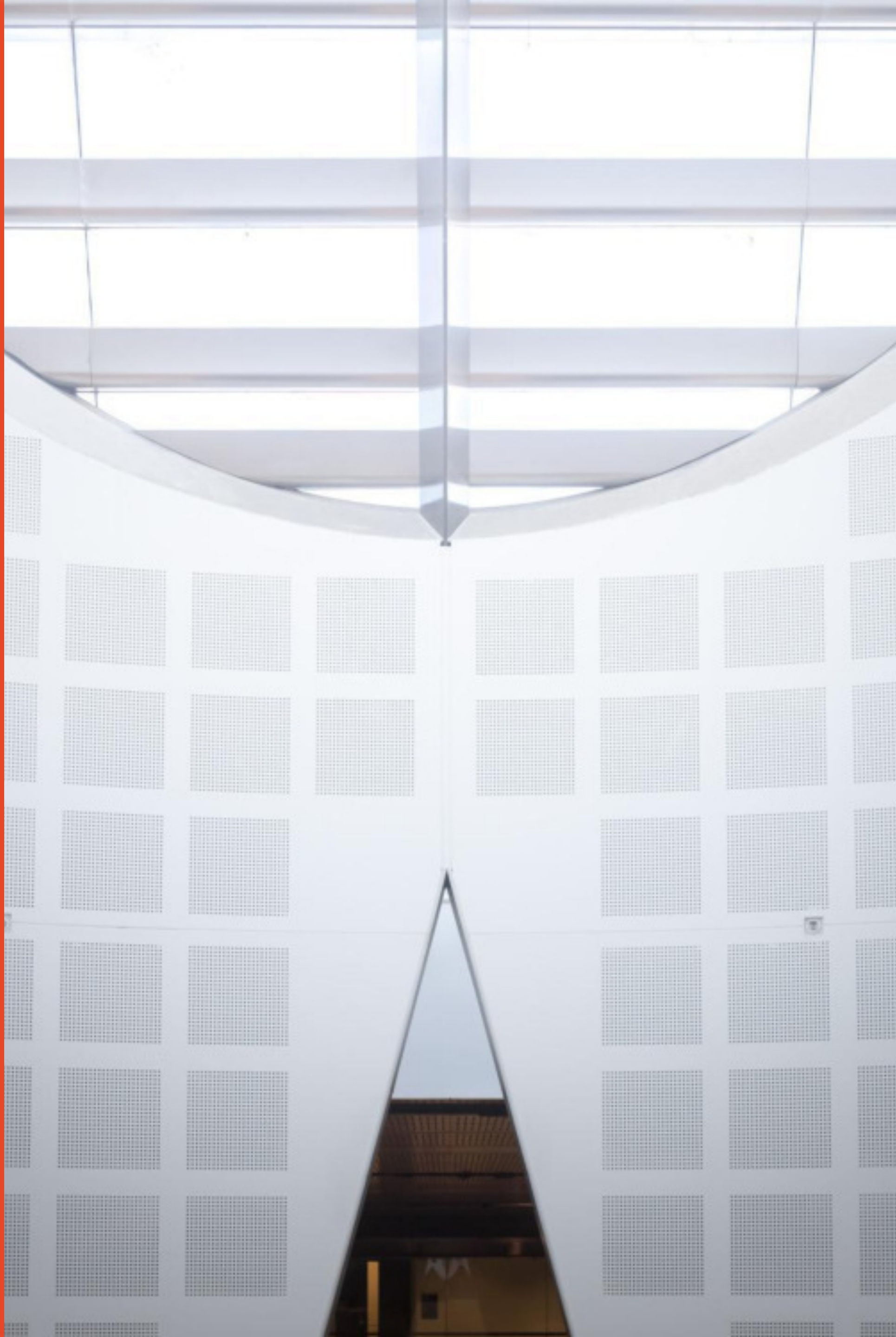
A1 - Sensors

AUSROS 2024
Donald Dansereau

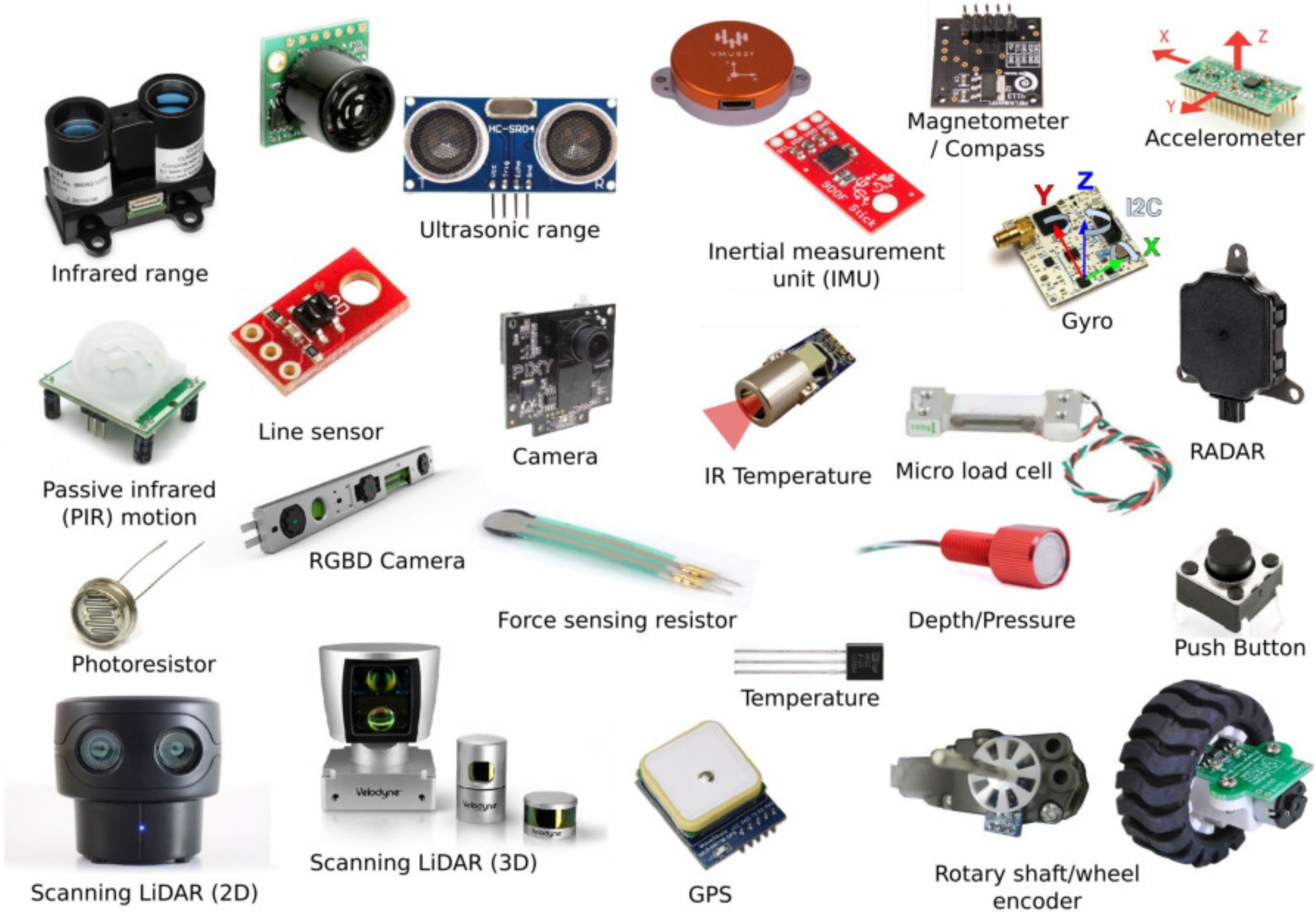


THE UNIVERSITY OF SYDNEY

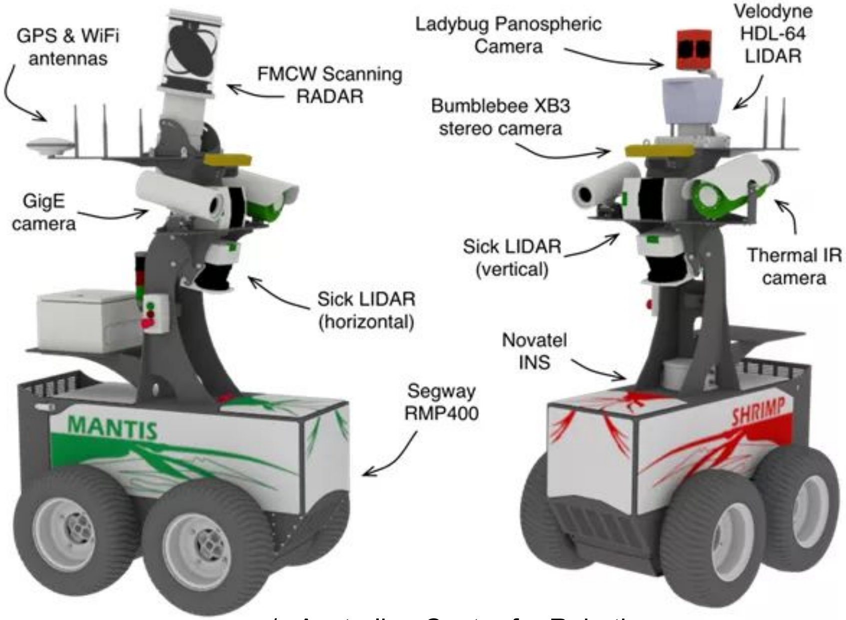
Understanding Sensors : Why Sense?

https://www.youtube.com/watch?v=g0TaYhjpOfo

Examples of Sensors

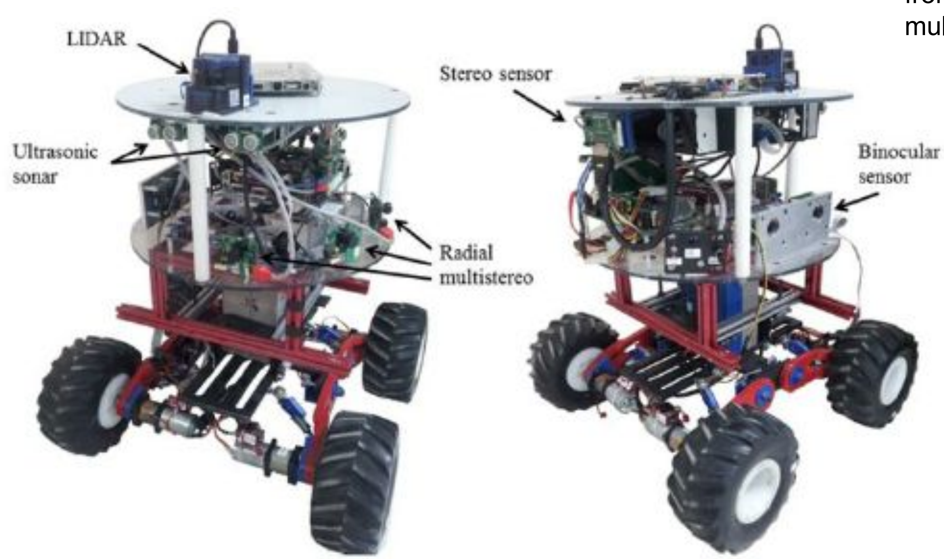


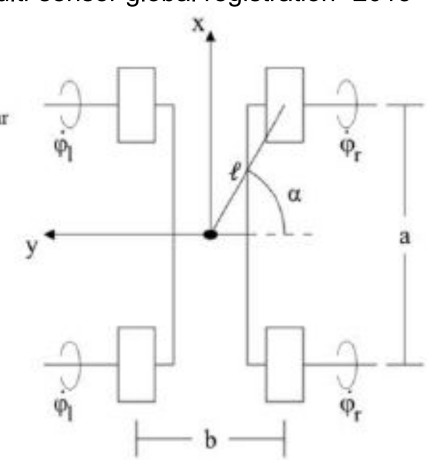
Examples of Sensor Suites



c/o Australian Centre for Robotics

from Rivero-Juarez et al "3D Heterogeneous multi-sensor global registration" 2013





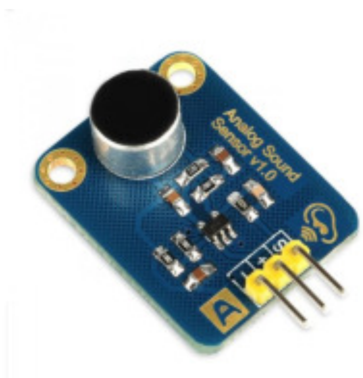
Types of Sensors: Proprioceptive vs Exteroceptive

Proprioceptive: about internal states

- Balance, acceleration
- Joint angles, wheel turns
- Humans: hunger Robots: battery level

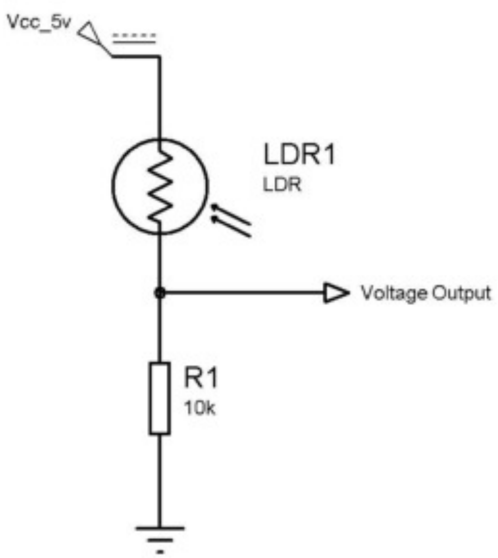
Exteroceptive: about external states

- Light, colour
- Temperature
- Magnetic, electric fields
- Sound
- SONAR, RADAR, LiDAR
- Chemical, gas
- Humidity
- Touch, force, pressure



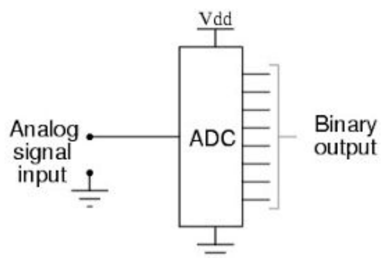
Types of Sensors: Analog vs Digital

At the core of all sensors is a *transducer* that transforms one physical phenomenon (temperature, pressure, light, sound) into another (resistance, capacitance, inductance)



A circuit then typically converts this into an analog *voltage*, e.g. via a terminating resistor

For digital systems, an analog-to-digital converter then converts to a digital signal



Some microcontrollers come with built-in analog-to-digital converters

Q: is a push-button switch an analog or digital sensor?

Types of Sensors: Synchronous vs Asynchronous

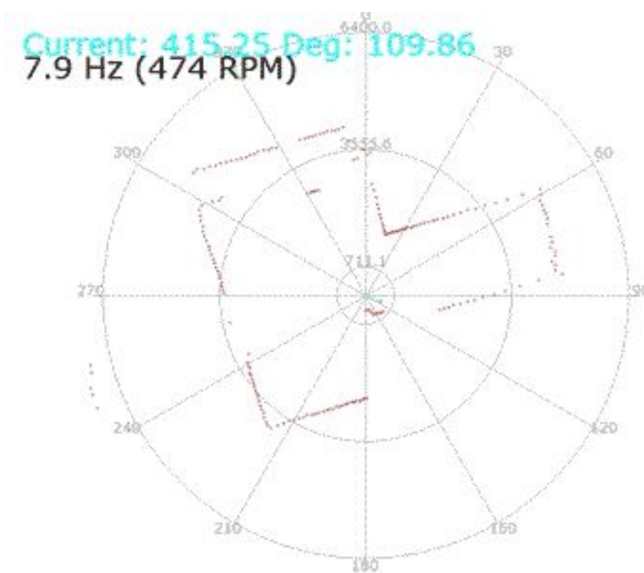
From the point of view of the system:

Synchronous capture

- Sensor is queried on a system-mandated schedule
- e.g. A camera with trigger line taking frames on a fixed schedule, synchronised to a flash

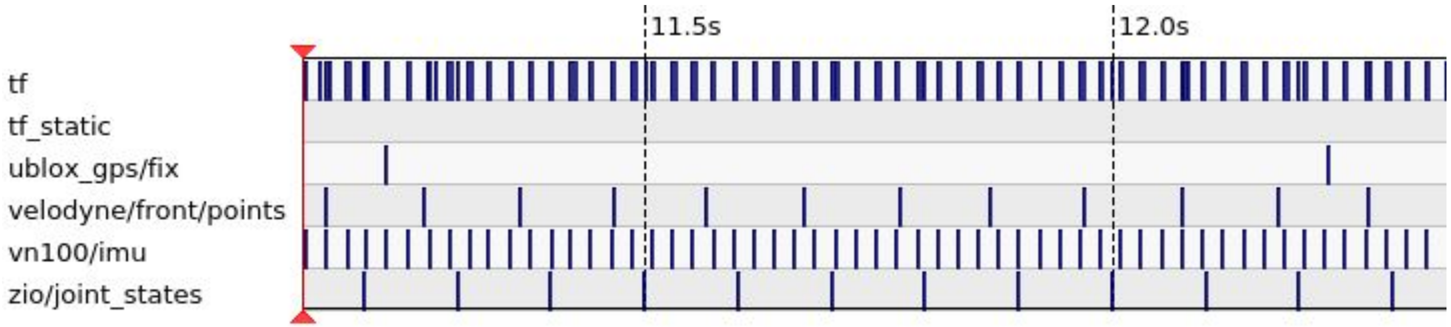
Asynchronous capture

- Sensor takes measurements on its own schedule
- Measurement timing can fluctuate, isn't easily synchronised to other sensors
- e.g. Spinning LiDAR, free-running camera



Reporting can also be synchronous or asynchronous. e.g. a camera with a trigger that captures synchronously, but sends imagery via an asynchronous network connection

Asynchronous Capture



Asynchronous sensing is common

Design for event-driven processing

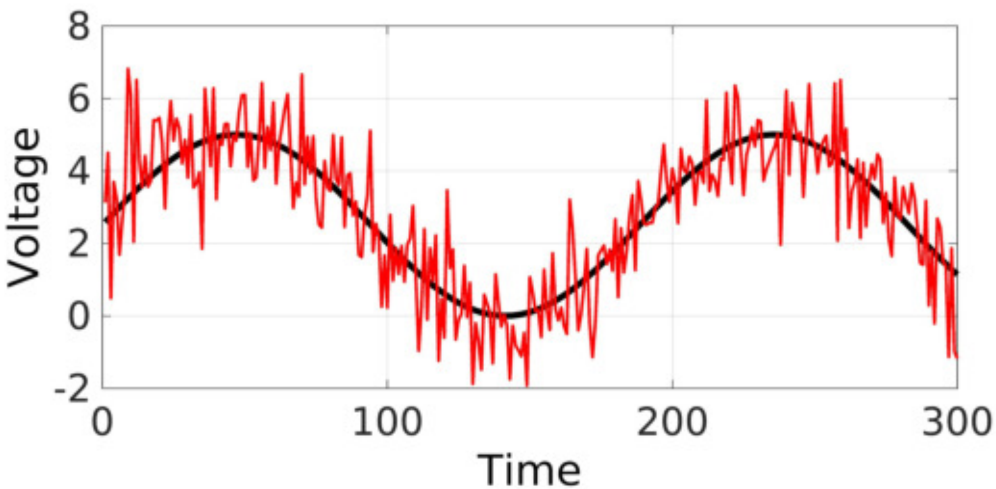
- Don't sit busy-waiting for one sensor to respond
- Process sensor reports as they arrive
- Don't assume sensors are temporally aligned

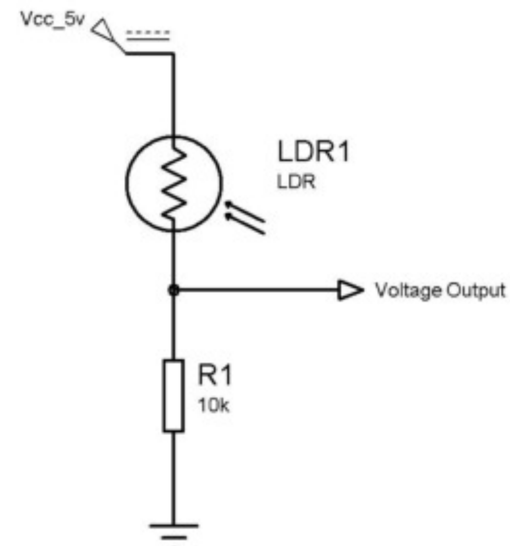
Account for variable timing

- e.g. calculating velocity from an irregularly spaced series of position measurements
- Timestamps are critical!

Non-Idealities: A Simple Experiment

- I built this circuit in my office…
- and measured the output on an oscilloscope.
- With nothing moving in the scene, what do you expect I measured?

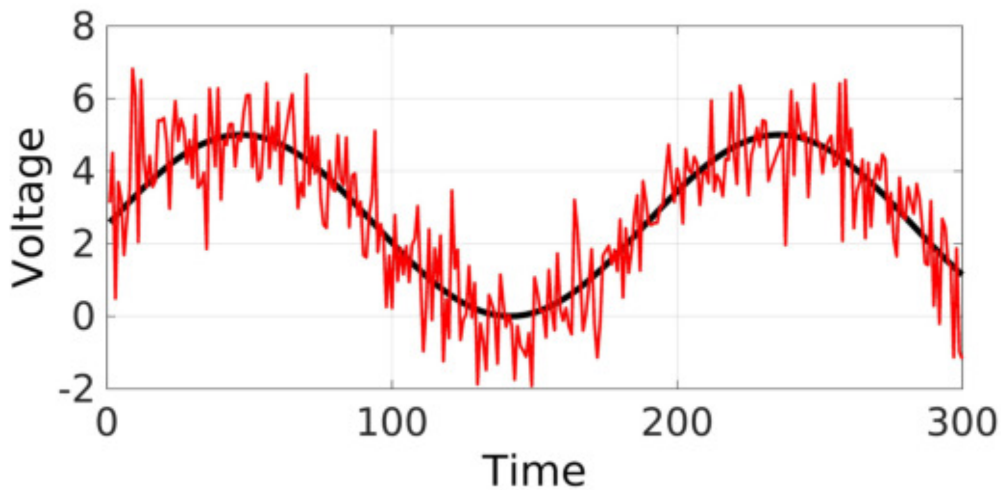


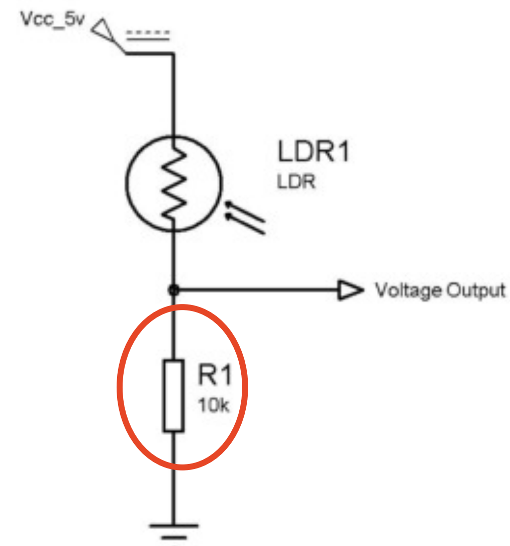


- What's causing the oscillation?
- Hint: it's at 100Hz (in my Australian office)
- What's causing the noise?

Non-Idealities: Thermal Noise

- Random thermal motion of charge carriers *inside the sensor and its analog circuitry*

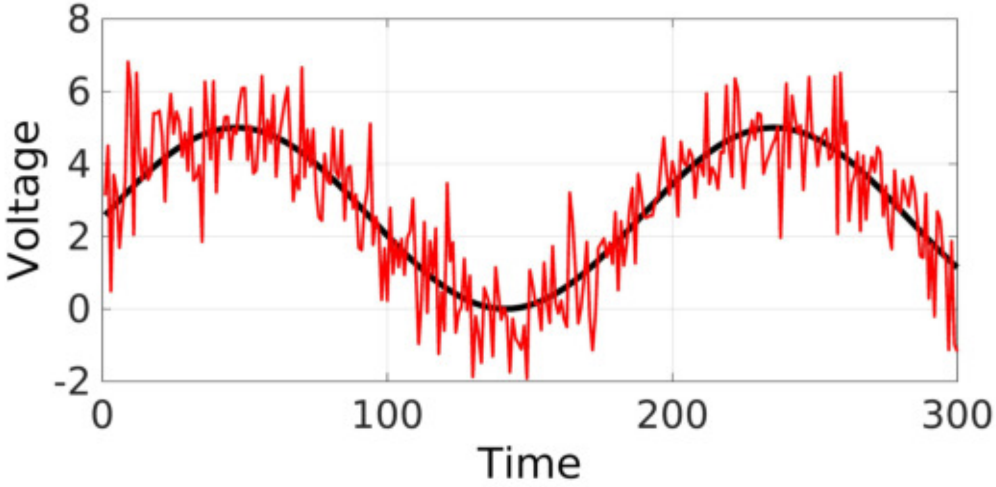


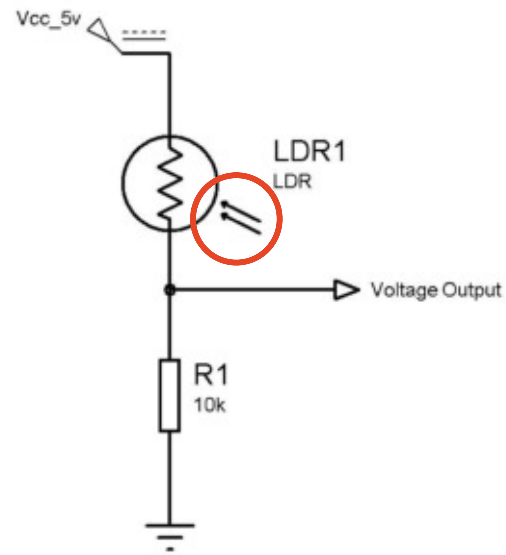


- Present in all electronic components above absolute zero
- Terminating resistors are a major and unavoidable source
- Generally modelled as additive, white, and Gaussian
  - White: Equal power at all frequencies
  - Gaussian: Amplitude follows a Gaussian distribution

Non-Idealities: Noise *in the Scene* ?

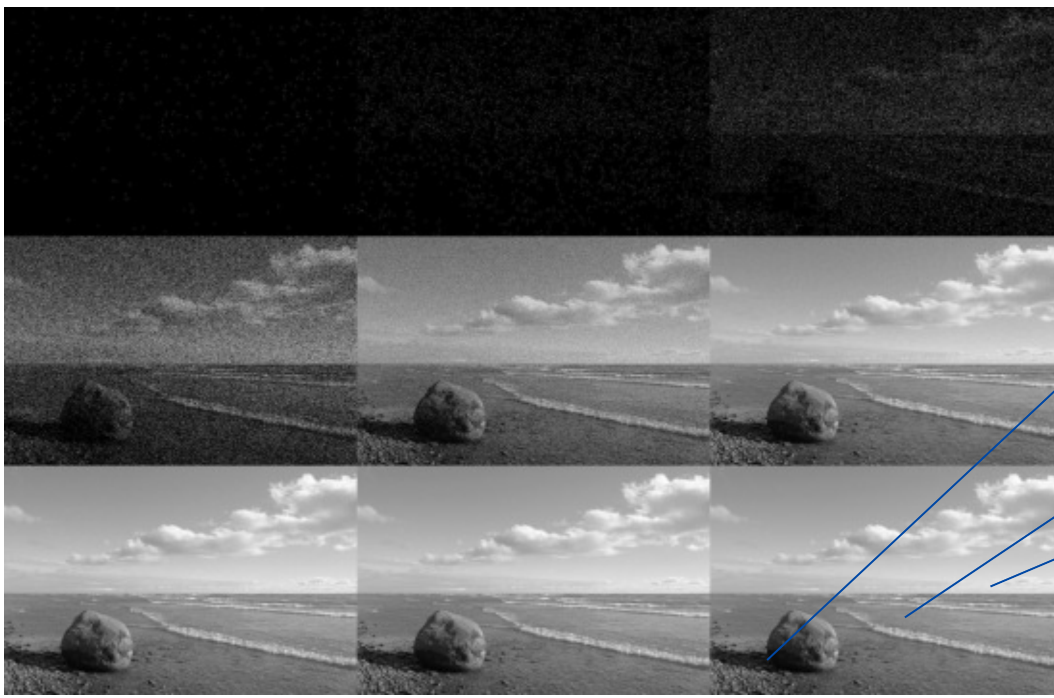
- Random fluctuation in every *counted, random* event
- Poisson-distributed

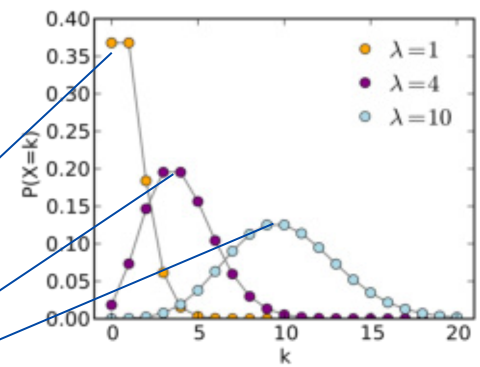




Poisson Noise

- …or when sensing light “Photon noise”
- Characteristic of the signal, not the sensor
- e.g. lightning strikes in a year, photons arriving at a sensor
- Variance = mean; stronger signal = *more* variance!

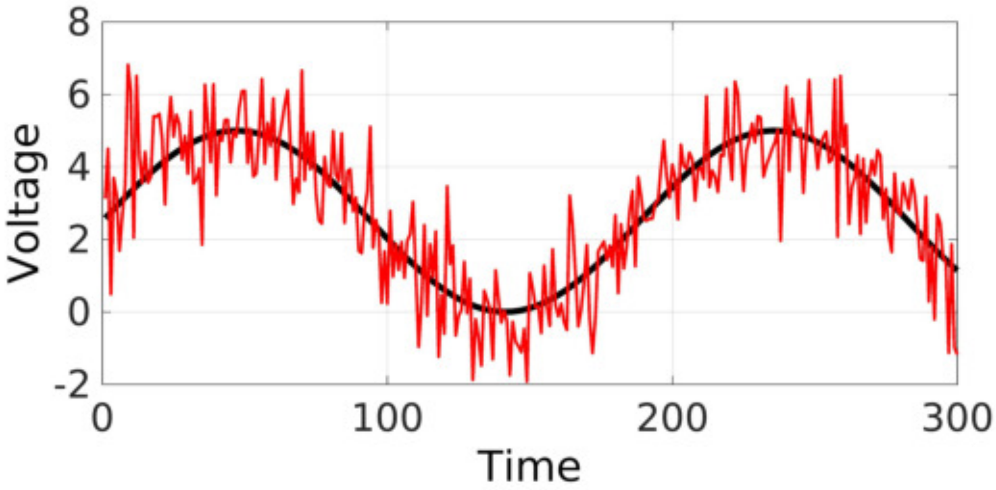


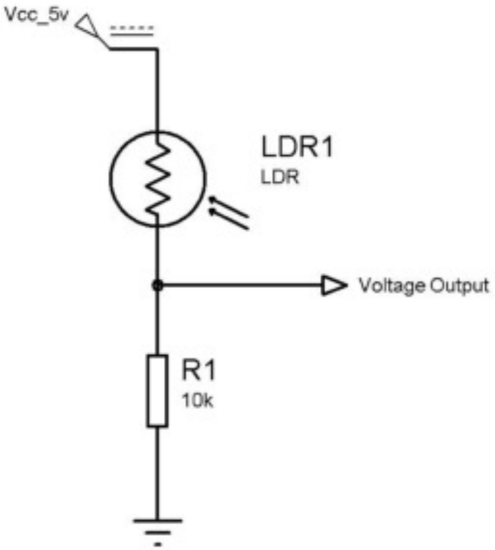


[https://commons.wikimedia.org/wiki/File:Photon-noise.jpg]

Non-Idealities: Model Error

- My assumptions about the world were wrong

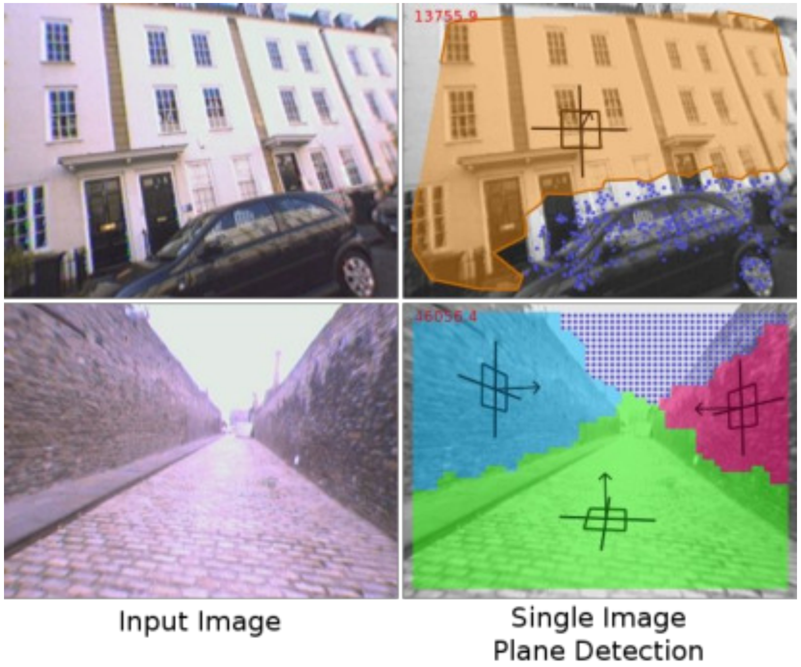




- My office has fluorescent lights
- These fluctuate with the power supply, 50Hz
- The fluctuation is with power not voltage, thus 100Hz
- Could be considered model error or interference

Model Error

- Simplification of reality to make system design tractable
- e.g. assuming flat terrain and zero-slip wheels when performing dead reckoning with wheel counts
- Colloquially sometimes called “noise”. It’s not, it’s a real difference between reality and our approximations of reality!



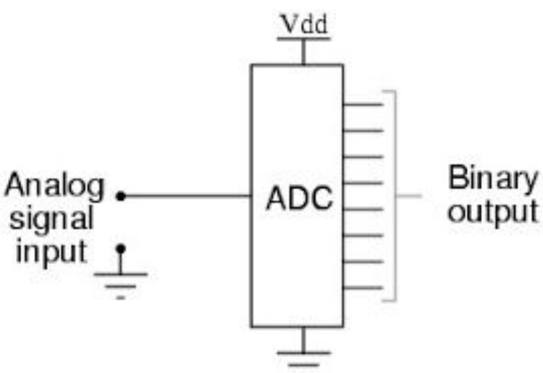
[Haines & Calway 2015 "Recognising planes in a single image"]

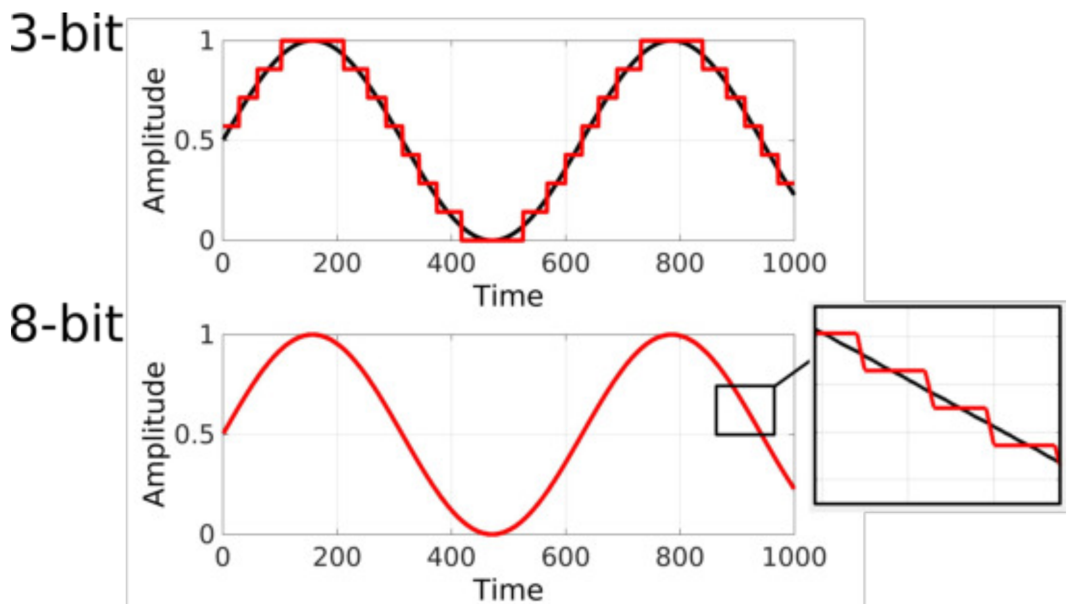
Interference

- An unwanted signal coupling onto a sensor
- Can come from the outside world (strong radio, light, sound sources)…
- … or inside the robot (active sensors interfering with each other, unwanted electrical coupling between components)
- Colloquially sometimes called “noise”. It’s not, it’s a real signal!

Non-Idealities: Quantization

- Introduced at analog-to-digital conversion
- Digital signals approximate continuous signals with a fixed set of levels
- More bit-depth = less quantization error

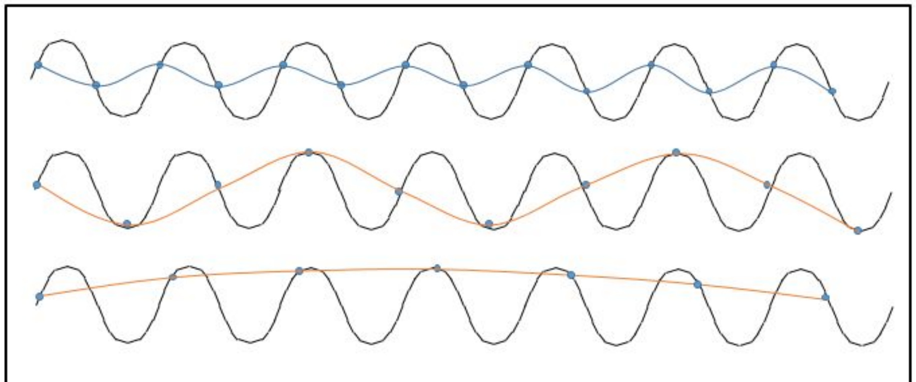




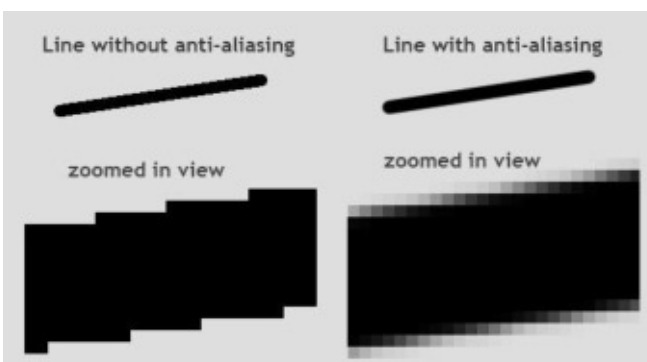
An ideal analog sine wave (black) sampled by 4-bit and 8-bit ADCs (red)

Non-Idealities: (Frequency) Aliasing

- When a signal at one frequency appears as though it were at another
- Comes from sampling a signal at discrete moments
- Often best dealt with by anti-aliasing filters *at capture time*
  - Average measurements over a window - lowpass filter
- It's predictable so can be useful
  - Measure high frequency events with low-frequency sensor

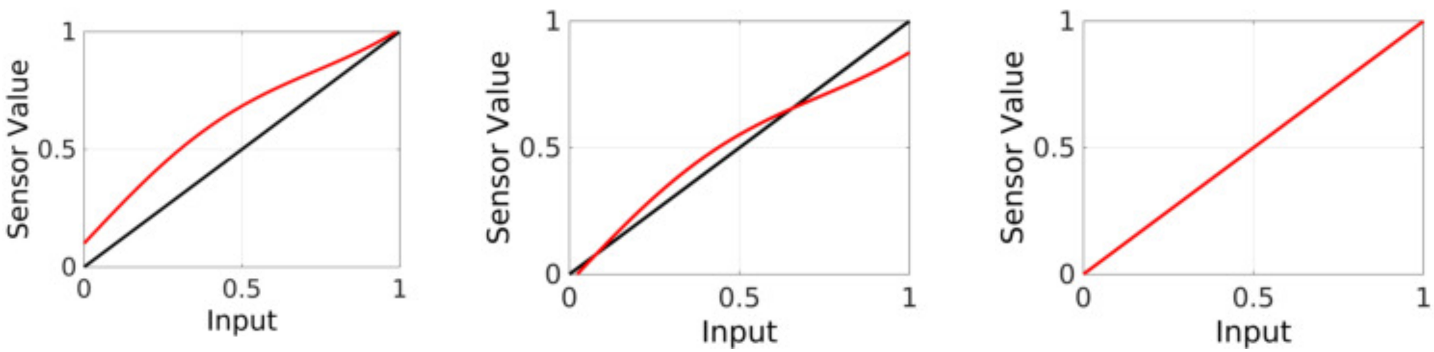


Aliasing Examples



Non-Idealities: Non-linearity, scaling, and bias

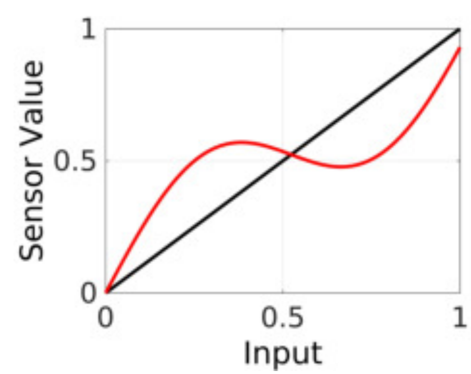
- Bias: additive offset from ideal
- Scaling: multiplicative offset from ideal
- Non-linearity: warped / deviated with respect to ideal
- These non-idealities can sometimes be reduced or eliminated through *"intrinsic"* calibration, measuring the sensor's *internal* behaviour



Black: ideal
Red: measured

A sensor with no calibration, bias removal, and ideal calibration

Q: Could this sensor be perfectly corrected through calibration?



Aleatoric vs Epistemic Uncertainty

<u>Aleatoric</u>

Due to random, unpredictable events

e.g. thermal noise, Poisson noise

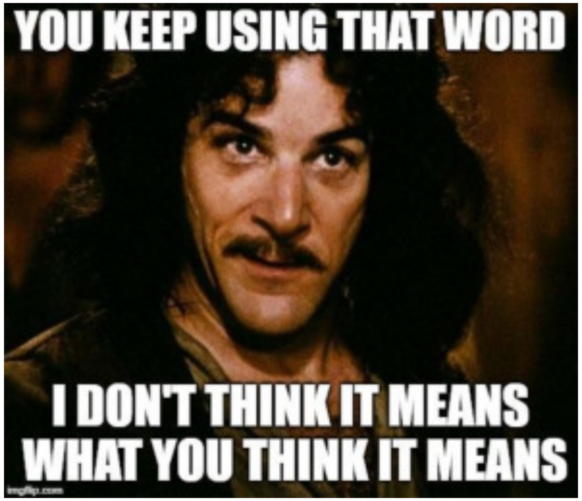
From “alea”, dice

<u>Epistemic</u>

Due to incomplete knowledge about the world

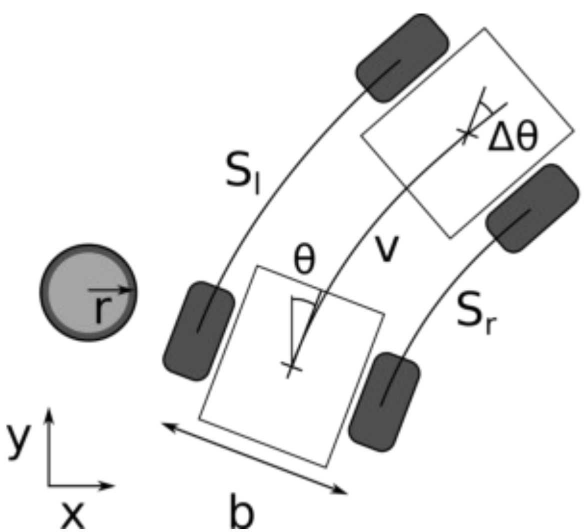
e.g. model error, calibration error

from Greek “epistēmē”, knowledge

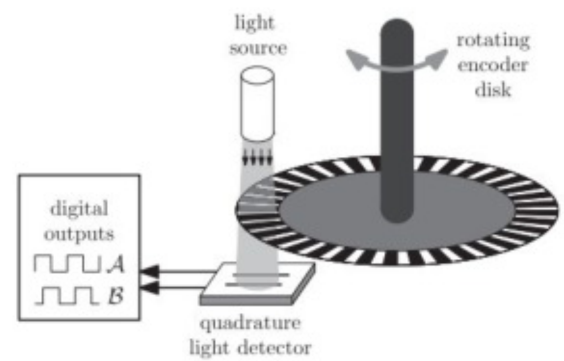


Example: Odometry From Wheel Encoders

- Dead reckoning (sometimes “deduced” or “ded” reckoning, it’s debated whether this is the original sense)
- Counting wheel turns tells you how far you’ve driven
- Differencing left and right wheels tells you how you’ve turned
- Lots to know about using this well



$$v \approx 2\pi r(S_l+S_r)/2$$
$$\Delta\theta \approx 2\pi r(S_l-S_r)/b$$
$$\Delta x \approx v \sin(\theta)$$
$$\Delta y \approx v \cos(\theta)$$

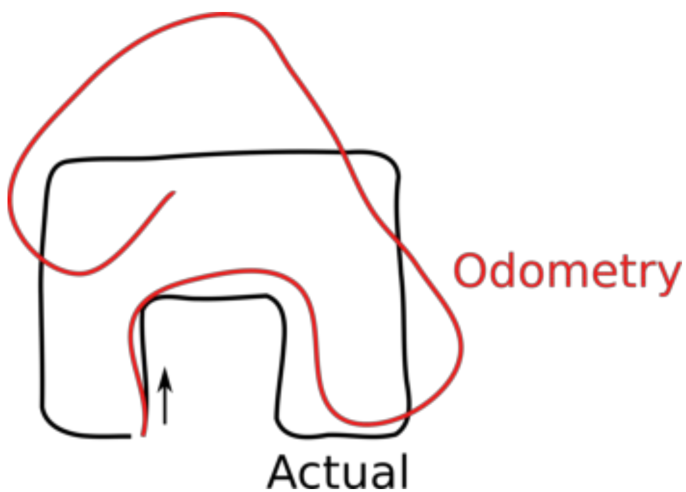


https://bharat-robotics.github.io/blog/dc-motor-speed-control/

Example: Odometry From Wheel Encoders

Problem: Over long periods, odometry error grows, why?

- *Sensor noise? (Thermal? Poisson? Quantisation?)*
- Miscalibration: baseline, wheel size
- Model error: Wheel slippage, irregular terrain, wheel compression
- Interference: wind, unruly students
- Small angular errors result in large position error over time
- Error accumulates without bound



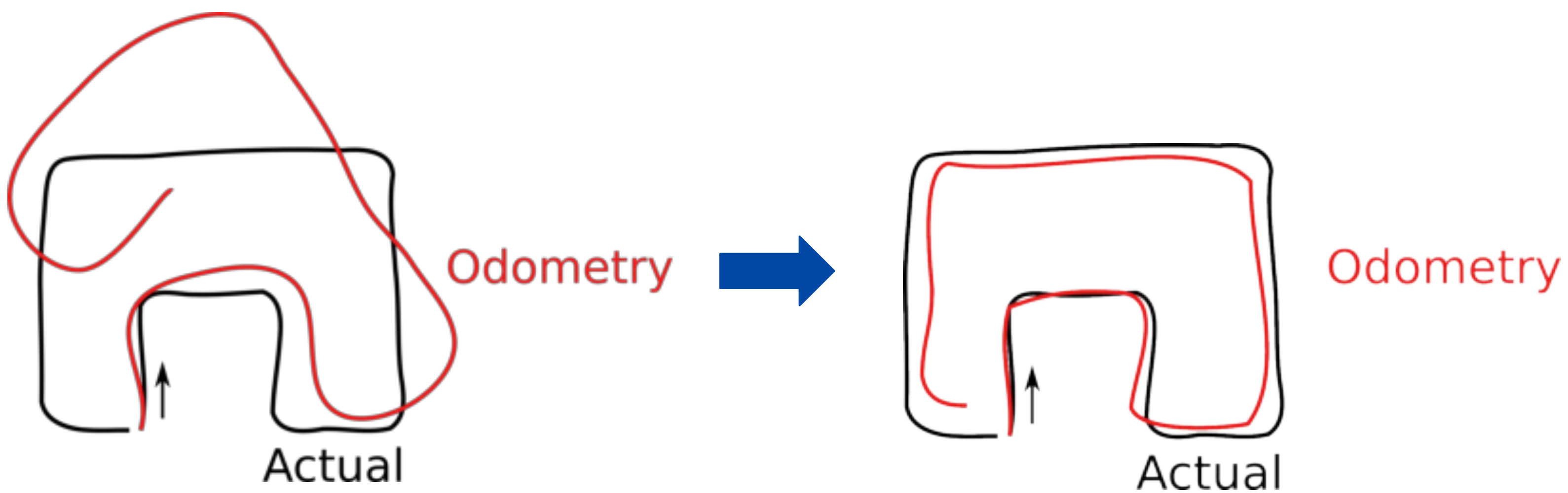
Complementary Sensors and Sensor Fusion

Take the most useful characteristics of each sensor and combine them in a joint solution

- Complementary filter *(think "smart averaging")*
- Kalman filter *(think "fancy averaging that knows about noise/uncertainty")*
- Generally requires relative pose between sensors, *"extrinsic"* calibration

A very simple example:

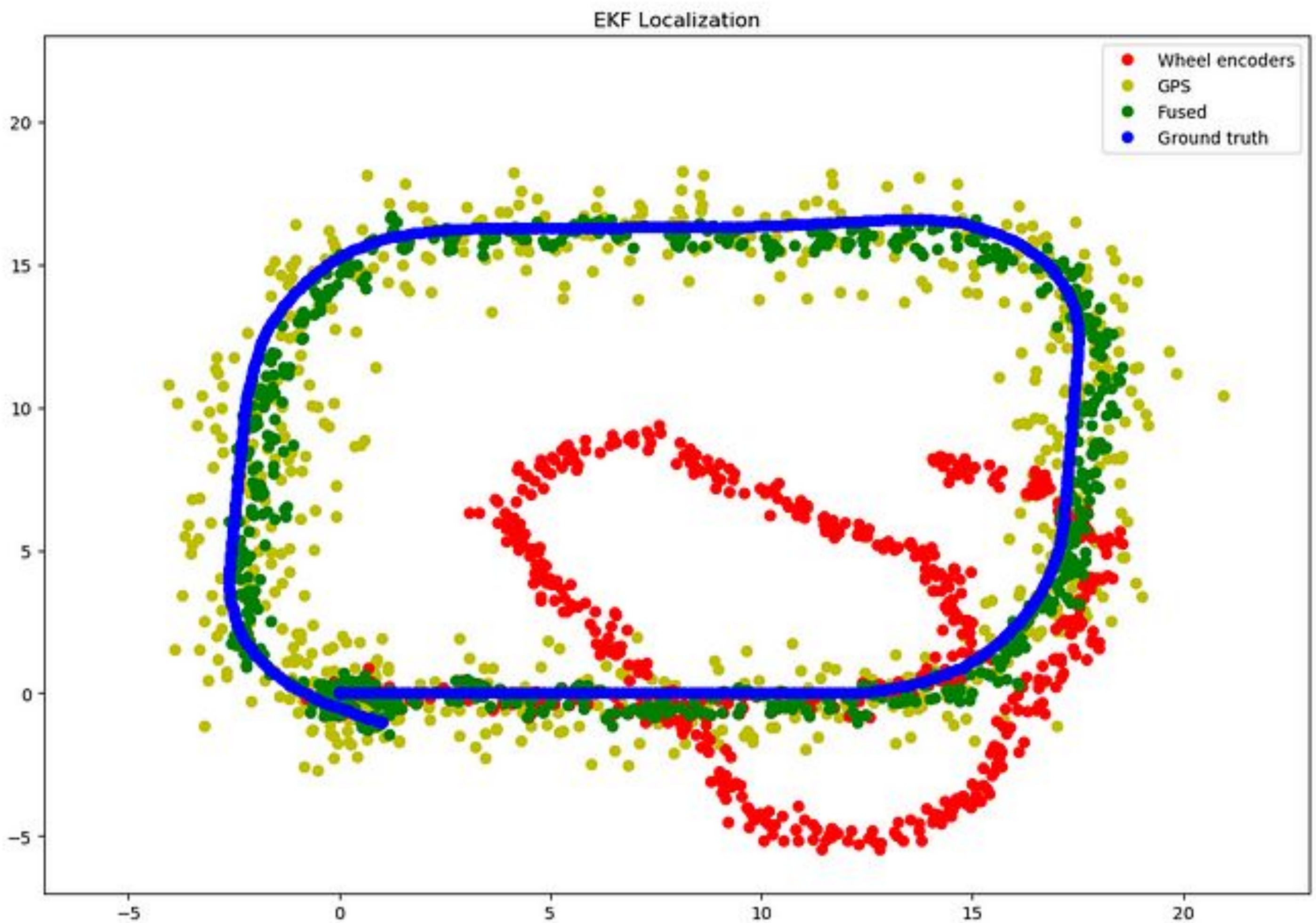
- Wheel turns for distance travelled - locally pretty good
- Compass for direction - direction error doesn't accumulate



Example Complementary Sensors

GPS: short-term noisy, long-term stable

Wheel odometry: short-term accurate, long-term accumulates error

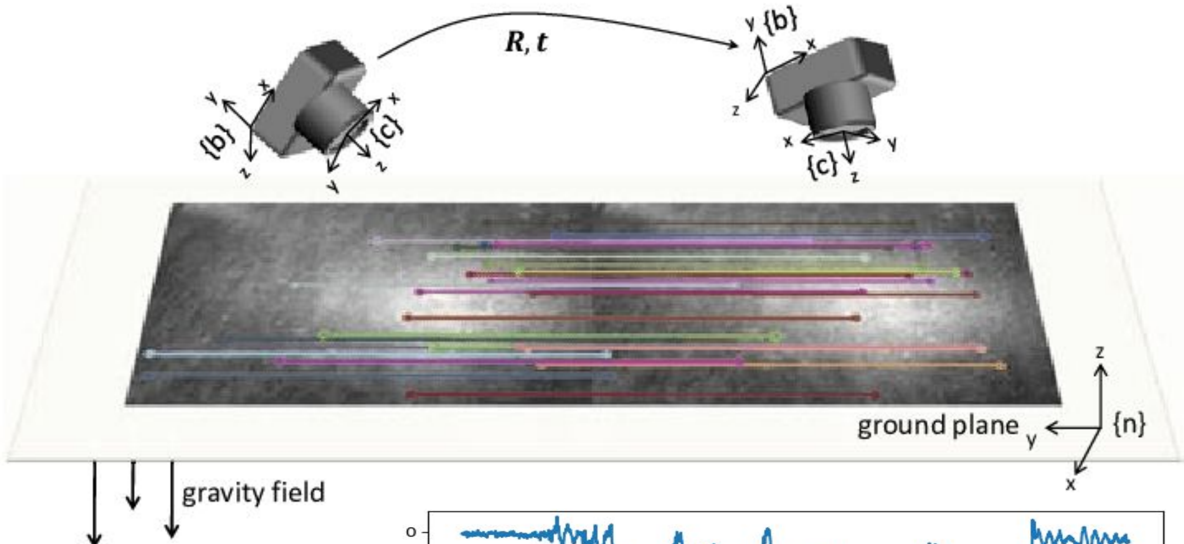


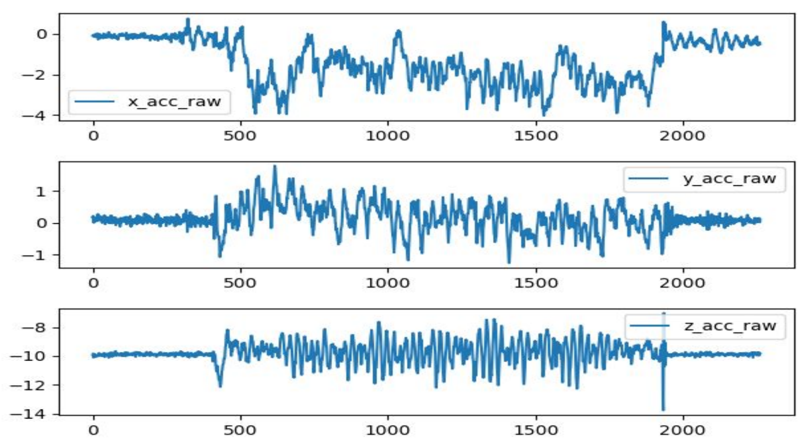
https://www.blackcoffeerobotics.com/blog/gps-based-localization-for-self-driving-robots

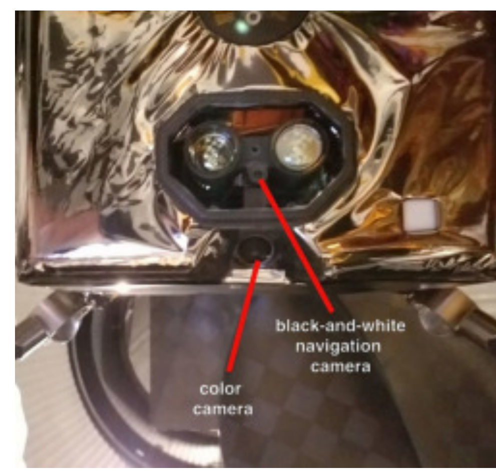
Example Complementary Sensors

Camera: low frequency, no drift

IMU: very high frequency, some stable (compass / gravity), some drift







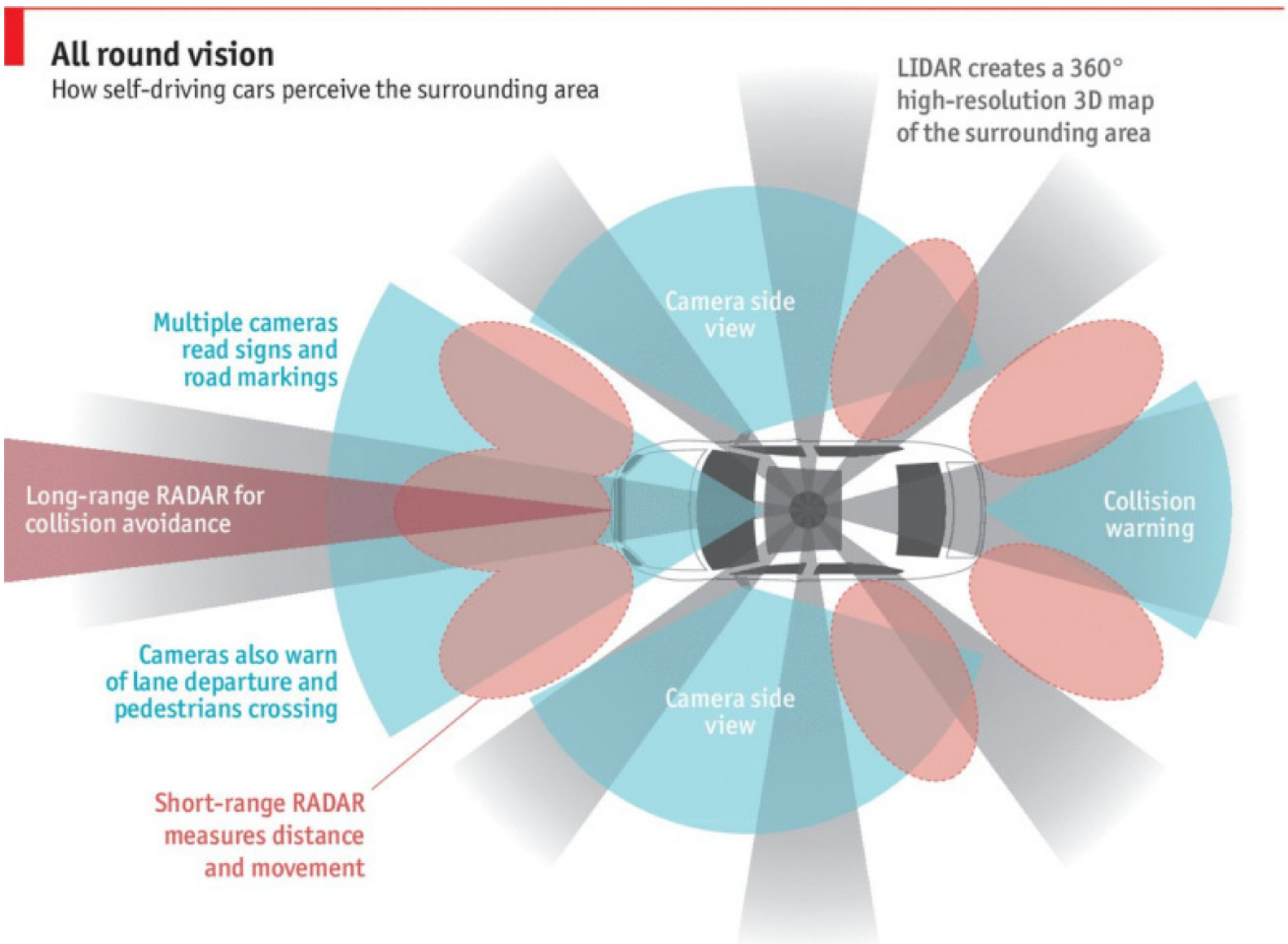
Example Complementary Sensors

LiDAR: colour-blind, depth

Camera: “depth-blind”, colour

[wang2023]

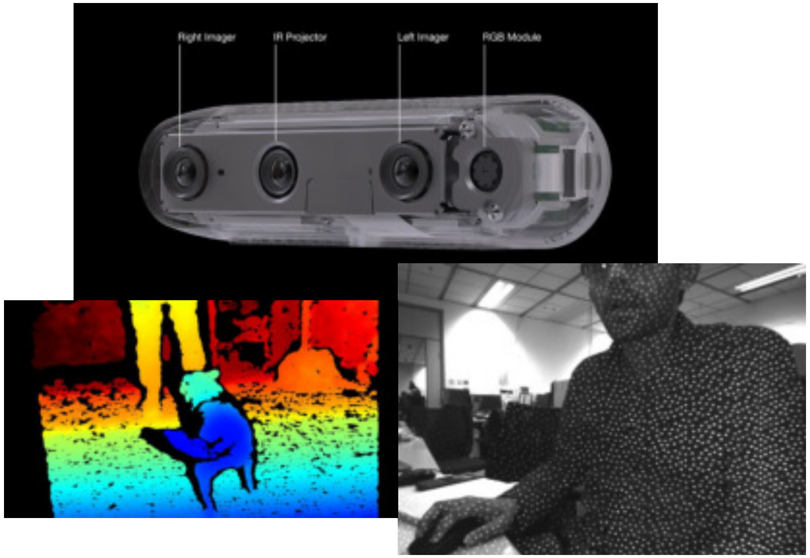
Example Complementary Sensors



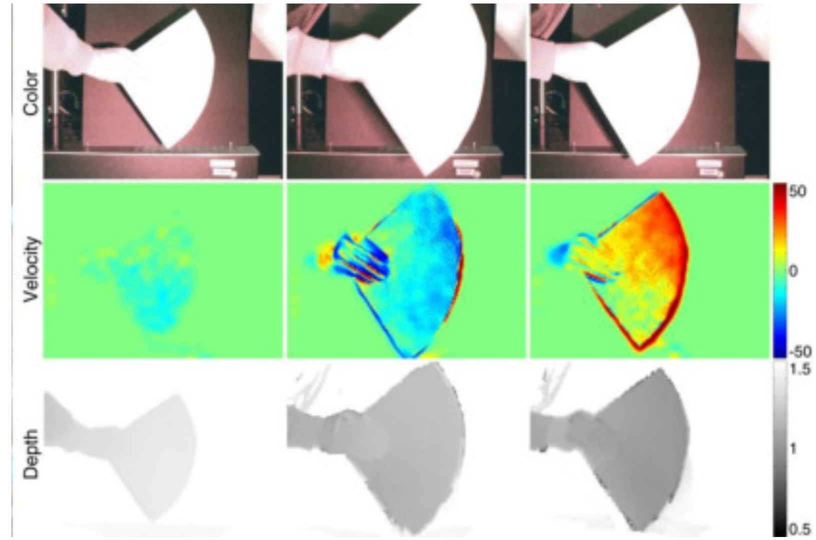
https://www.economist.com/graphic-detail/2018/03/02/self-driving-cars-need-plenty-of-eyes-on-the-road

Modern and Emerging Sensors

[Active] Stereo

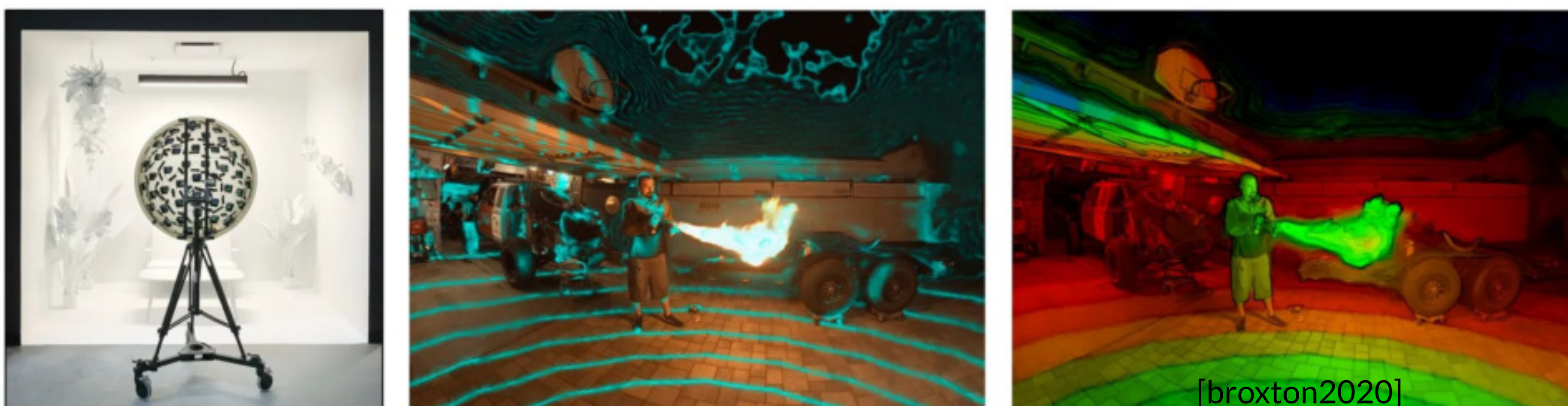


[Doppler] Time of Flight



[heide2015, zhang2020]

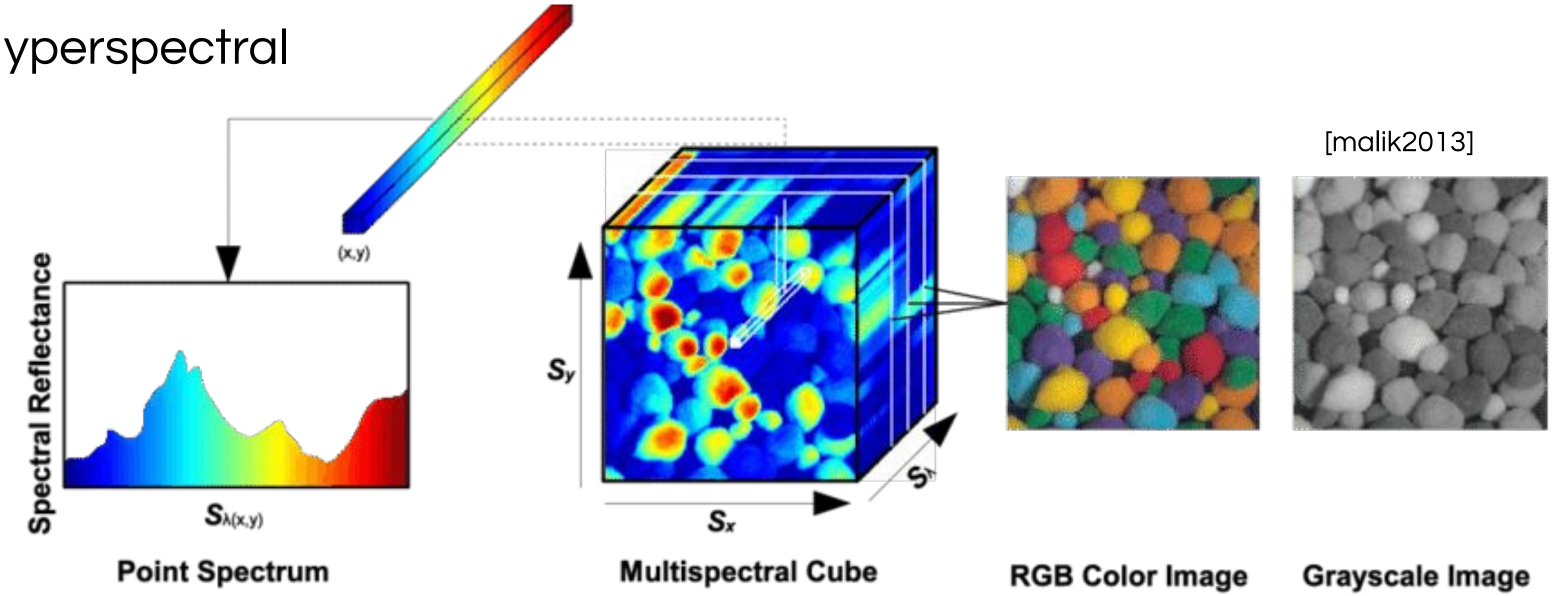
Light Field



(a) Capture Rig (b) Multi-Sphere Image (c) Layered Mesh Representation

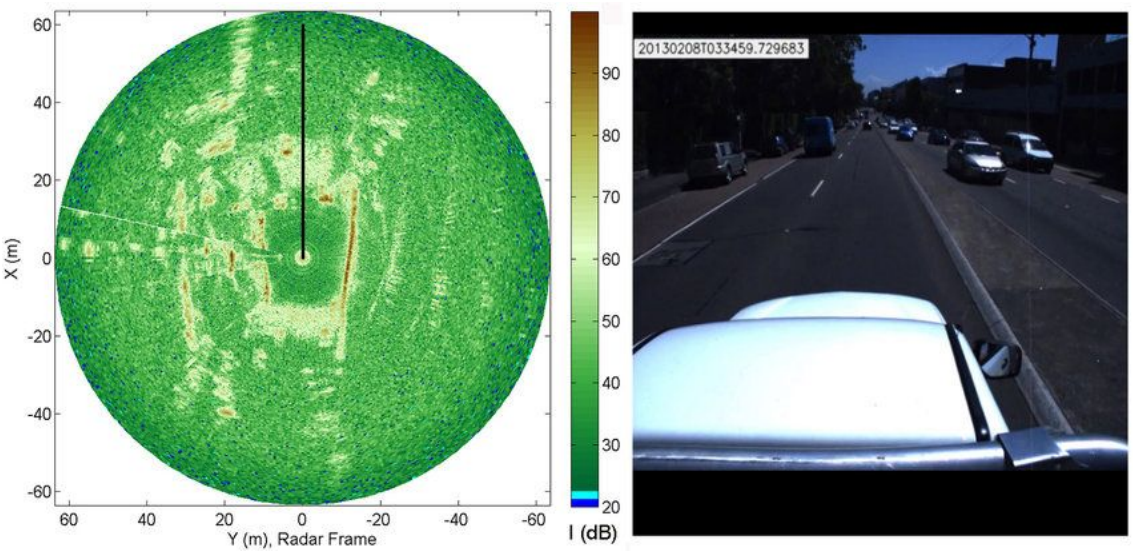
Modern and Emerging Sensors

Hyperspectral



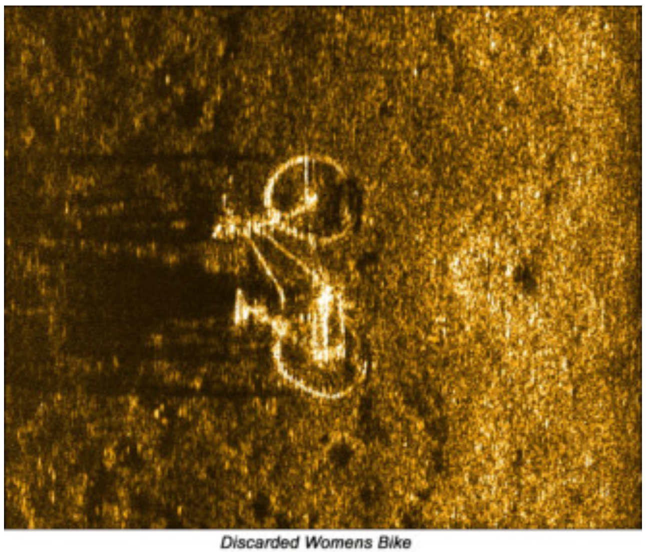
[malik2013]

Radar



[reina2015]

Sonar



Sensors

Kids of Sensors:

- Proprioceptive, Exteroceptive
- Active vs. Passive
- Analog, Digital
- Synchronous, Asynchronous

Non-Idealities:

- Model error, thermal noise, poisson noise
- Quantisation, aliasing, interference
- Non-linearity, scaling, bias
- Calibration
- Aleatoric vs epistemic uncertainty

Example: Odometry From Wheel Encoders

Complementary Sensors and Sensor Fusion

Example Complementary Sensors

Modern and Emerging Sensors