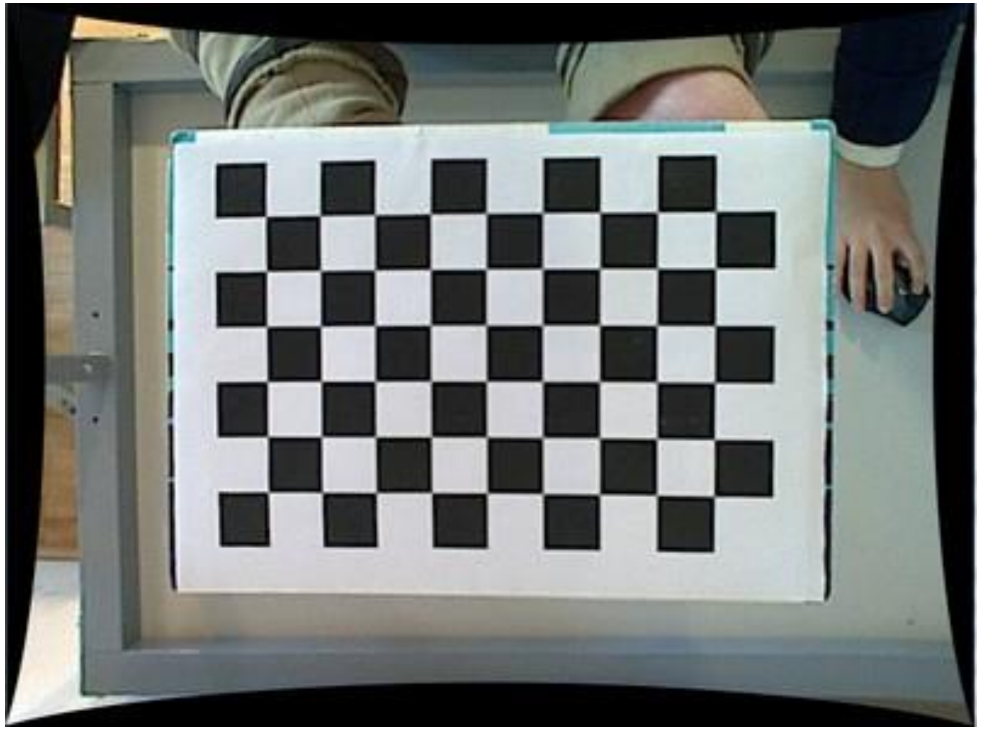
Problem: we just lost depth (Z) information by doing this projection, i.e. depth is now uncertain.

(2) Lens distortion

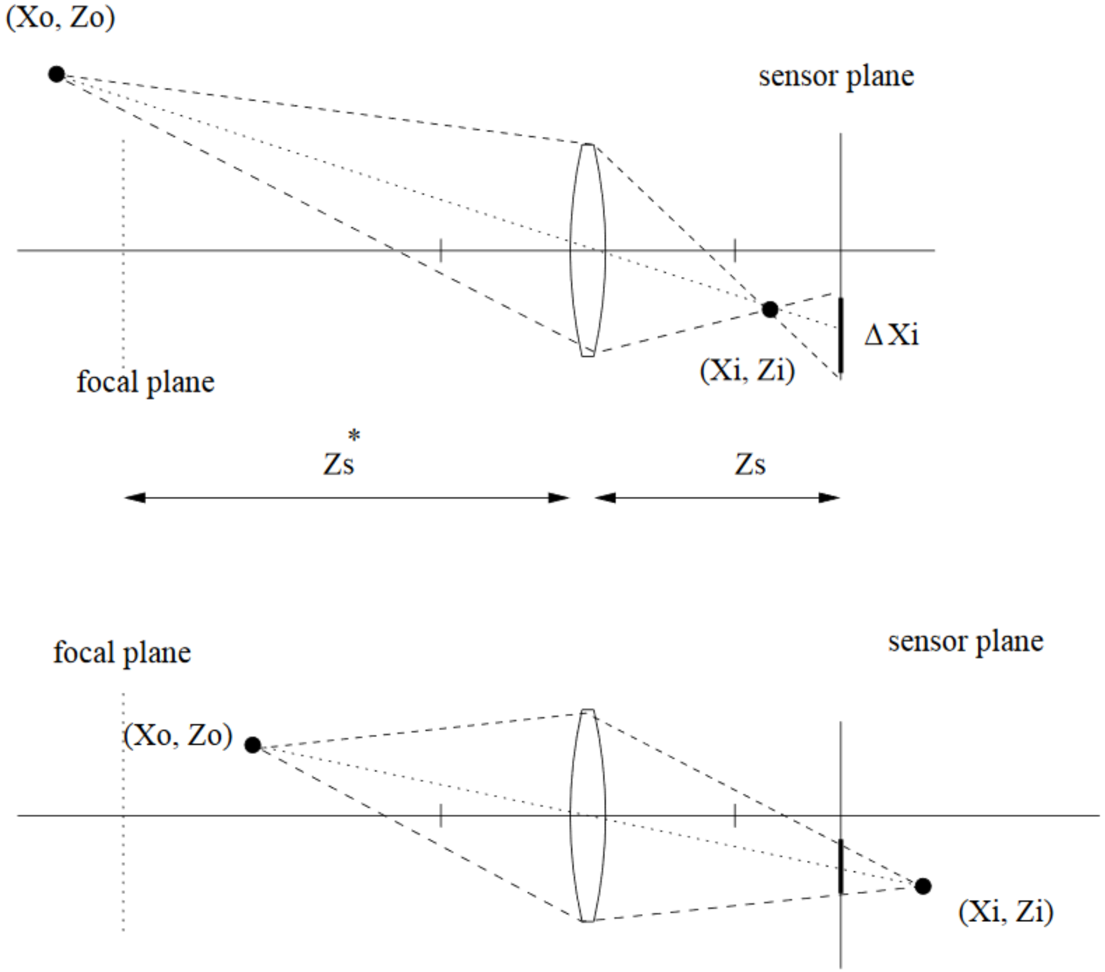


(2) Estimating parameters of lens distortion





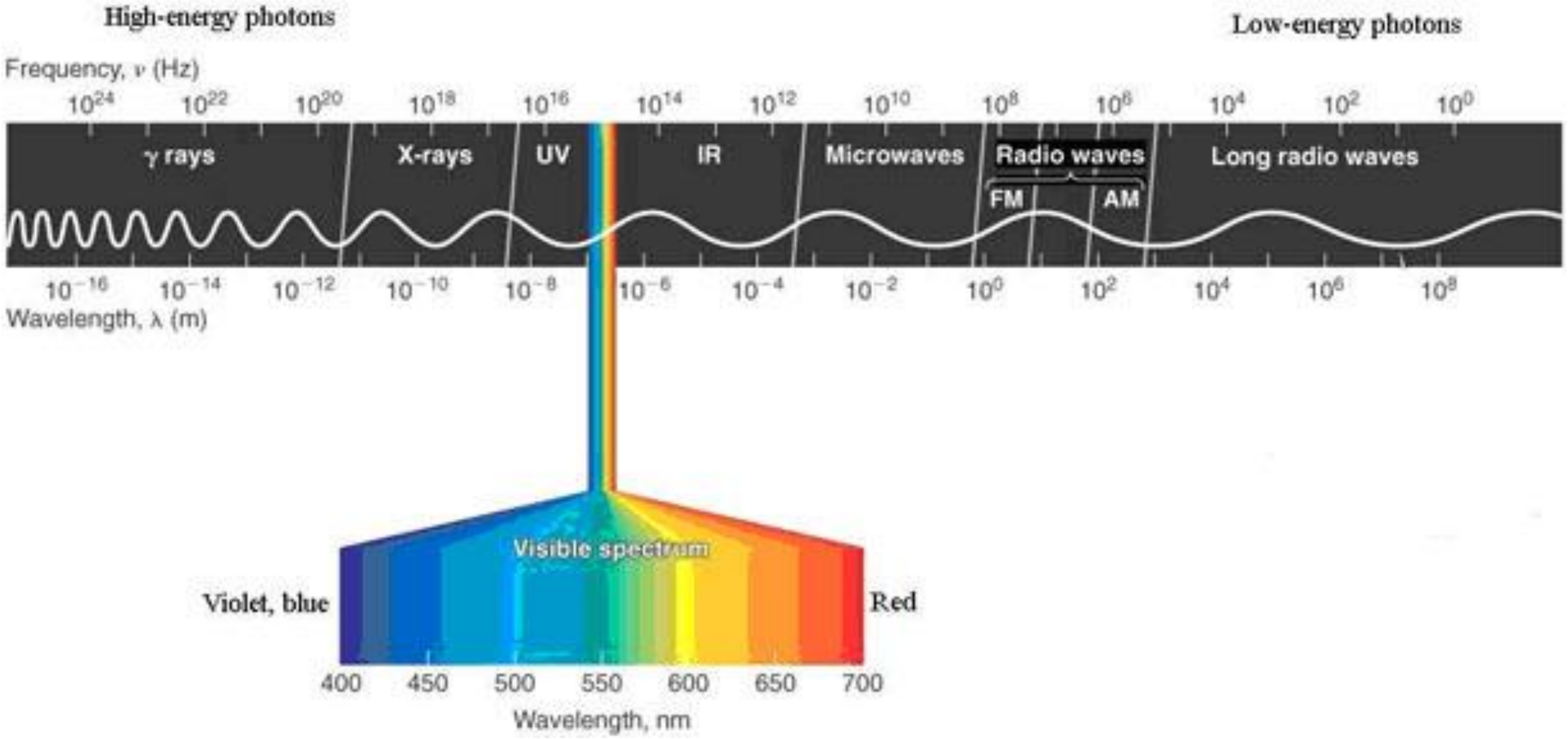
Non-pinhole cameras: thin lens model



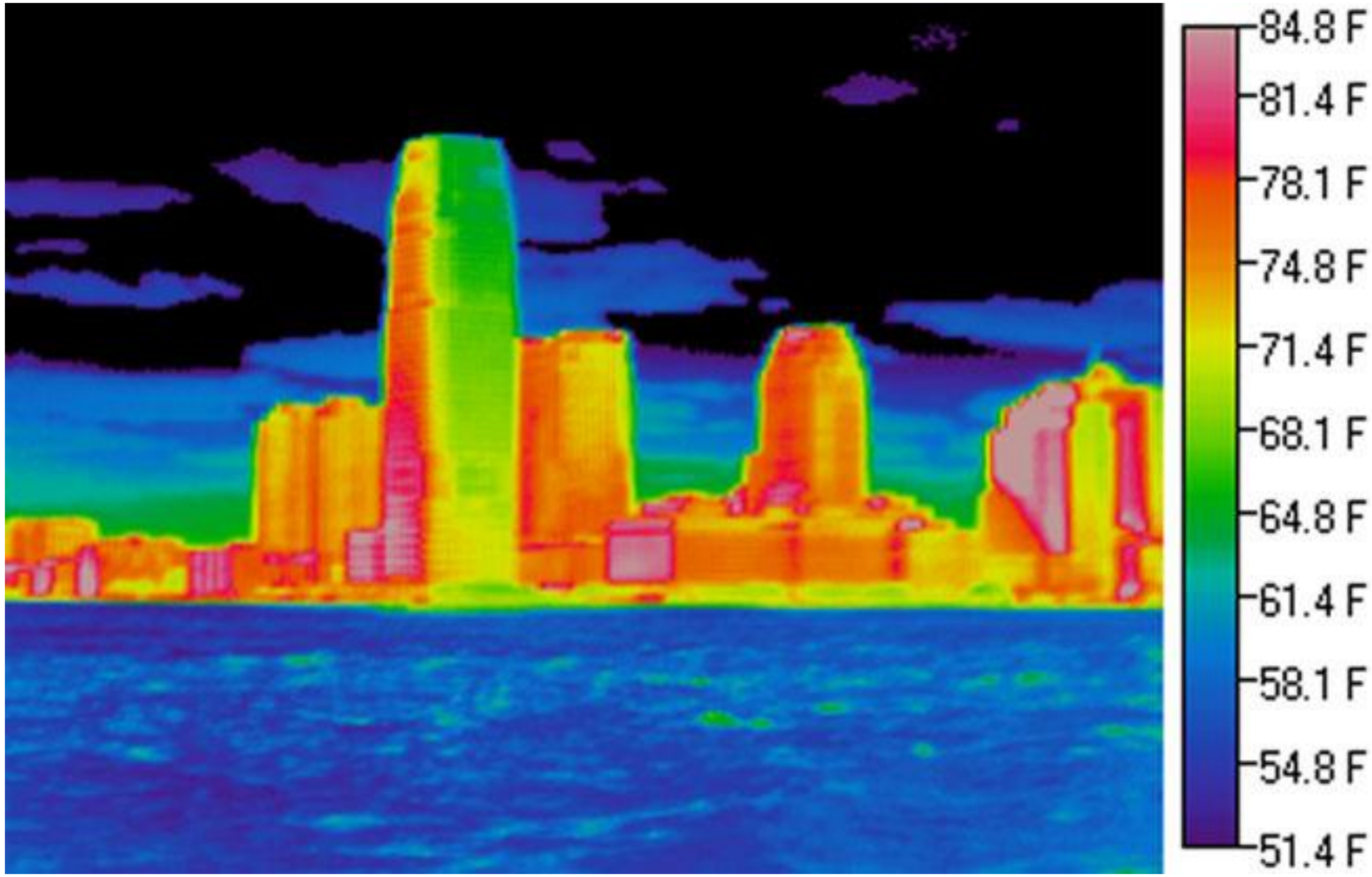
Unlike the pinhole camera, this is able to model blur.

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

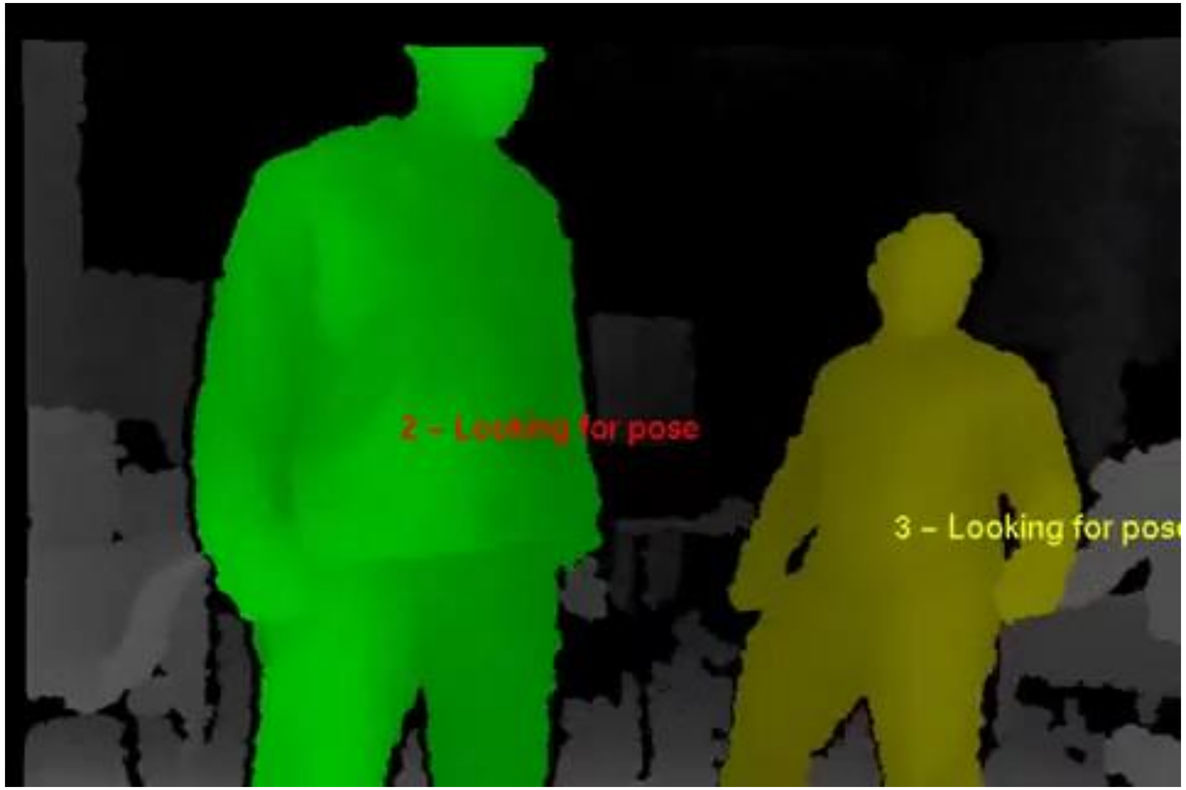
Beyond the visible spectrum: RGBD cameras

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

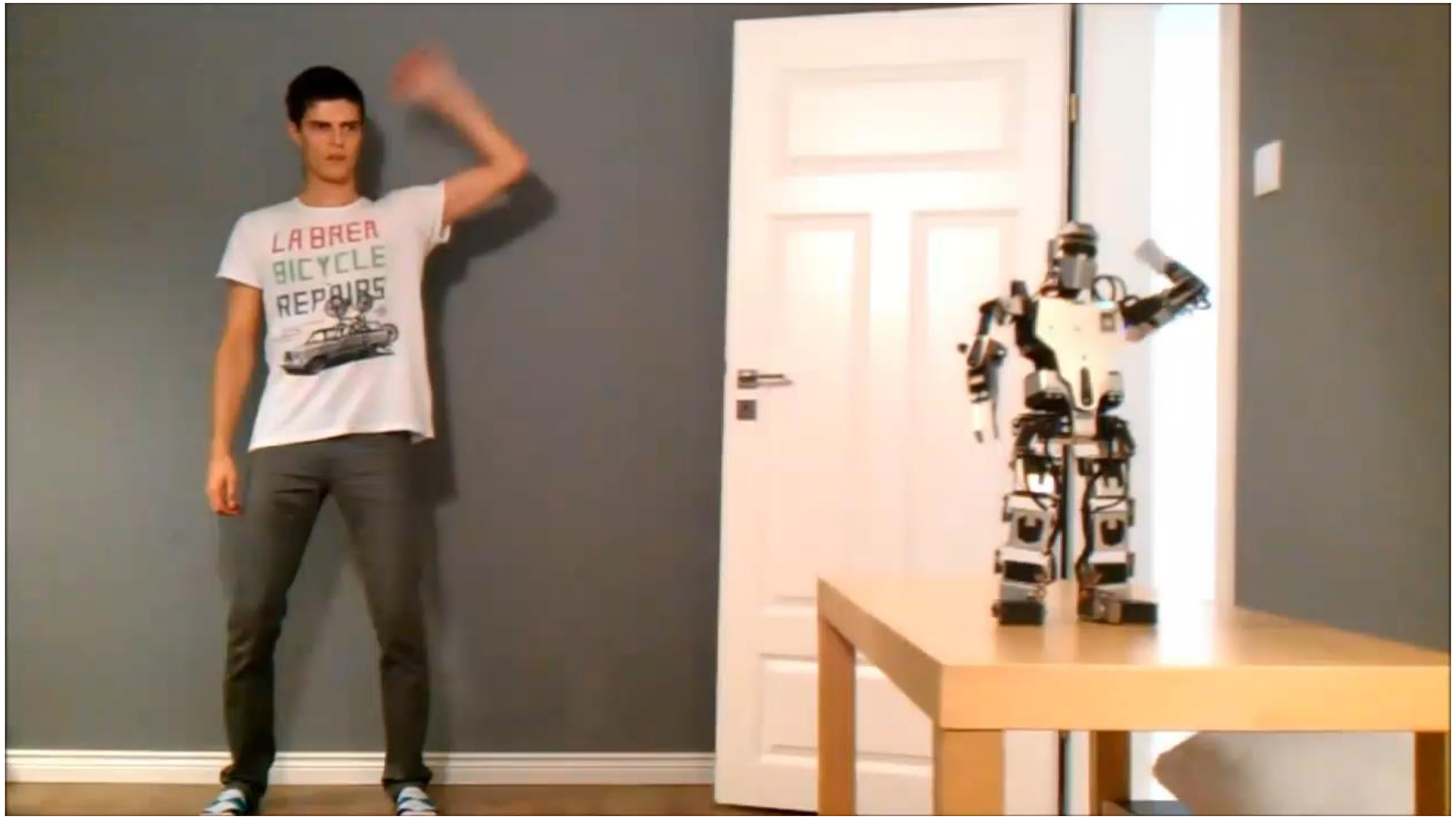
Beyond the visible spectrum: RGBD cameras

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.

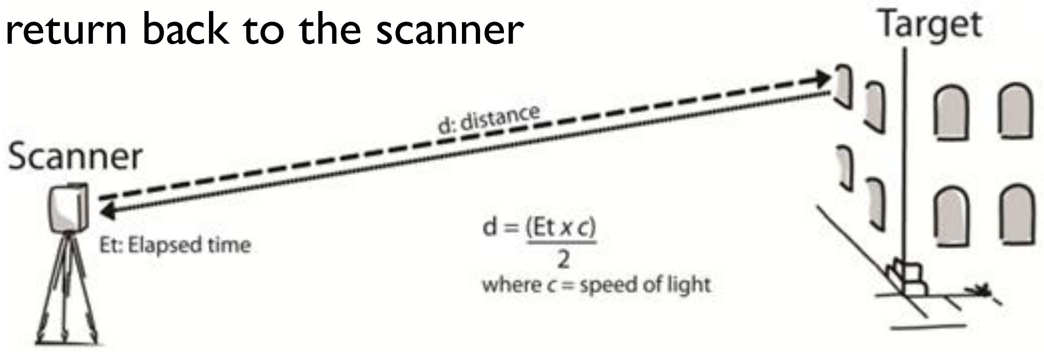


3D LIDAR (Light detection and ranging)

Produces a pointcloud of 3D points and intensities

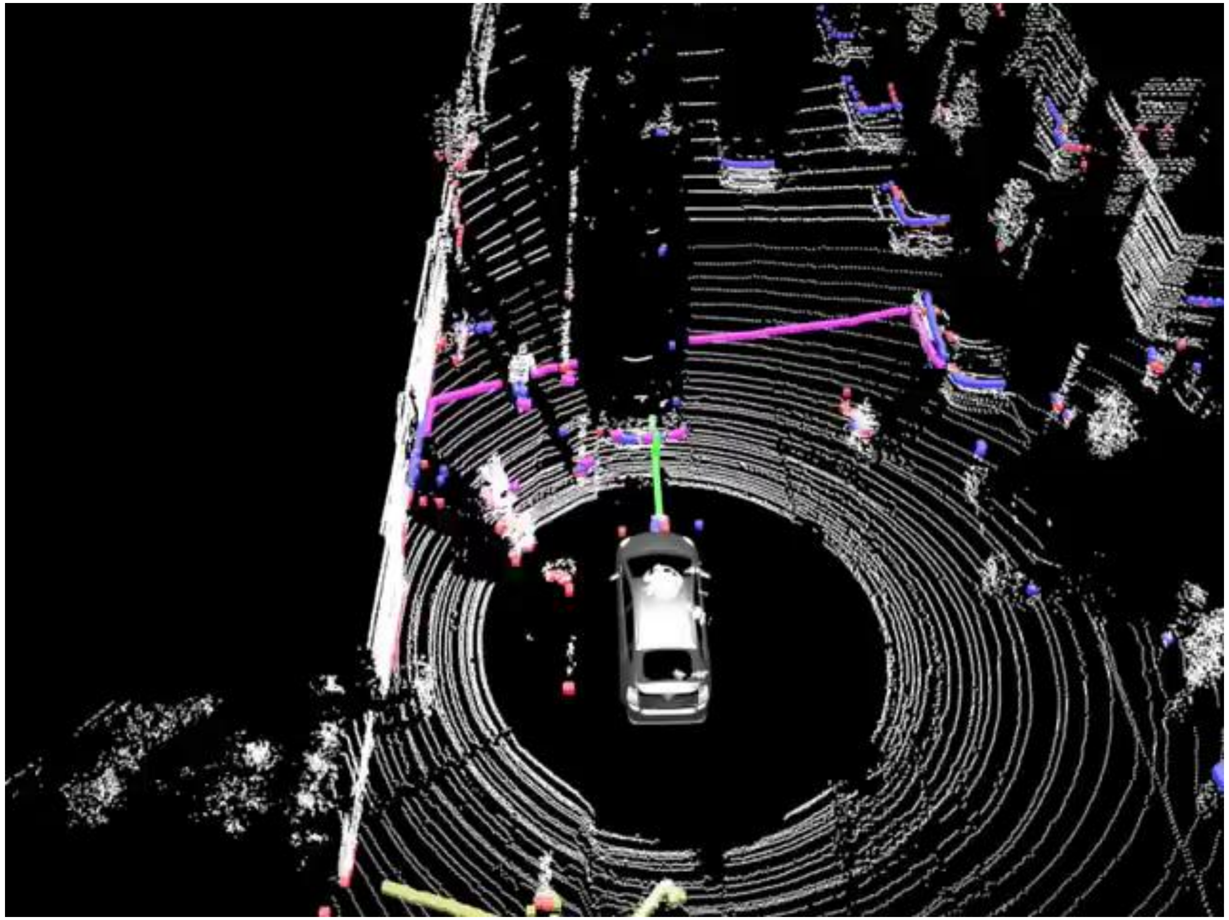
- (x,y,z) in the laser's frame of reference
- Intensity is related to the material of the object that reflects the light

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.

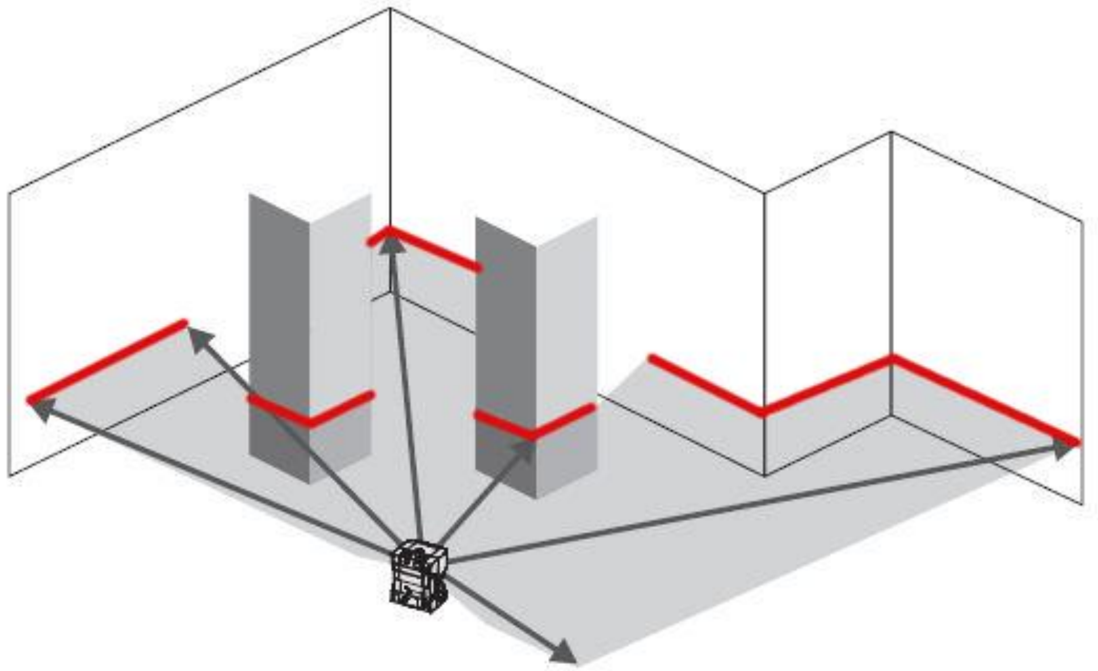


Usually around 1million points in a single pointcloud

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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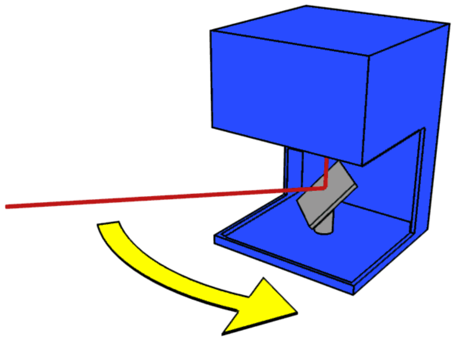
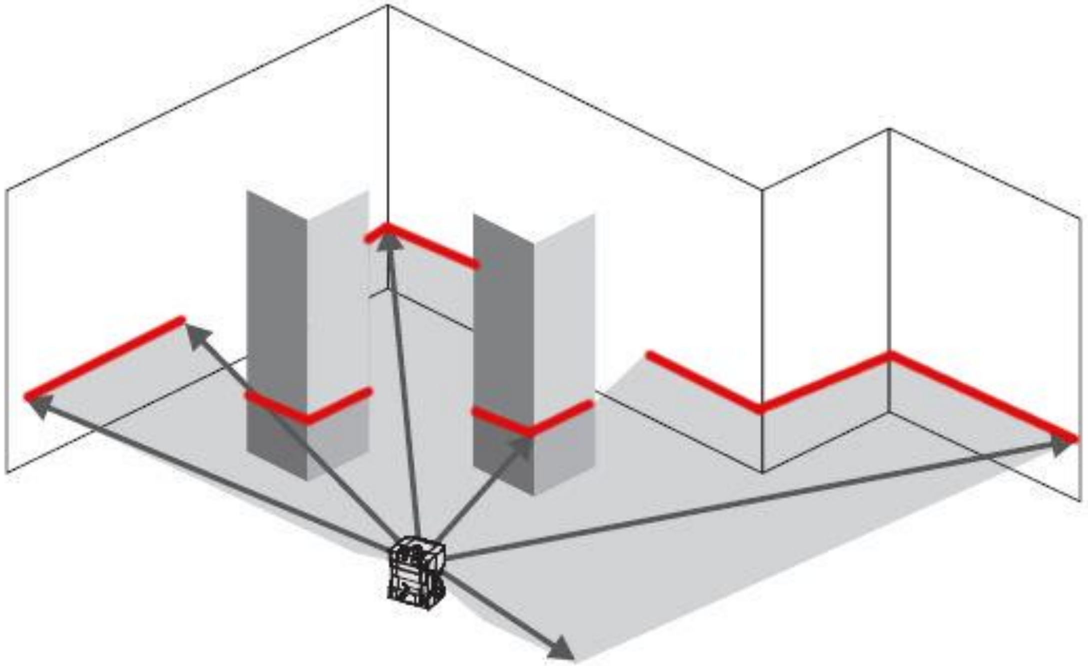


Lots of moving parts: motors quickly rotate the laser beam and once complete (angle bound reached) a scan is returned. I.e. points are not strictly speaking time-synchronized, even though we usually treat them as such.



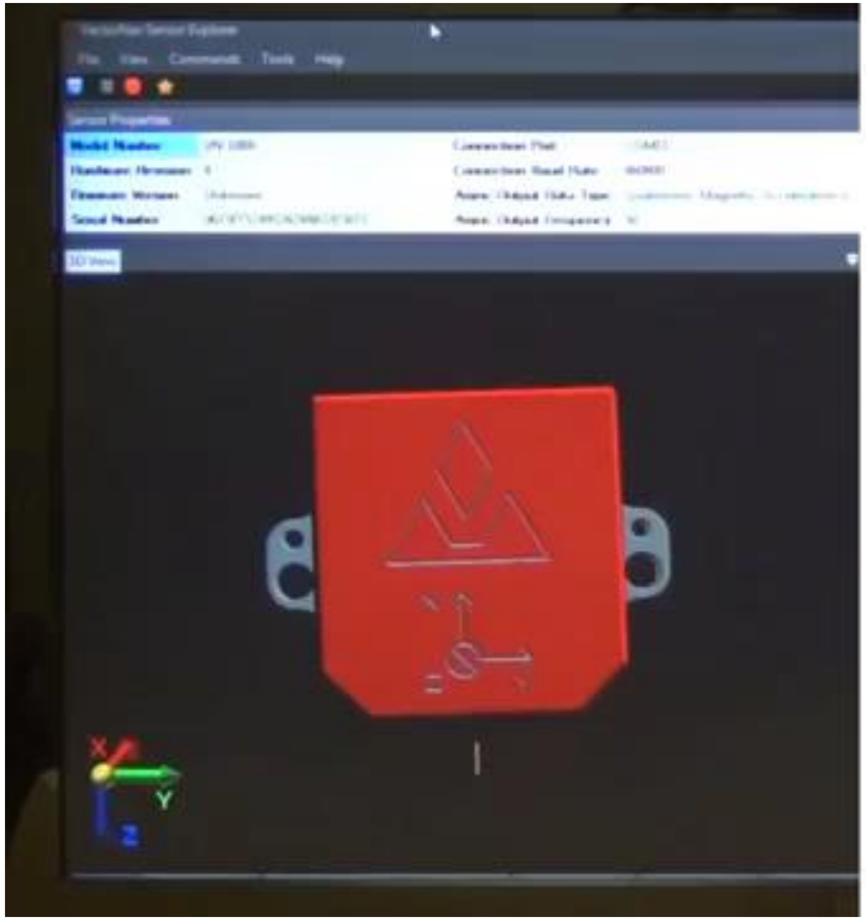
Usually around 1024 points in a single scan.

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



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, 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 0g
- 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

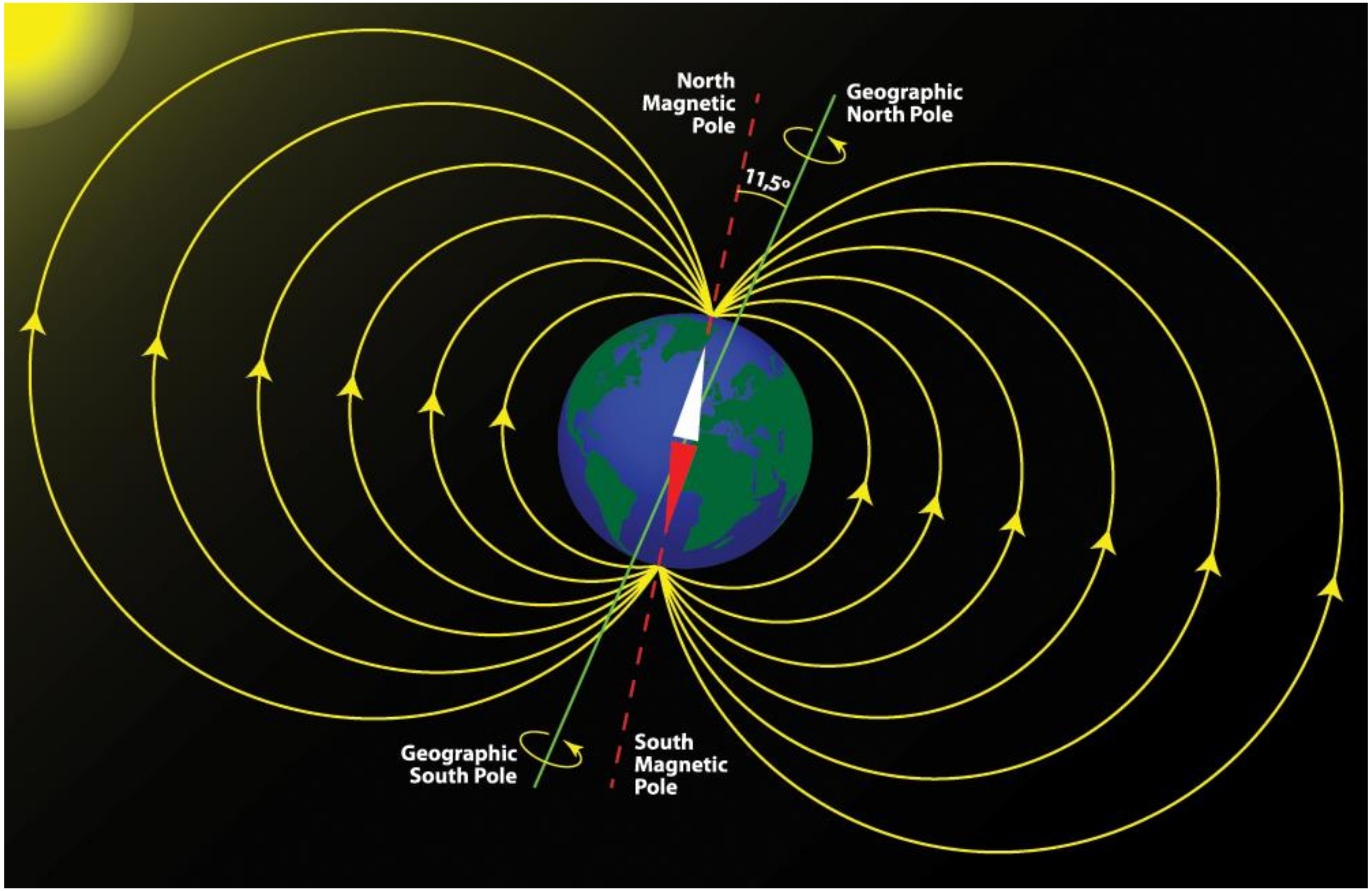
Measure the surrounding magnetic field in x,y,z.

Drawbacks:

- Need careful calibration
- Need to be placed away from moving metal parts, motors

Advantages:

- Can be used as a compass for absolute heading and finding true north



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

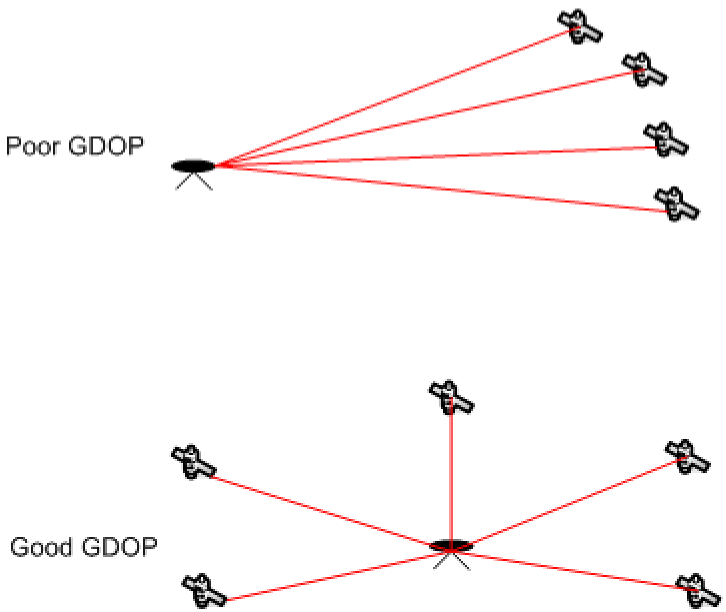
Global Positioning System: Satellites

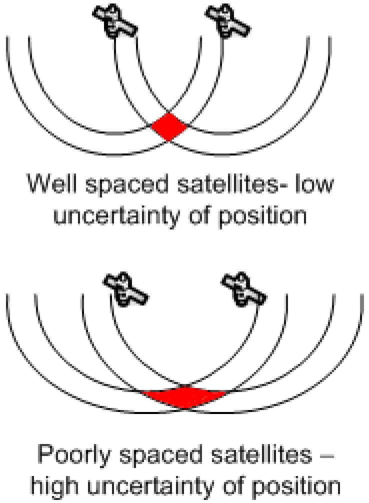
- Each GPS satellite periodically transmits:
  - [Coarse/Acquisition code] A 1023-bit pseudorandom binary sequence (PRN code), which repeats every 1 ms, unique for each satellite (no correlation with other satellites).
  - [Navigation frame] A 1500-bit packet that contains
    - GPS date, time, satellite 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

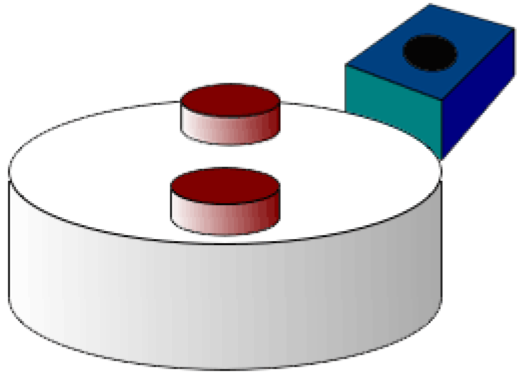
Global Positioning System: Receivers and Dilution of Precision





Geometry in 2-D (GPS Basics, 2000)

Hall Effect Sensor



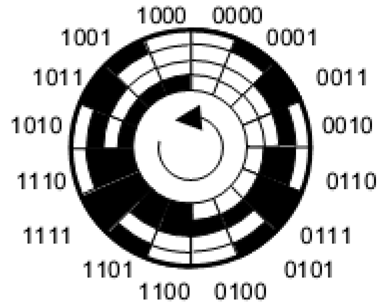
- Varies its voltage in response to a magnetic field
- Used as a proximity switch, to measure a full rotation of a wheel for example
- Used to measure rate of rotation of wheels

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/ı

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

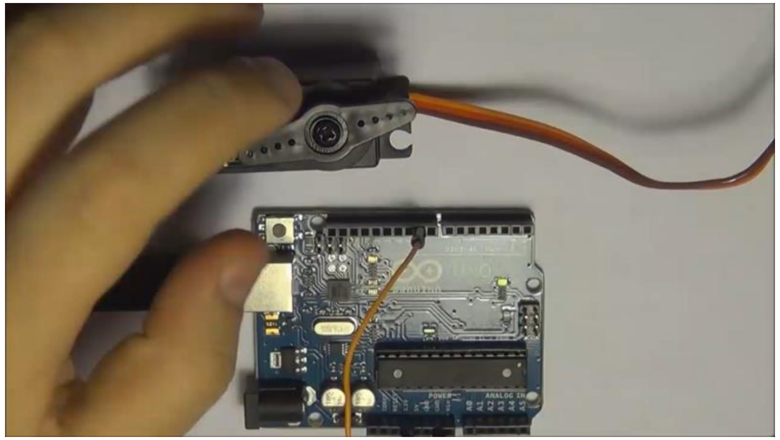


Gray code

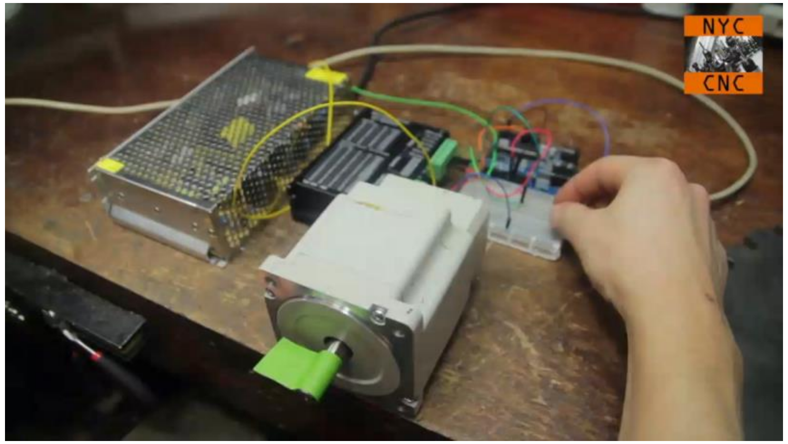
Example: flippers on the Aqua robot

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.

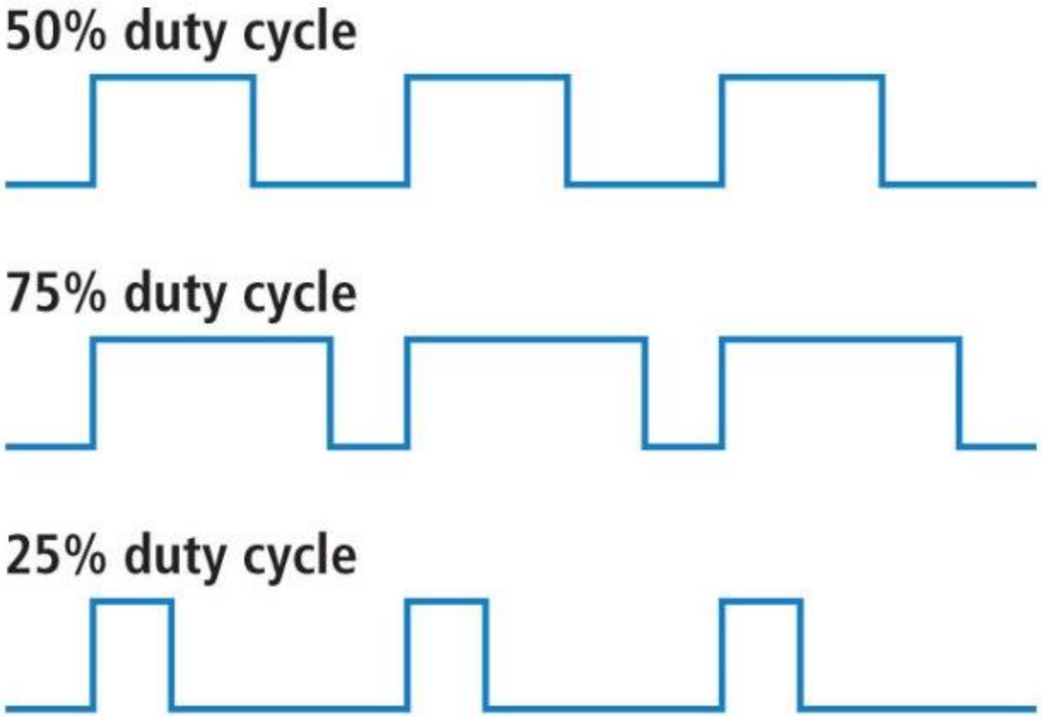


Servo motor
Usually includes: DC motor, gears, control circuit, position feedback
Precise control without free rotation (e.g. robot arms, boat rudders)
Limited turning range: 180 degrees



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