ECE 4960

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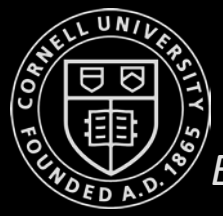
Fast Robots



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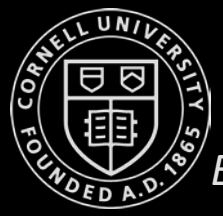
Tuesday (today):

1. Summary of lab workflows
2. Intro to Sensors
3. Distance Sensors
4. Odometry and errors
5. Sensor fusion

Thursday:

1. IMU and practical implementation
2. Discuss Lab 3



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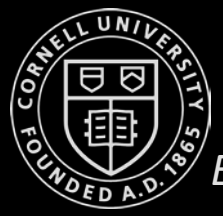
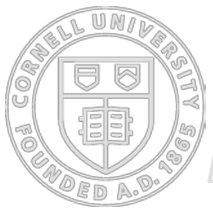
LAB WORKFLOW



ECE 4960: Lab Workflow

In this course, the lab exercises can be broadly grouped under three types:

1. **Python programming:**
   - **Simulation:** Program your virtual robots
   - **Offboard Processing:** Offload processing to your computer by sending and receiving data to/from your real robot using the Bluetooth module
2. **Arduino Programming:** Program the Artemis board on the real robot



ECE 4960: Lab Workflow

Workflow A

If you are not very comfortable with using Ubuntu and your VM is a bit sluggish, **this is the recommended minimal use of VM.**

HOST OS	Ubuntu VM
Arduino Programming	Simulation Programming Offboard Programming

Workflow B

In case your bluetooth module does not work with your Ubuntu VM, this is the bare-minimal use case for the VM.

HOST OS	Ubuntu VM
Offboard Programming Arduino Programming	Simulation Programming

Workflow C

If your VM is buttery smooth and you are comfortable with using Ubuntu, the **VM can serve as a one-stop shop** for all your needs! Setup Github in it and you don't even need to a shared folder with your Host OS.

HOST OS	Ubuntu VM
	Simulation Programming Offboard Programming Arduino Programming

ECE 4960: Lab Workflow

Workflow X

- This is a workflow for students who are comfortable with a UNIX based OS, the command line interface, and have taken a painstakingly long time to perfect a custom work environment in their Host OS.
- It essentially involves the following steps:
  a. Mount the VM's file system on your Host OS
  b. SSH into your VM with X forwarding
  c. Run the VM headless to reduce load on your system
- This way you can always stay in your Host OS, have access to all the files in the VM, and use X11 forwarding to get the GUI apps to show up in your Host OS
- References:
  a. SSH into VM: https://unix.stackexchange.com/questions/145997/trying-to-ssh-to-local-vm-ubuntu-with-putty
  b. MacOS file system mounting: https://osxfuse.github.io/
  c. Running VM in headless mode: https://superuser.com/questions/1153939/start-a-vm-in-virtualbox-without-gui

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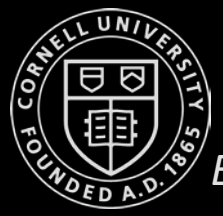
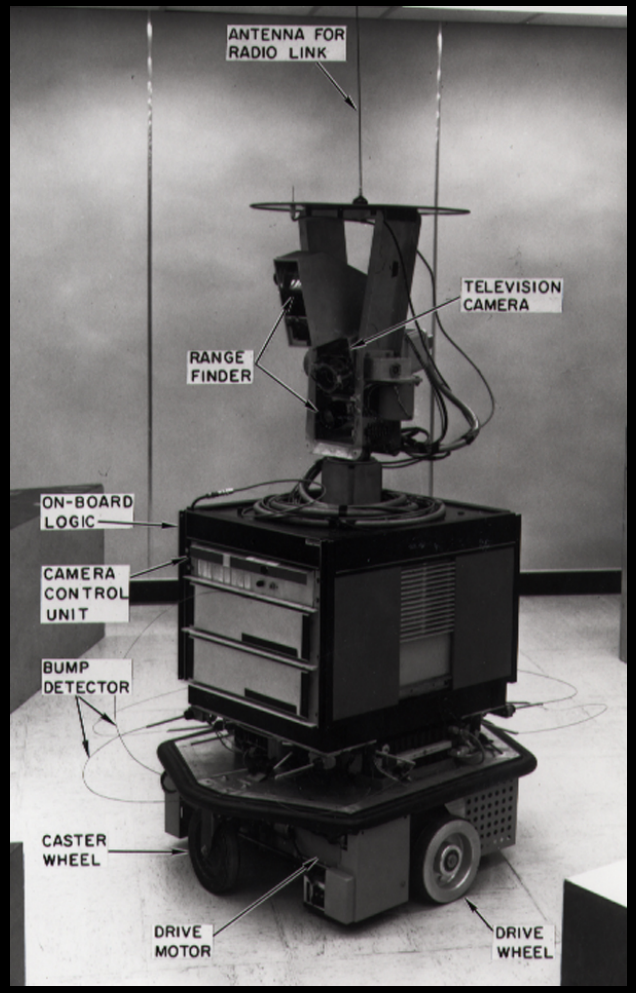
SENSORS



History



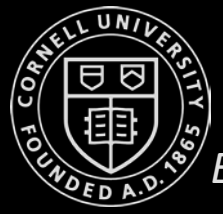
Shakey: Experiments in Robot Planning and Learning (1972), SRI

Sensor Classification

- **Proprioceptive**
  - Motor speed, wheel load, joint angles, battery voltage
- **Exteroceptive**
  - distance measurements, light intensity, sound amplitude
- **Passive Sensors**
  - Measure ambient environmental energy
  - E.g. temperature probes, microphones, light sensors
- **Active Sensors**
  - Senses reaction to emitted energy
  - E.g. wheel quadrature encoders, ultrasonic sensors, laser rangefinders

Classification

Type	Sensor	Prop/Exte	Passive/Active
Tactile (contact/closeness)	Contact switches, bumpers, Break beams, proximity Capacitive	Exteroceptive Exteroceptive Exteroceptive	Passive Active Both
Wheel/motor	Brush encoders Potentiometers Optical encoders Magnetic/inductive/capacitive encoders	Proprioceptive Proprioceptive Proprioceptive Proprioceptive	Passive Passive Active Active
Active ranging	Reflectivitiy sensors, ultrasonic, laser rangefinders, optical triangulation, etc.	Exteroceptive	Active
Heading	Compass Gyroscopes	Exteroceptive Proprioceptive	Passive Passive
Ground based beacons	GPS, RF, reflective beacons	Exteroceptive	Active
Motion/speed	Doppler radar, sound	Exteroceptive	Active
Vision	CCD/CMOS	Exteroceptive	Passive

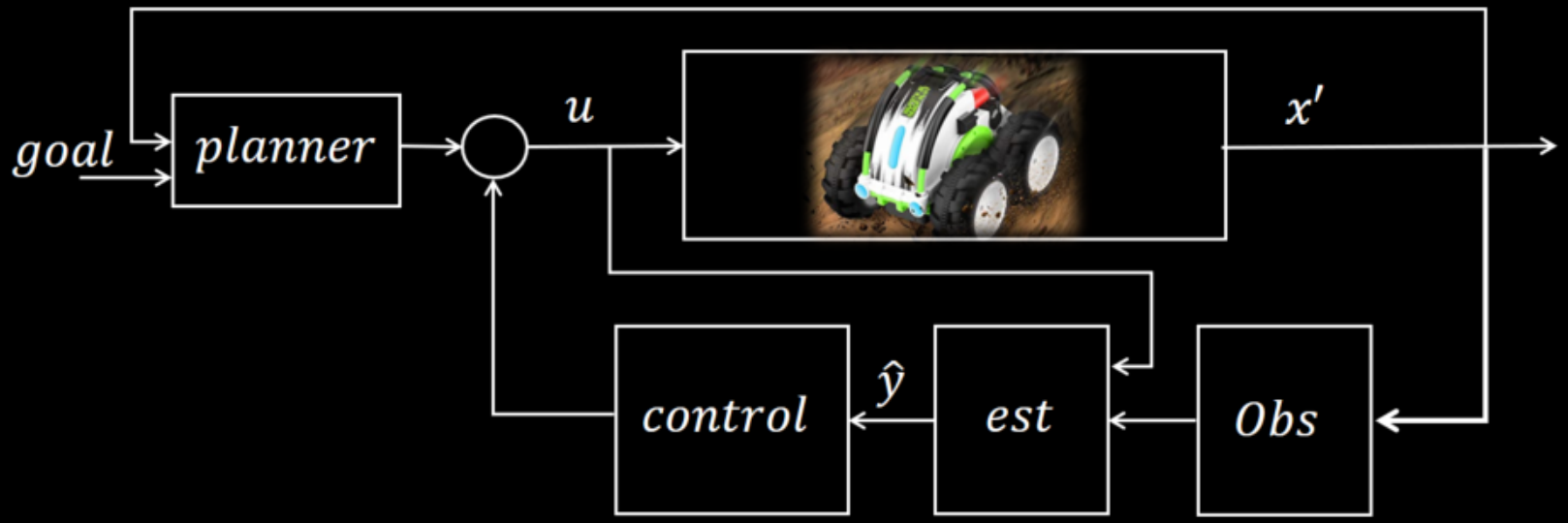


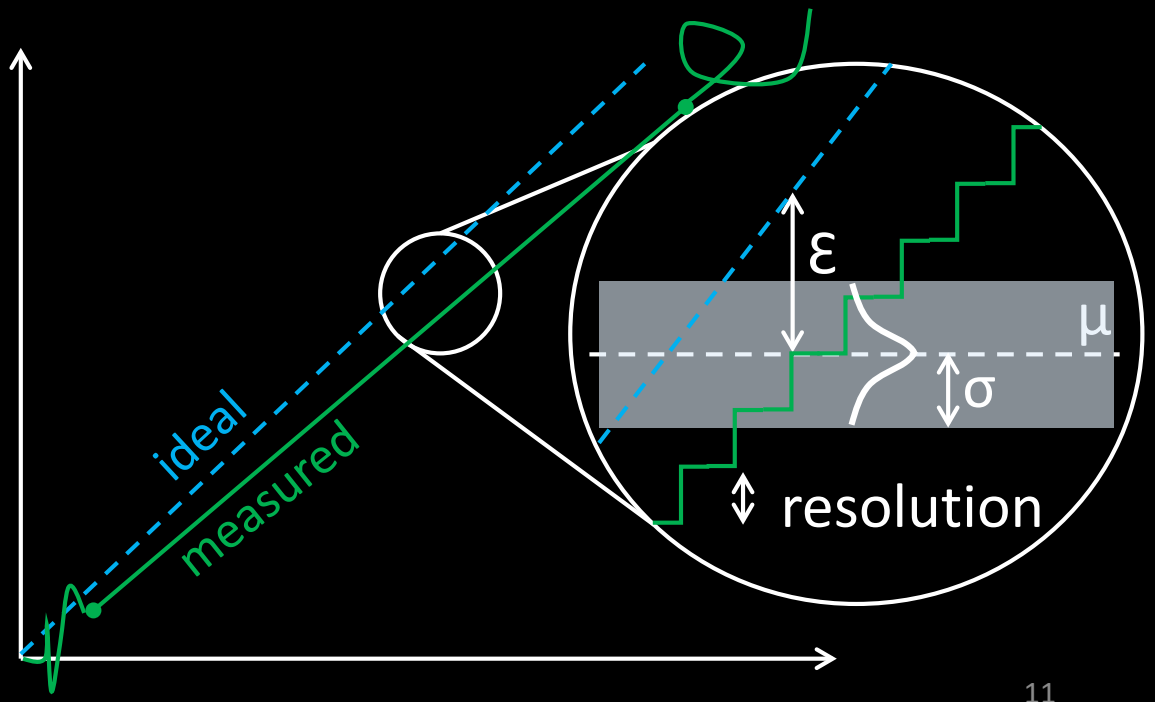
Sensor Characteristics

Name some examples

- Dynamic Range [dB]
- Range
- Resolution
- Linearity
- Bandwidth / Sampling Frequency

- Sensitivity
- Cross-sensitivity
- Accuracy
- Precision
- Error
  - Systematic
  - Random





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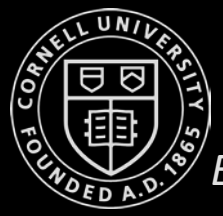
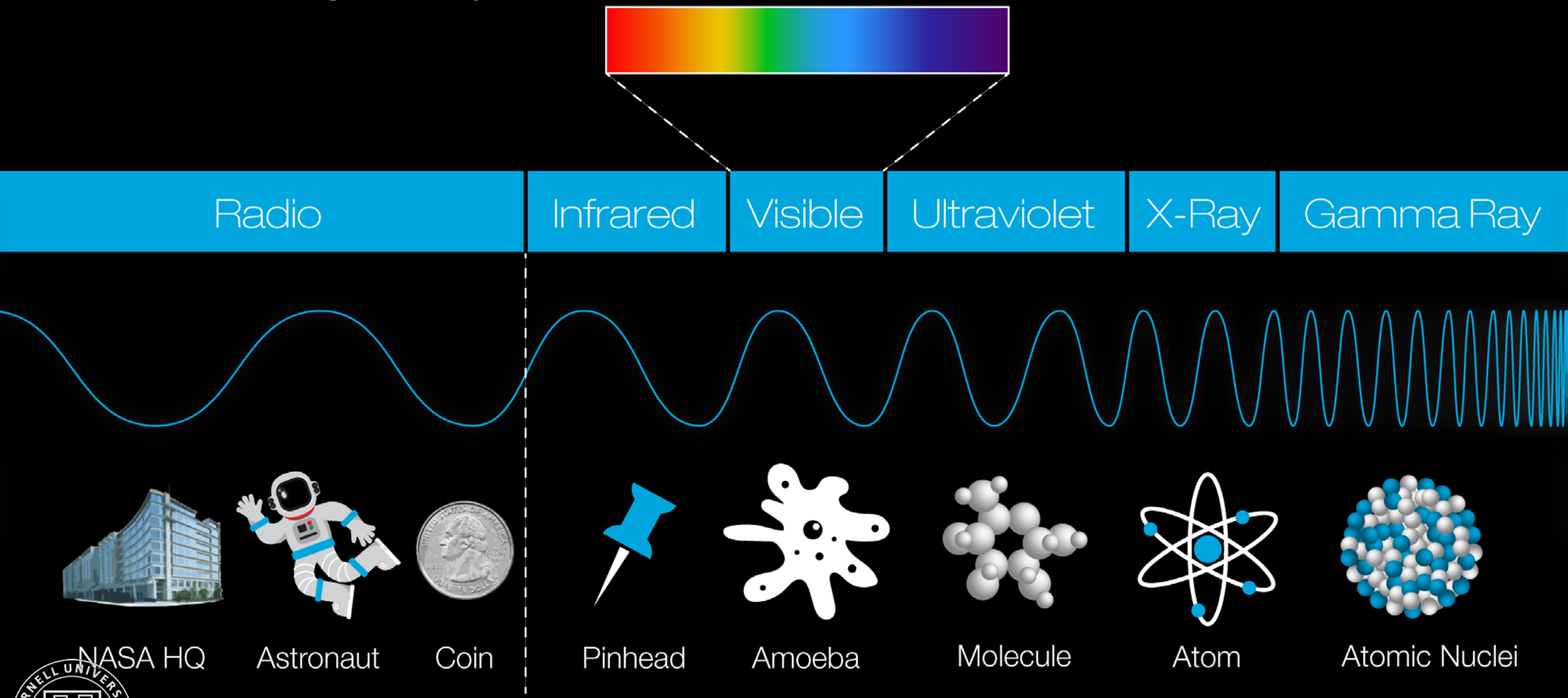
DISTANCE SENSORS



Distance Sensors

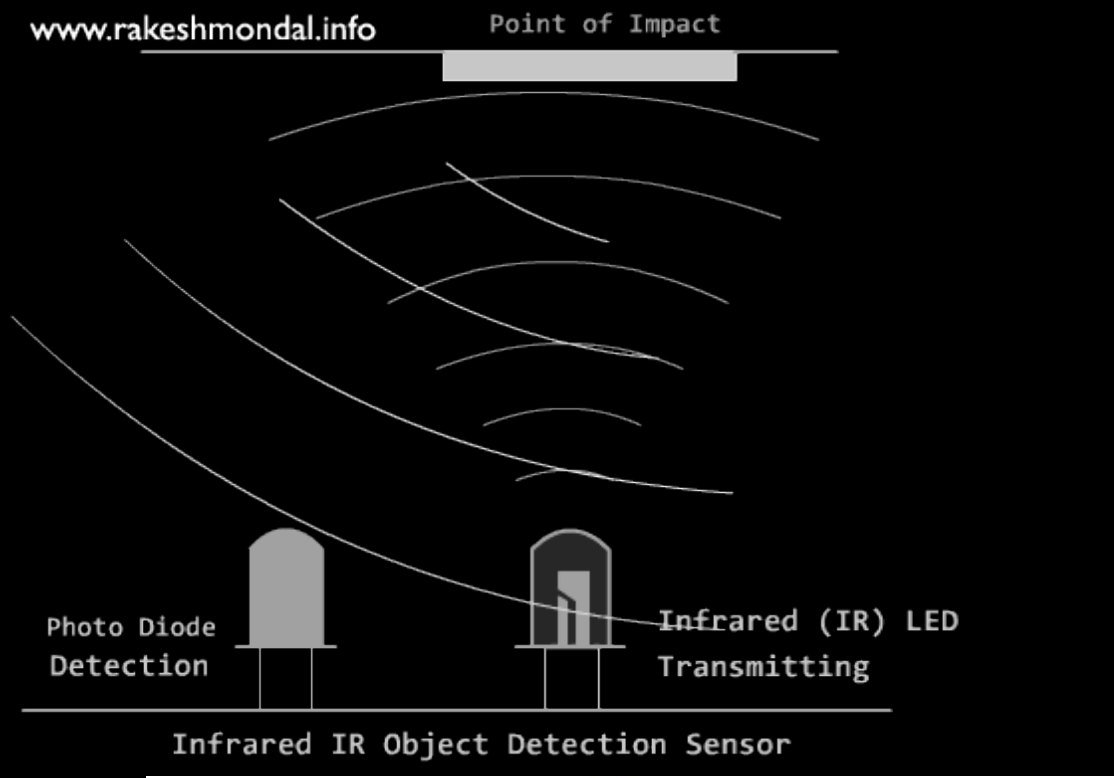
Technology	Application	Pros	Cons
Amplitude-based IR	<10cm	• ~ 0.5 USD • Small form factor	• Depends on target reflectivity • Does not work in high ambient light
IR triangulation	<1m	• Insensitive to surface color/texture/ambient light	• ~ 10 USD • Does not work in high ambient light • Bulky (1.75” × 0.75” × 0.53”) • Low sample rate (26Hz)
IR Time of Flight	0.1 - 4m	• High sample rate (4kHz) • Small form factor • Insensitive to surface color/texture/ambient light	• ~ 6.5 USD • Complicated processing • (Or 22 USD breakout board)
Ultrasonic	0.2 – 10m	• Low cost • Insensitive to ambient light and surface color • Works in rain and fog	• ~4 USD • Complicated processing • Resolution trade off with max range • Output depends on surface/geometry/humidity • Bulky, sample time (tens of milliseconds) • Hard to achieve a narrow FoV

The Electromagnetic Spectrum



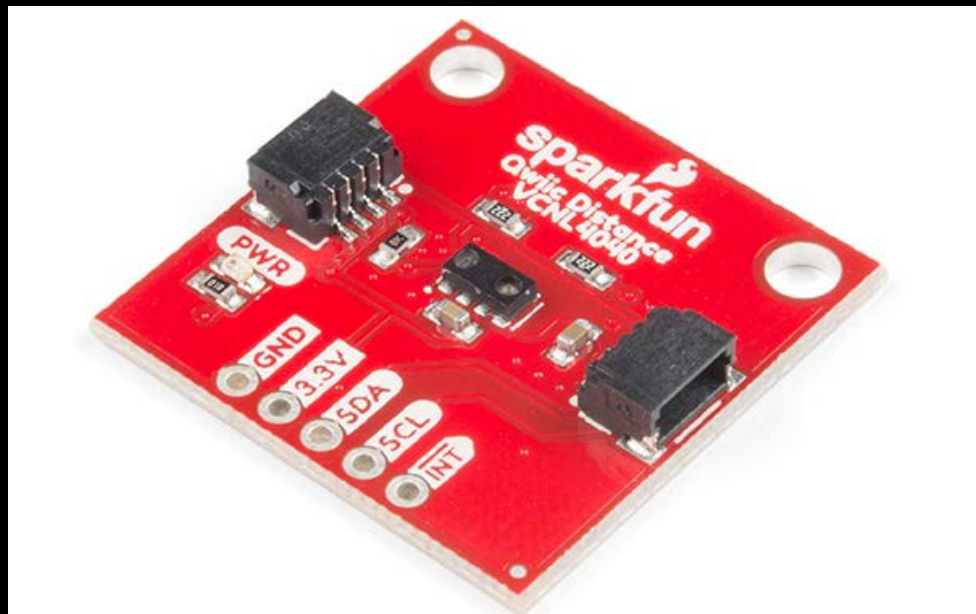
Amplitude –Based IR Distance Sensors

- Very cheap
- Very simple circuitry
- Works reasonably well for
  - Object detection
  - Break beam sensors
  - Classifying greyscale intensity at a fixed distance
  - Short-range distance sensor
- Sensitive to surface color, texture, and ambient light



VCNL4040

- $7
- Range 20cm
- Ambient light sensor
- Programmable DC



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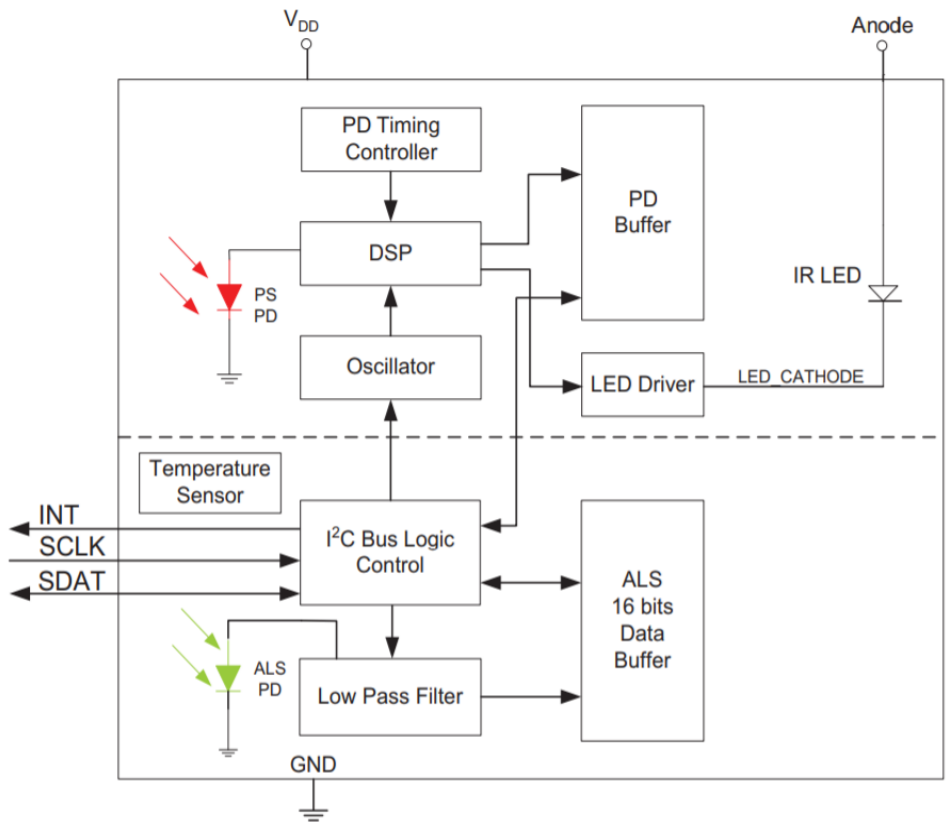

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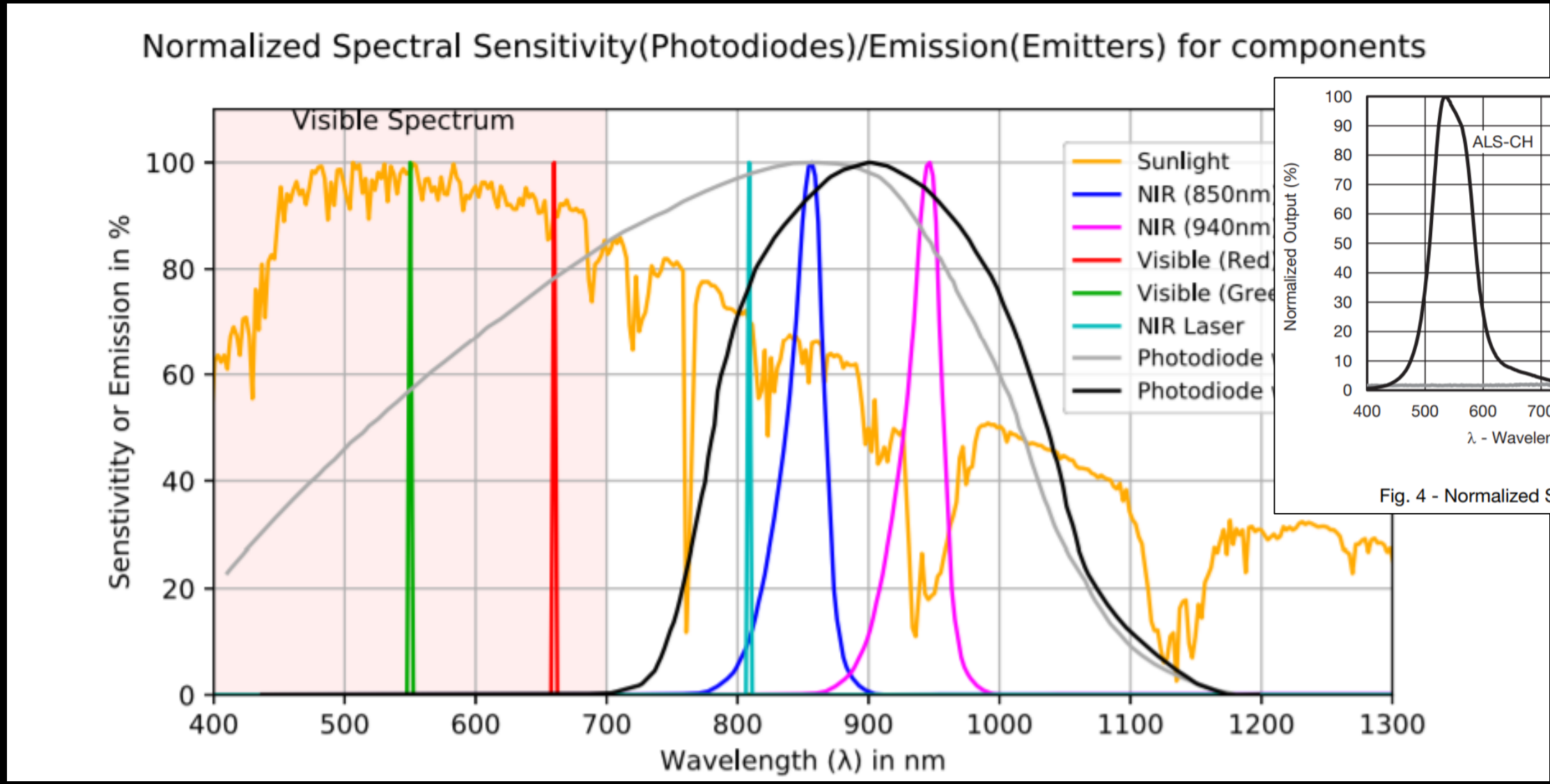
Amplitude –Based IR Distance Sensors

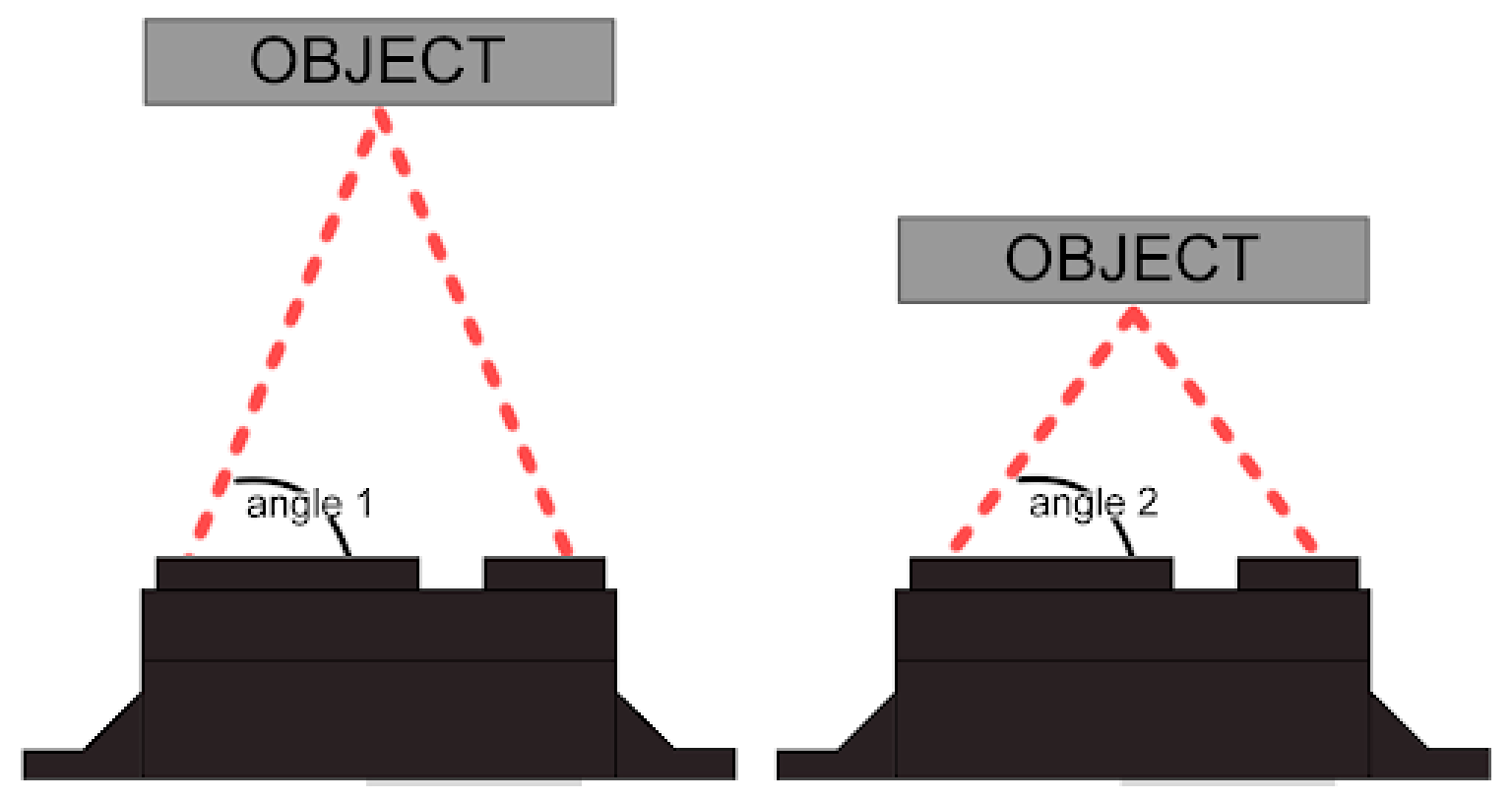


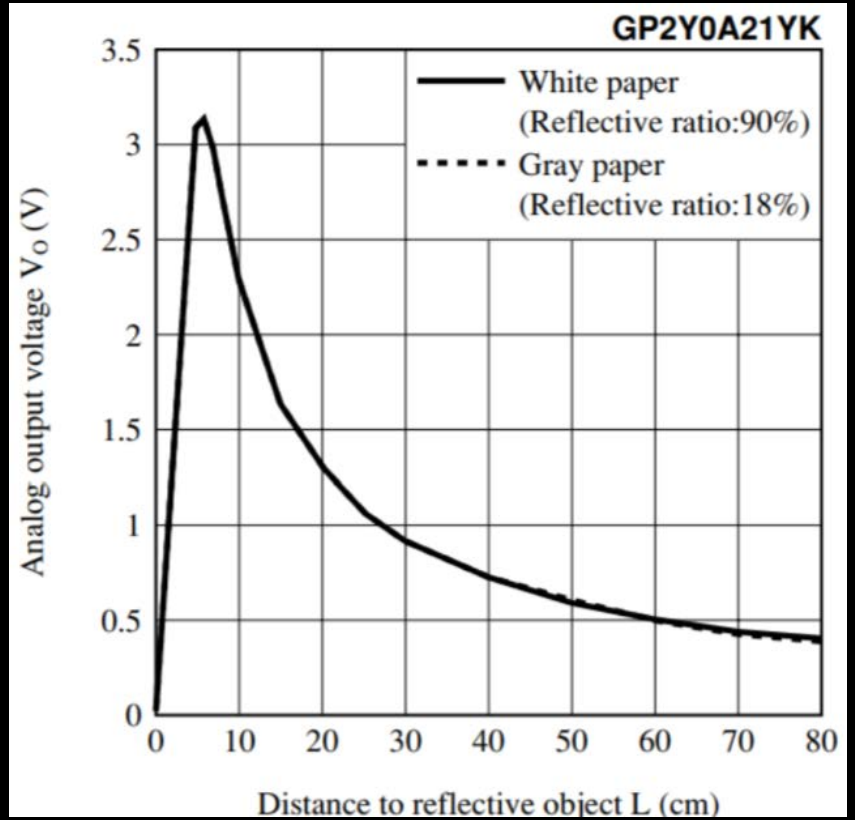
VNCL4040

Fig. 4 - Normalized Spectral Response

Triangulation–Based IR Distance Sensors

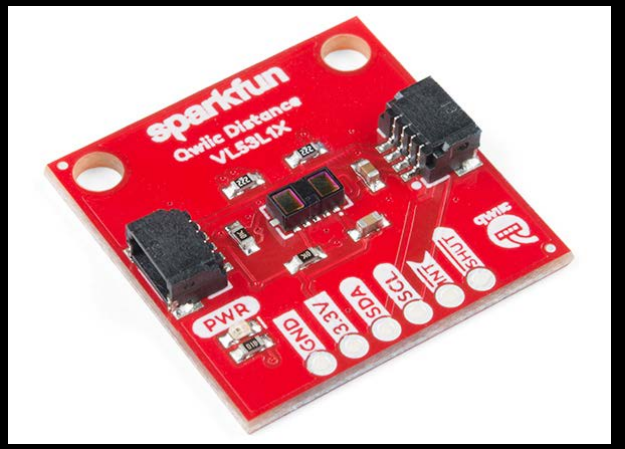
- Very simple circuitry
- Less sensitive to color, texture, ambient light
- Medium range (0.05 - 1 m)
- Cost 5-25 USD

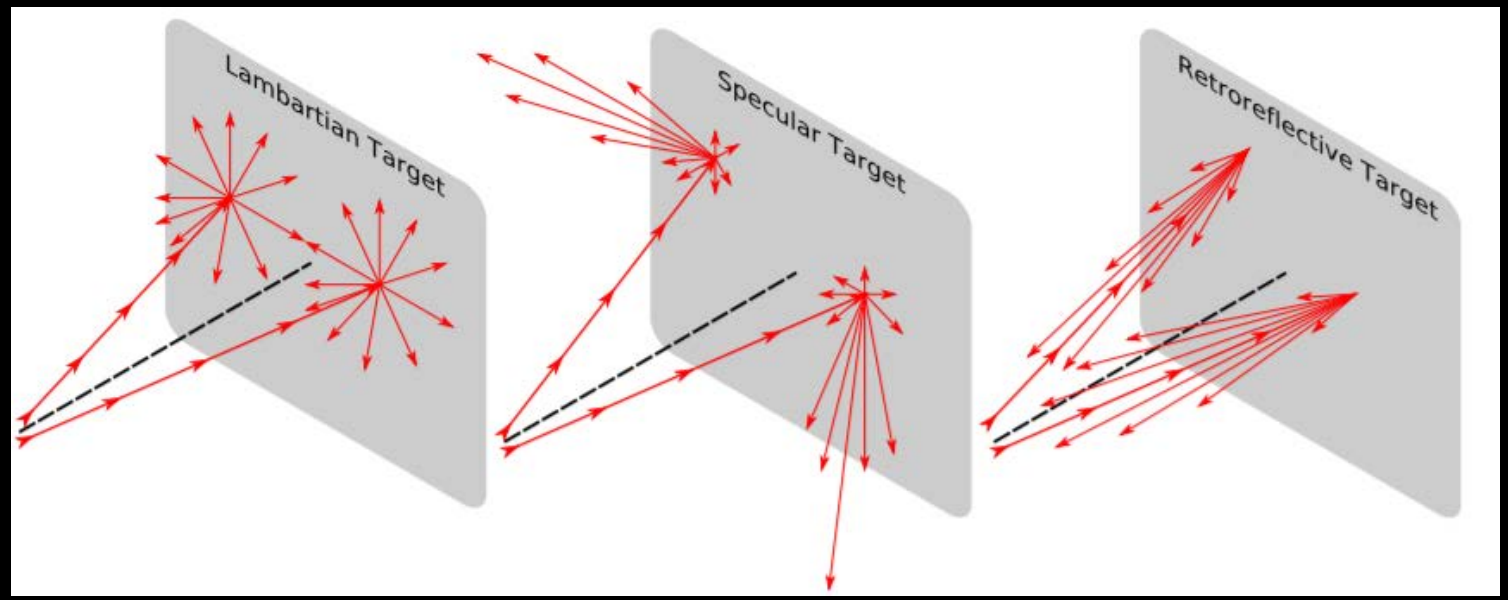


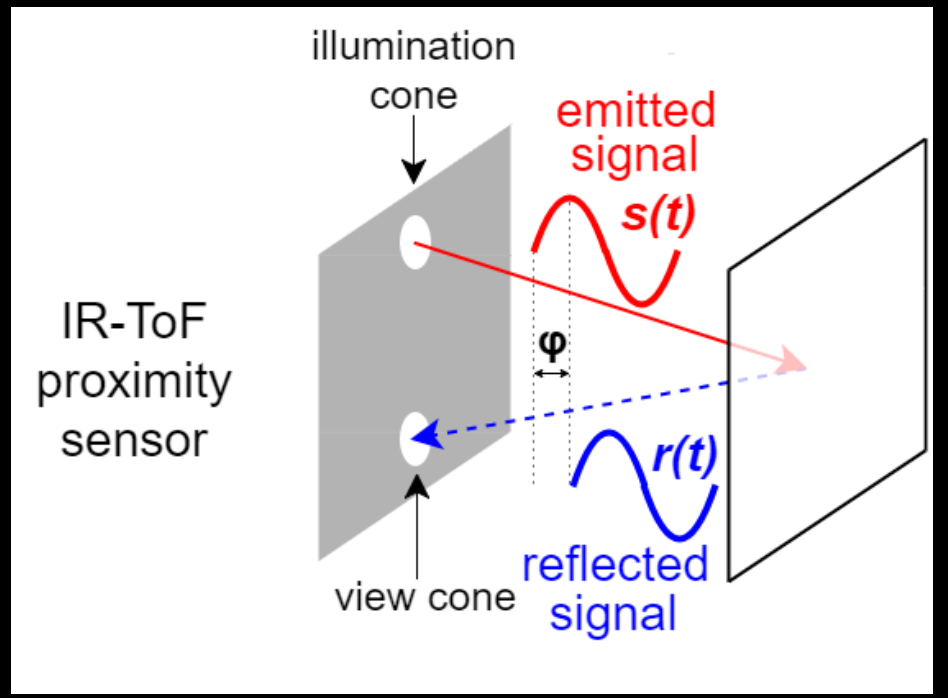


Time of Flight IR Sensor

- Emit a pulse modulated signal, record time *t* until return!
  - r = t*c/2
  - c = speed of light = 299,792,458 m/s
- Mostly insensitive to texture, color, ambient light







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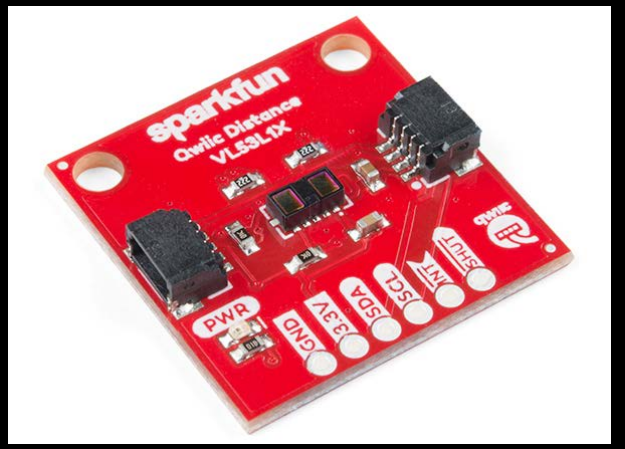

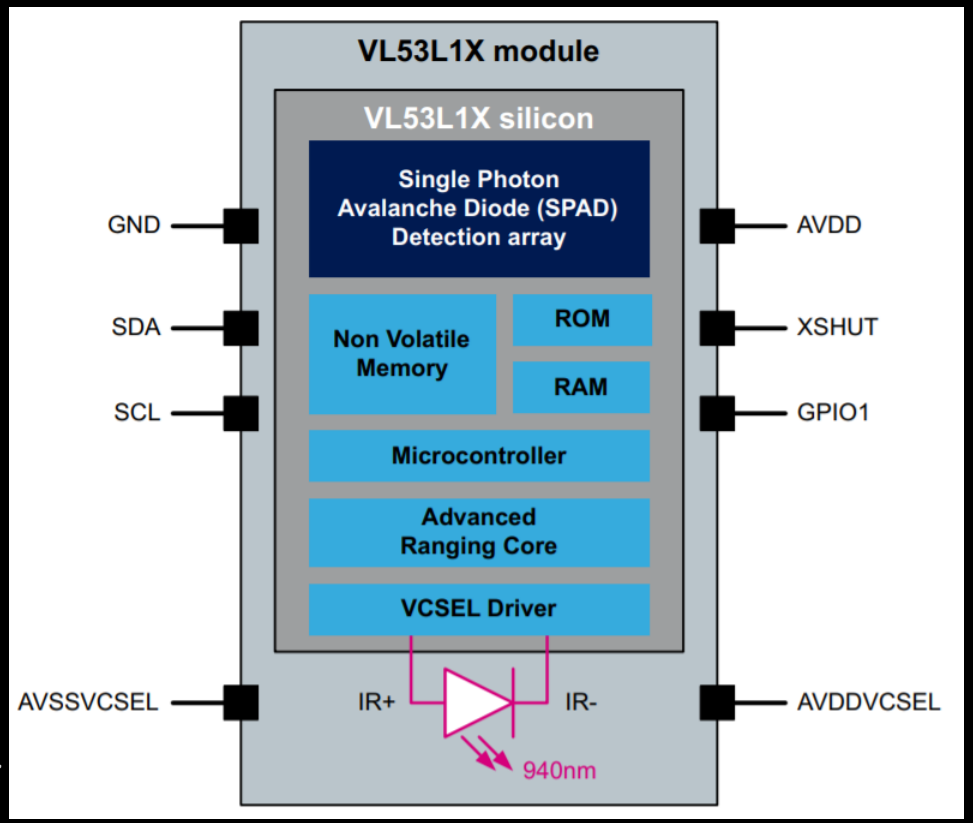

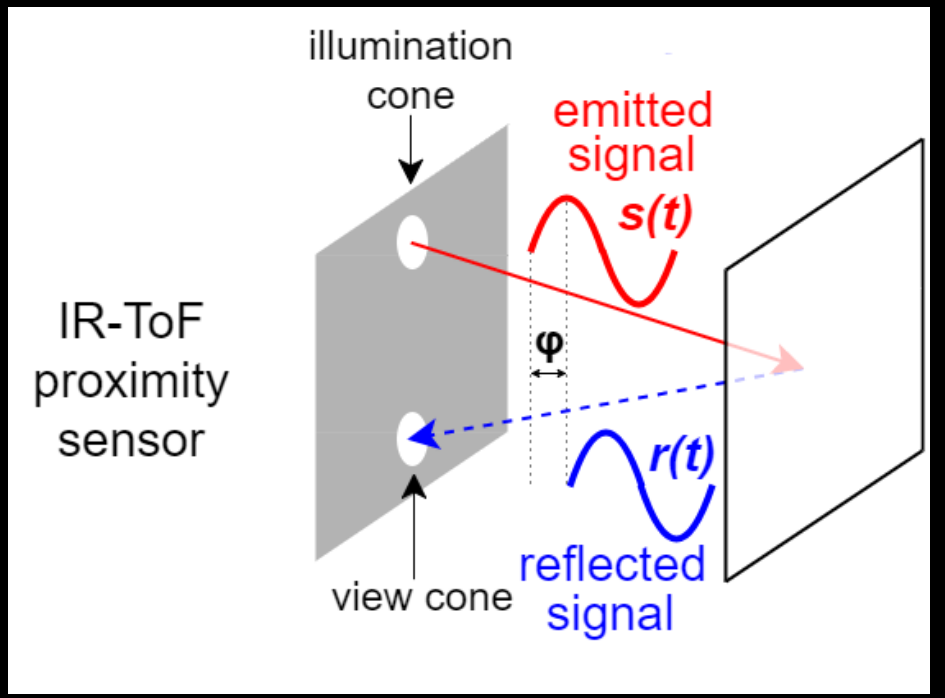

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  - r = t*c/2
  - c = speed of light = 299,792,458 m/s
- Mostly insensitive to texture, color, ambient light
- Outputs (Distance in mm, return signal rate, ambient signal rate, range status)
- Programmable FOV
- Timing budget
  - 20ms: short distance mode (0.05 - 1.3m)
  - 33ms: all distance modes (0.05 - 3.6m)
  - 140ms: improve reliability errors

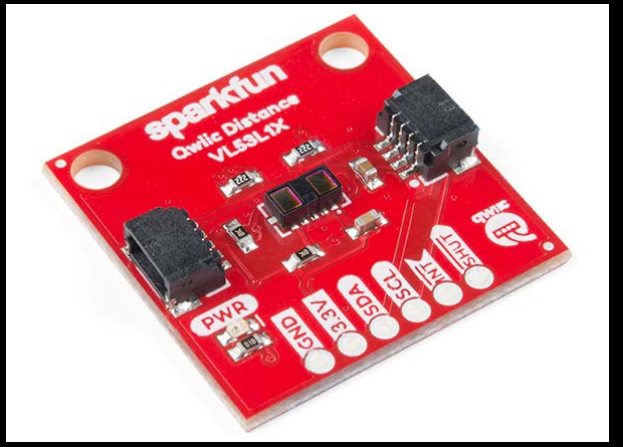
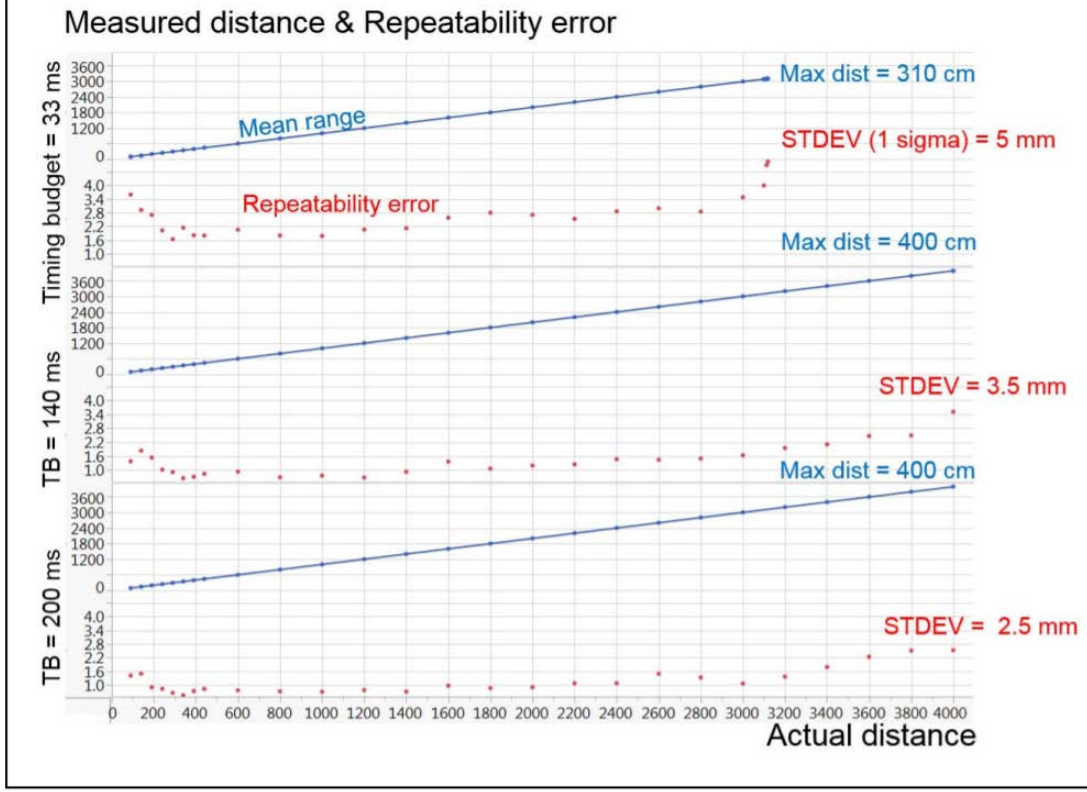
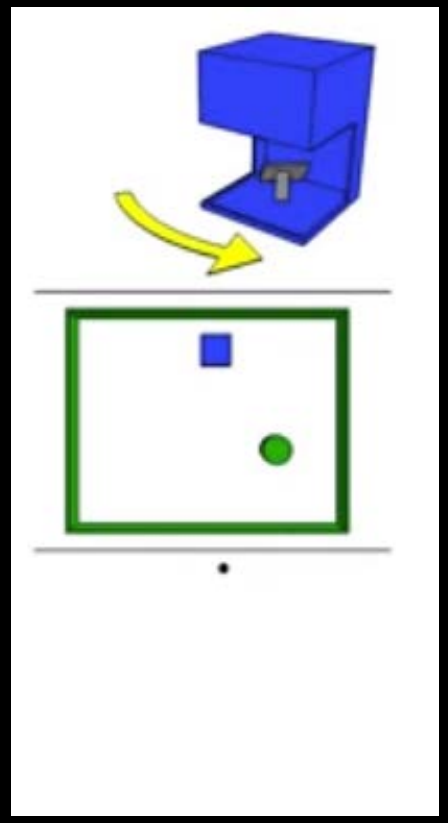


Figure 6. Maximum distance and repeatability error vs. timing budget

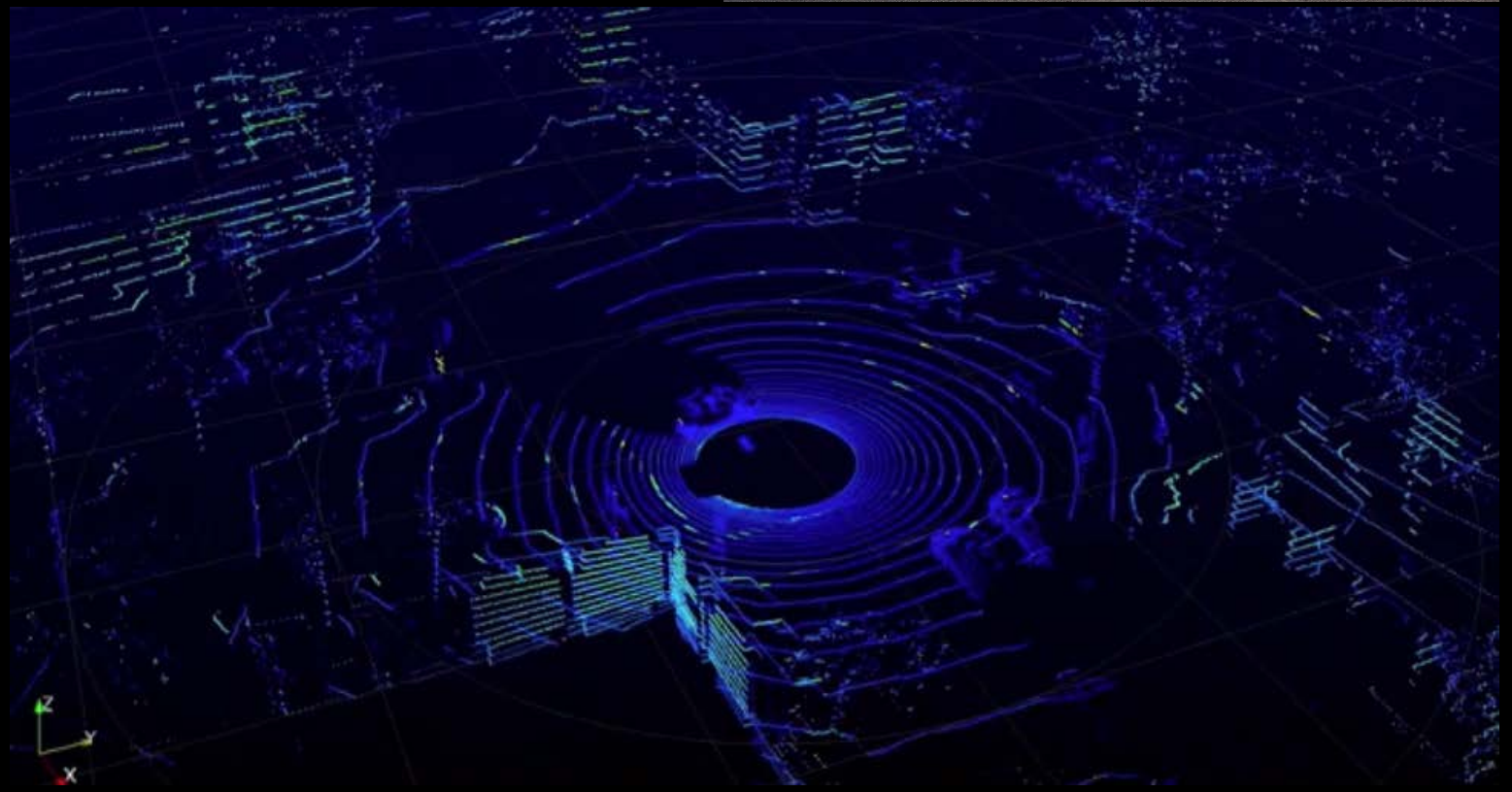


Light Detection and Ranging Sensors

- Most common sensors on autonomous cars and robots
- Single points, line scans, full 3D
- $$$

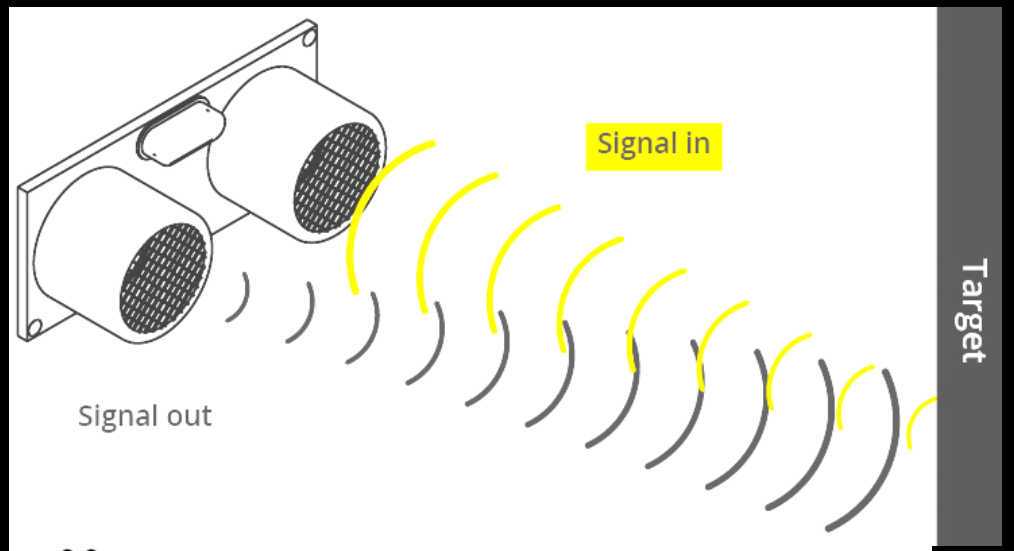


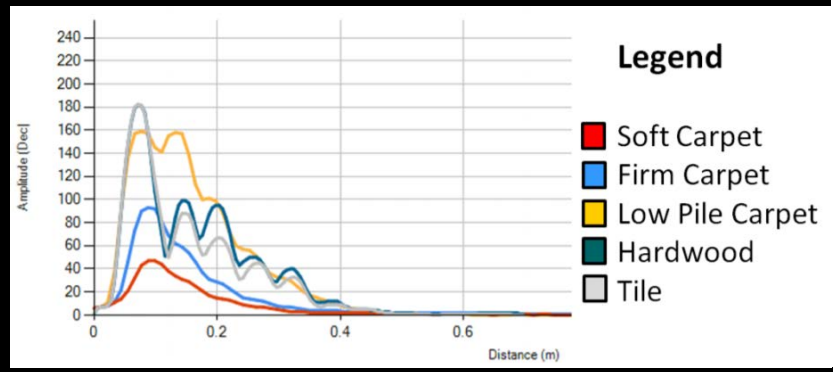
What does the color represent?

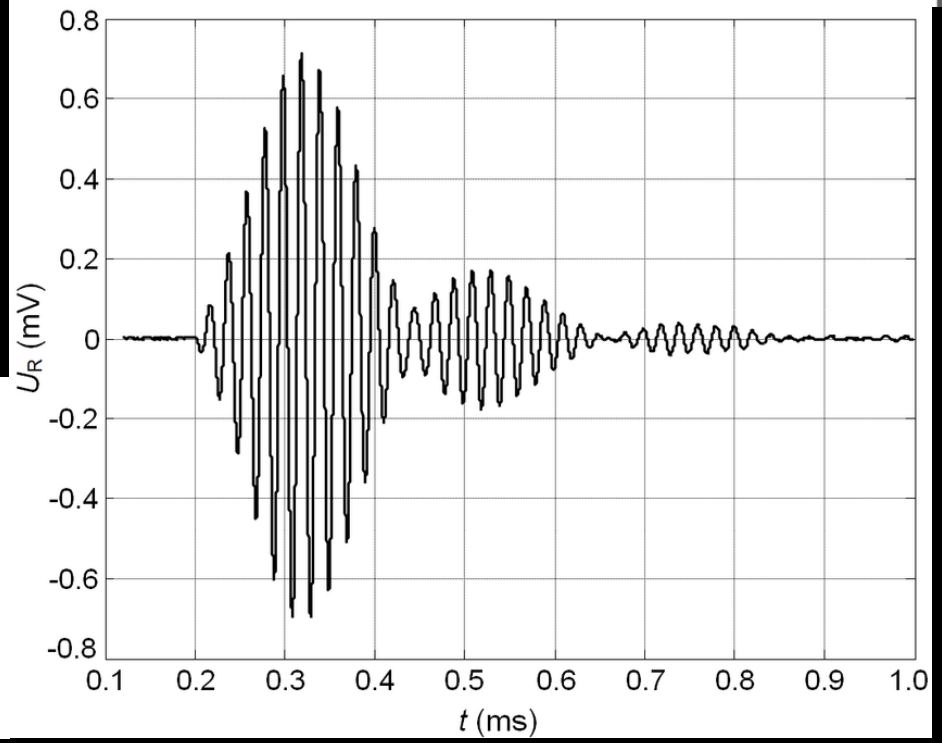


Ultrasound (Time of Flight) Distance Sensors

- Measure the reflections of an emitted sound wave
  - $r = t * c_{sound}$
  - $c_{sound} = 343$ m/s
- Frequency versus resolution and range
  - 58kHz: cm resolution, range < 11m
  - 300kHz: mm resolution, range < 0.3m
- Cost is low (Sparkfun module: 4 USD)
- Insensitive to color, texture, glass, fog, dust, etc.
- Sensitive to humidity, temperature, audible noise, and geometry







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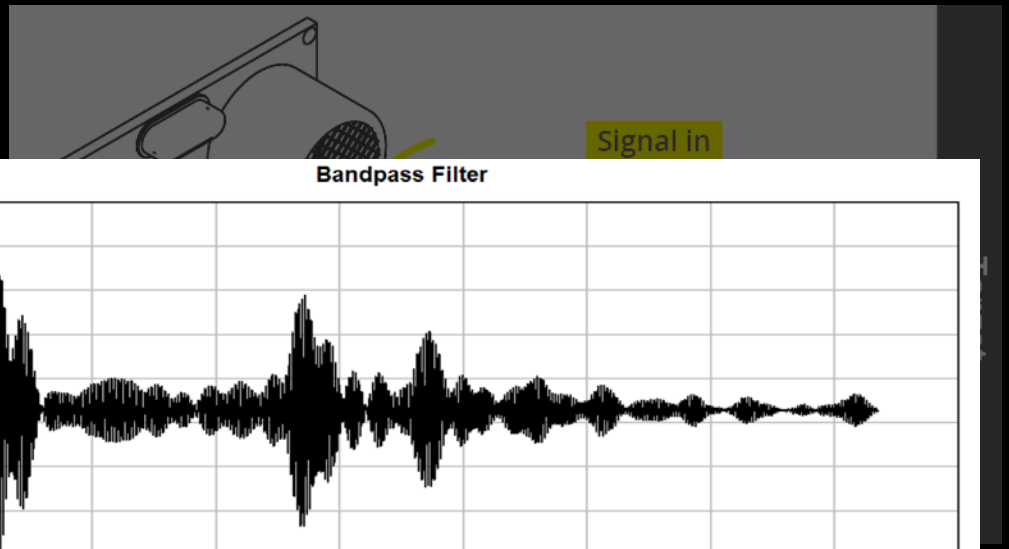

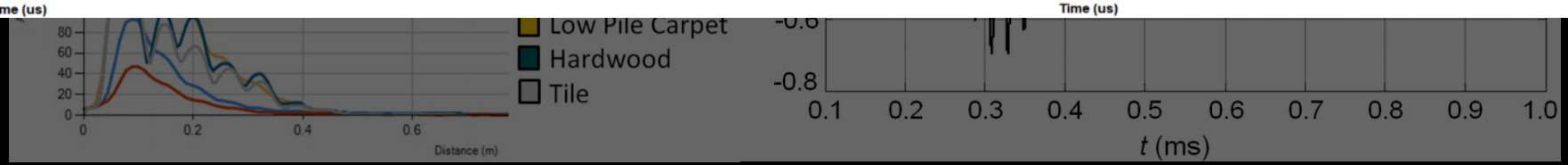

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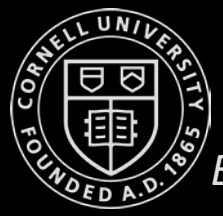
ODOMETRY SENSORS

(the process of inferring your position by the integration of speed)

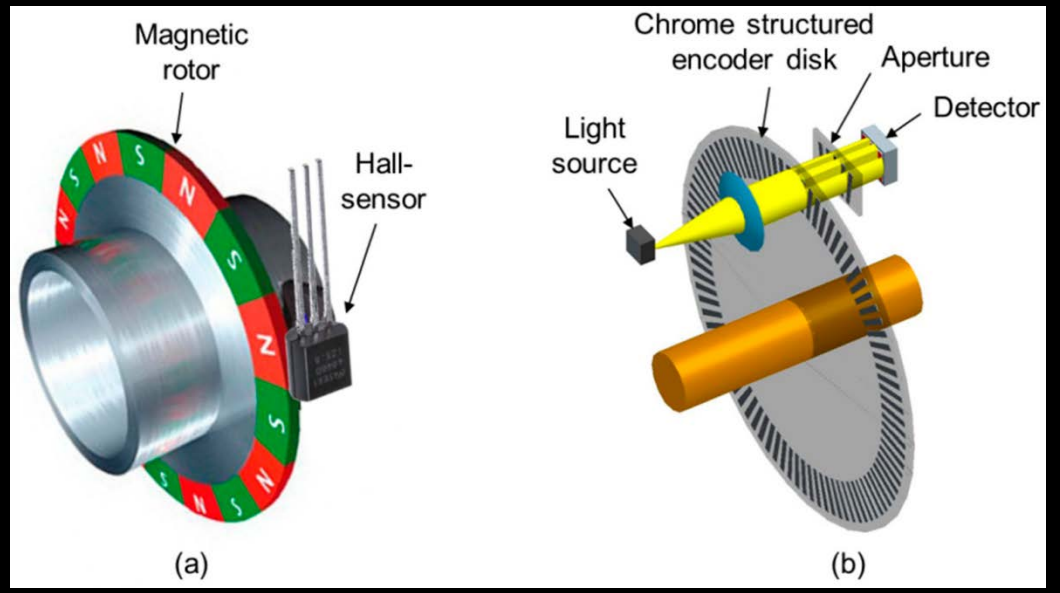
- Wheel encoders
- IMU
- Optical flow

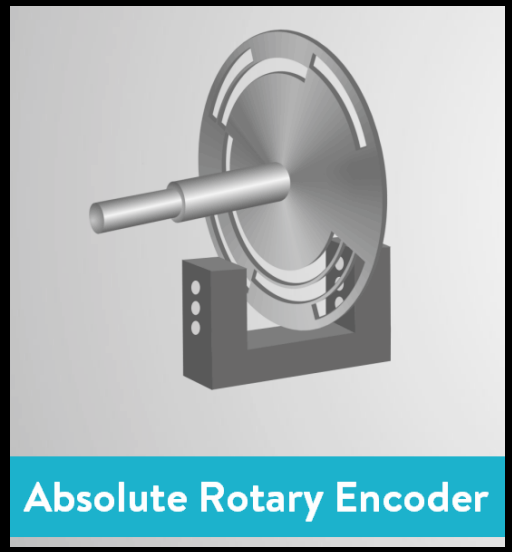


Encoders

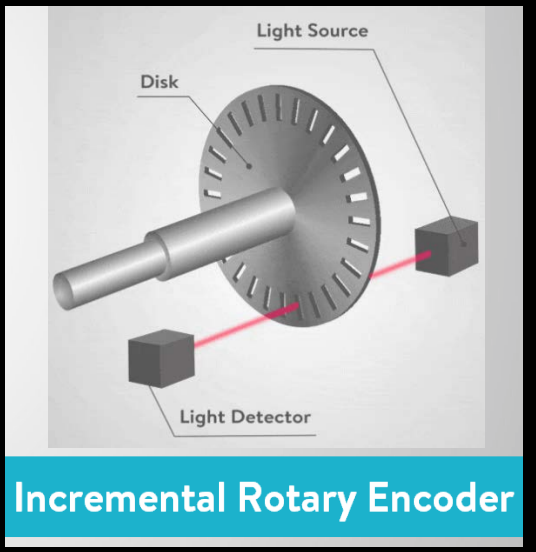
- Technology
  - Magnetic
  - Optical
  - Inductive, Capacitive, Laser
- Rotary (shaft) Encoders
  - Absolute Rotary Encoders (angular position)
  - Incremental Rotary Encoders (distance, speed, position)

How to add encoders to your robot?





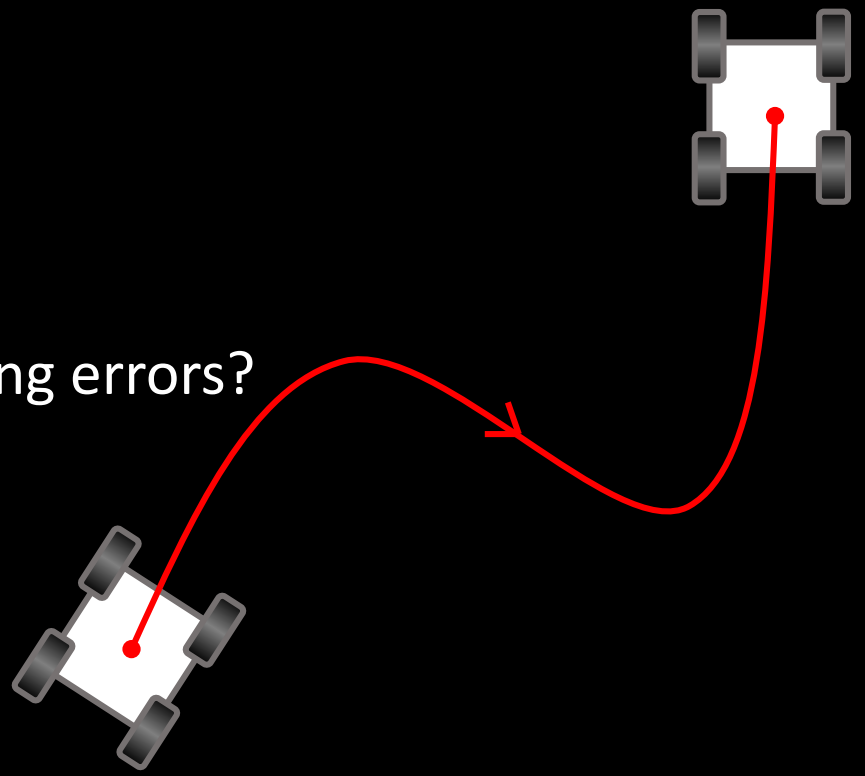
Absolute Rotary Encoder



Incremental Rotary Encoder

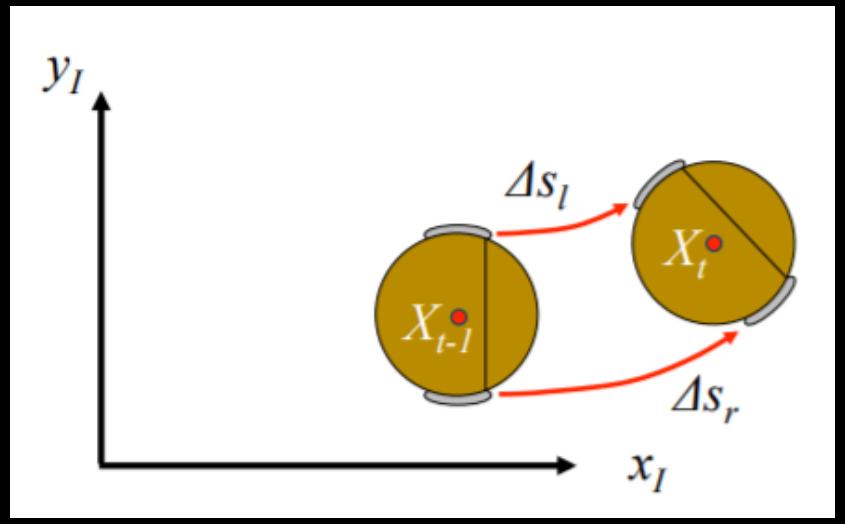
Dead Reckoning

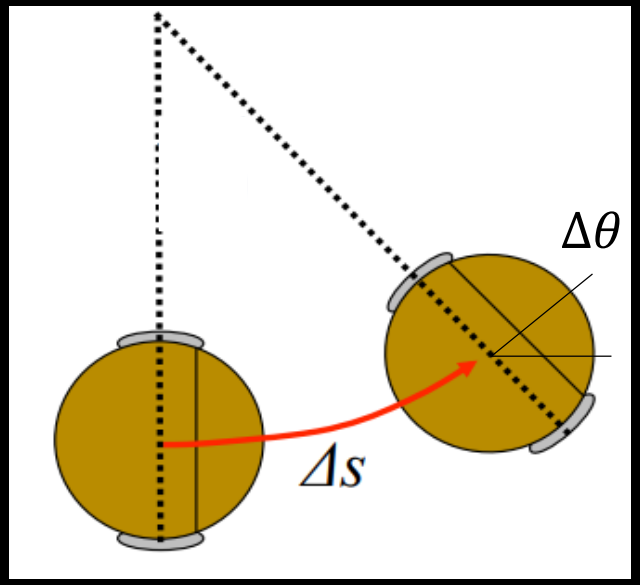
- Map the present state and wheel encoder measurements to the new robot state
  - $X_t = f(X_{t-1}, U_{t-1})$
  - Pro: Easy to implement
  - Con: Errors integrate and grow unbounded
- ***Sources of error?***
  - Limited resolution during integration
  - Unequal wheel diameter
  - Variation in the contact point of the wheel
  - Variable friction > slipping
- How do wheel rotation errors propagate into positioning errors?



Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle s_r$ and $\triangle s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
  - (assume that the robot is travelling on a circular arc of constant radius)





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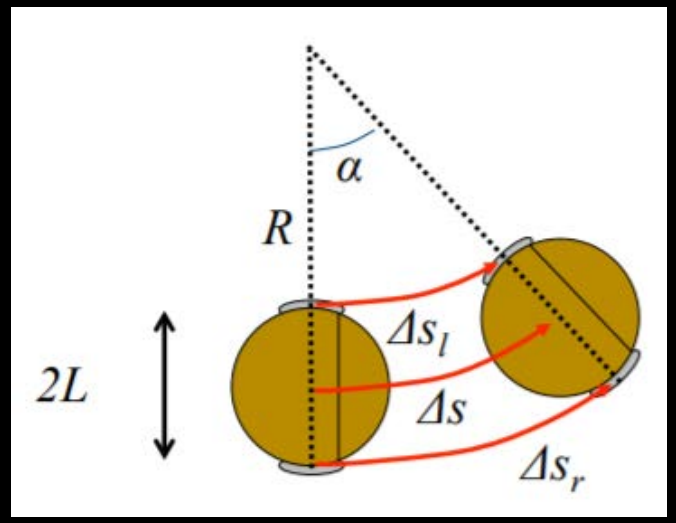


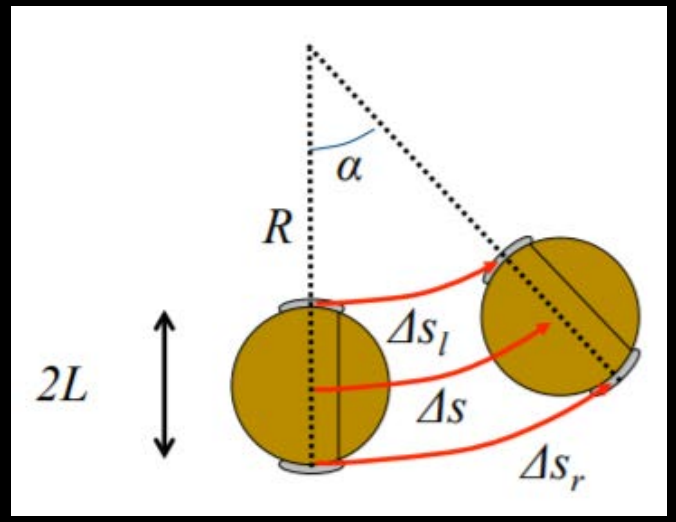
For circular arcs:

- $(1)\ \Delta s_l = R\alpha$
- $(2)\ \Delta s_r = (R + 2L)\alpha$
- $(3)\ \Delta s = (R + L)\alpha$

- Use (1) and (2) to compute (4):
  - $L\alpha = \frac{(\Delta s_r - R\alpha)}{2}$
  - $= \frac{\Delta s_r}{2} - \frac{\Delta s_l}{2}$
- Insert into (3): $\Delta s = \Delta s_l + \frac{\Delta s_r}{2} - \frac{\Delta s_l}{2} = \frac{\Delta s_l + \Delta s_r}{2}$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
  - (assume that the robot is travelling on a circular arc of constant radius)



For circular arcs:

- (1) $\Delta s_l = R\alpha$
- (2) $\Delta s_r = (R + 2L)\alpha$
- (3) $\Delta s = (R + L)\alpha$
- (4) $\Delta s = \frac{\Delta s_l + \Delta s_r}{2}$

- (or note that the distance traveled by the robot center, is simply the avg distance traveled by each wheel)

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
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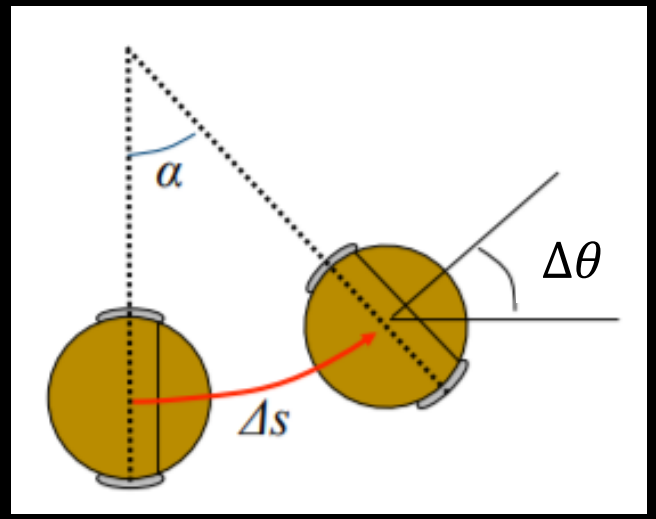

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- (3) $\Delta s = (R + L)\alpha$
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- The change in angle, $\Delta\theta$:
  - $\Delta\theta = \alpha$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
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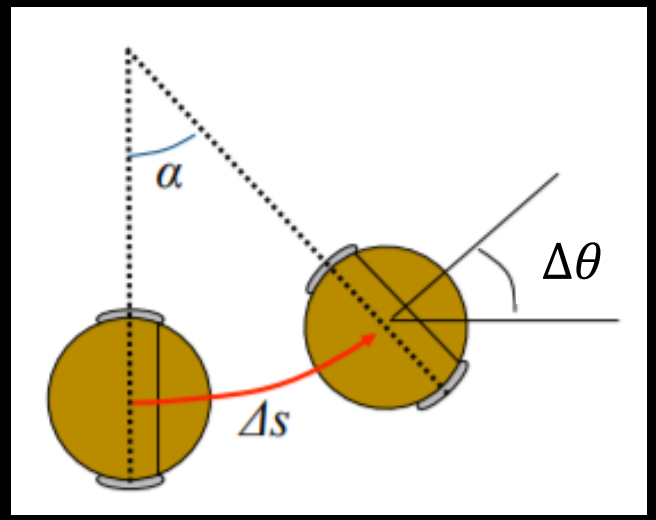

For circular arcs:

- (1) $\Delta s_l = R\alpha$
- (2) $\Delta s_r = (R + 2L)\alpha$
- (3) $\Delta s = (R + L)\alpha$
- (4) $\Delta s = \frac{\Delta s_l + \Delta s_r}{2}$

- Use α in (1) and (2):
  - $\frac{\Delta s_l}{R} = \frac{\Delta s_r}{R+2L} \leftrightarrow (R + 2L)\Delta s_l = R(\Delta s_r)$
  - $\leftrightarrow\ 2L\Delta s_l = \mathrm{R}(\Delta s_r - \Delta s_l)$
  - $\leftrightarrow\ R = \frac{2L\Delta s_l}{\Delta s_r - \Delta s_l}$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
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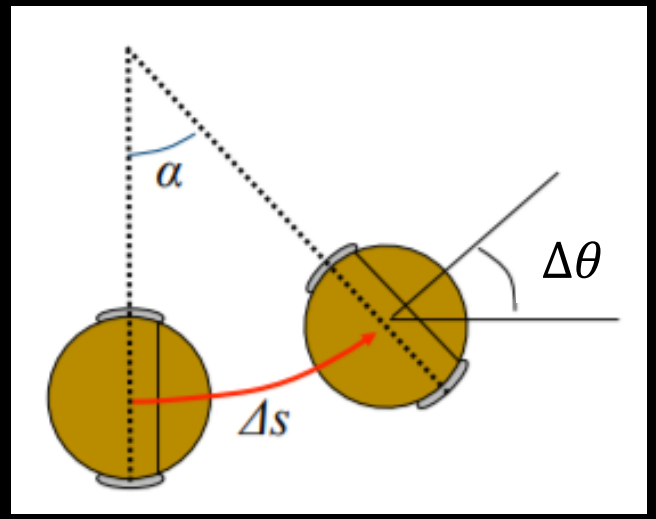

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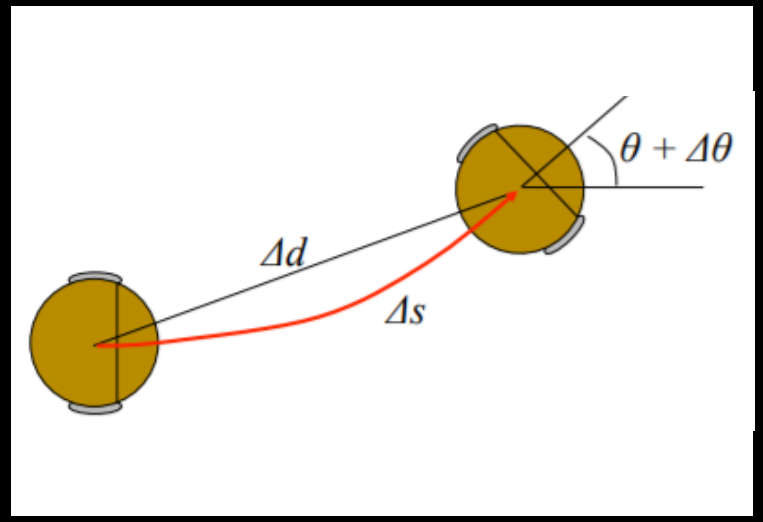
- (3) $\Delta s = (R + L)\alpha$

- (4) $\Delta s = \frac{\Delta s_l + \Delta s_r}{2}$
- (5) $R = \frac{2L\Delta s_l}{\Delta s_r - \Delta s_l}$

- Use (5) in (1) :
  - $\alpha = \frac{\Delta s_l}{R} = \frac{\Delta s_l(\Delta s_r - \Delta s_l)}{2L\Delta s_l} = \frac{\Delta s_r - \Delta s_l}{2L} = \Delta\theta$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
  - (assume that the robot is travelling on a circular arc of constant radius)
  - (assume that the motion is small, $\Delta d \approx \Delta s$)



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- (5) $R = \frac{2L\Delta s_l}{\Delta s_r - \Delta s_l}$
- (6) $\Delta\theta = \frac{\Delta s_r - \Delta s_l}{2L}$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
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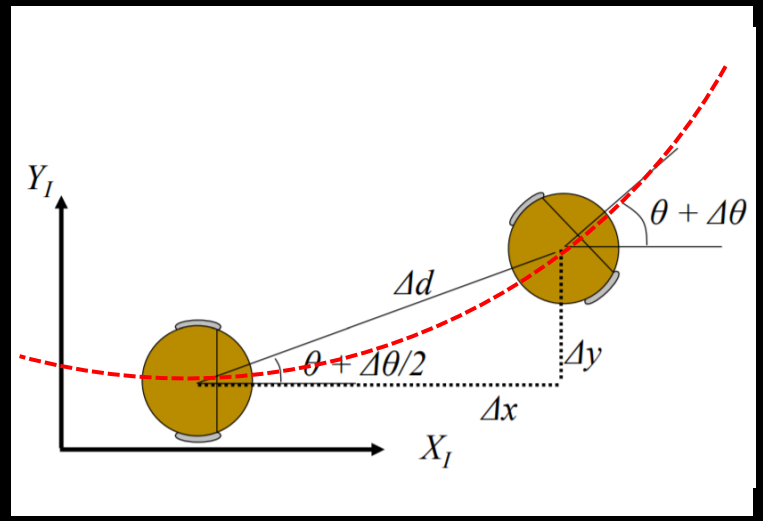

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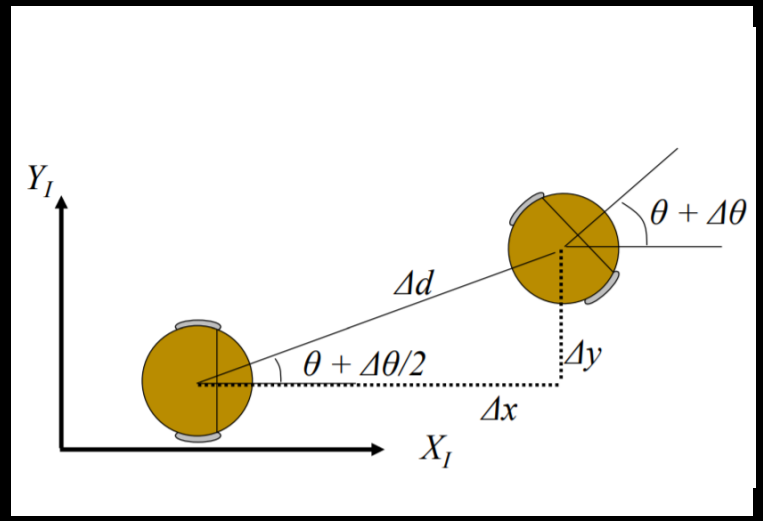
- (5) $R = \frac{2L\Delta s_l}{\Delta s_r - \Delta s_l}$
- (6) $\Delta\theta = \frac{\Delta s_r - \Delta s_l}{2L}$
- (7) $\Delta x = \Delta s\ cos(\theta + \Delta\theta/2)$
- (8) $\Delta y = \Delta s\ sin(\theta + \Delta\theta/2)$

Modeling Motion

- Start at pose X_{t-1}, move right/left wheel by $\triangle\ s_r$ and $\triangle\ s_l$, what is pose X_t?
- Model the change in angle $\Delta\theta$ and the distance travelled Δs
  - (assume that the robot is travelling on a circular arc of constant radius)
  - (assume that the motion is small, $\Delta d \approx \Delta s$)

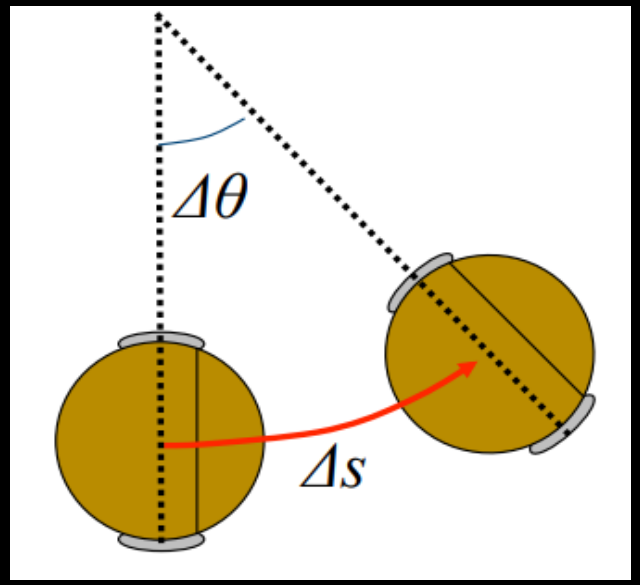


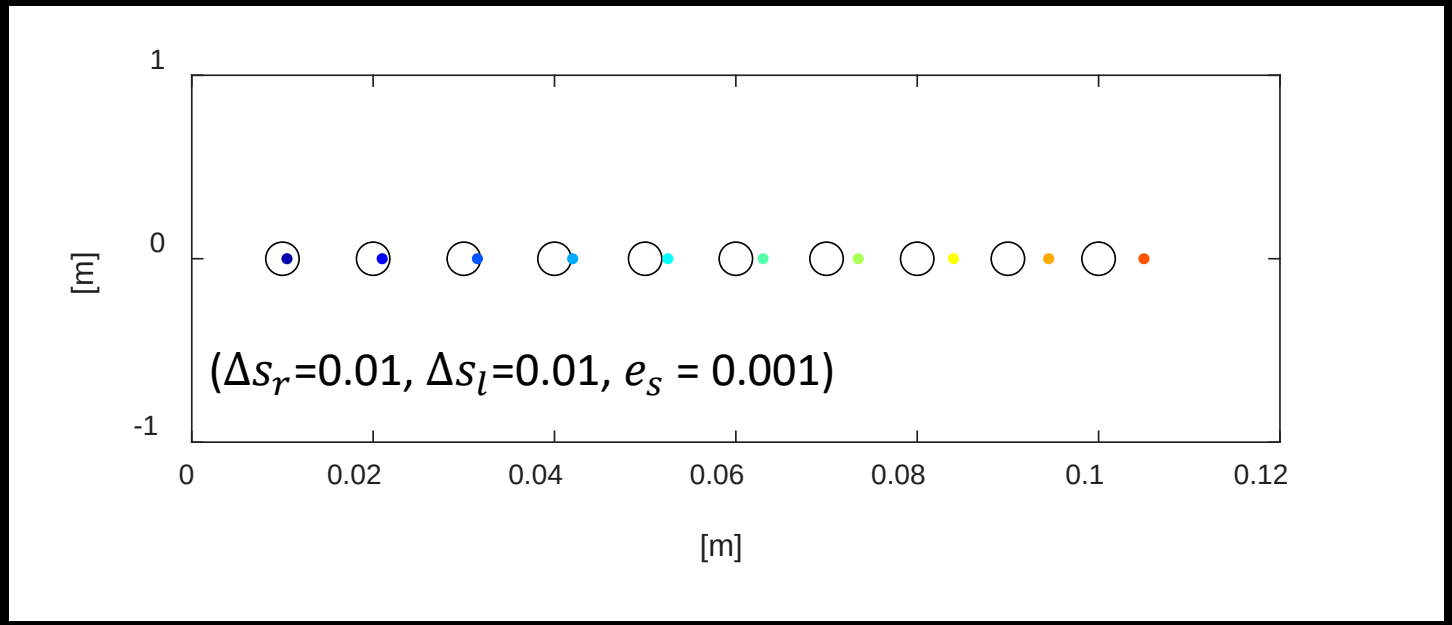
- (4) $\Delta s = \frac{\Delta s_l + \Delta s_r}{2}$
- (6) $\Delta\theta = \frac{\Delta s_r - \Delta s_l}{2L}$
- (7) $\Delta x = \Delta s\ cos(\theta + \Delta\theta/2)$
- (8) $\Delta y = \Delta s\ sin(\theta + \Delta\theta/2)$
- $X_t = f(x, y, \theta, \Delta s_r, \Delta s_l)$
- $X_t = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta\theta \end{bmatrix}$

$$= \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{\Delta s_l + \Delta s_r}{2} cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right) \\ \frac{\Delta s_l + \Delta s_r}{2} sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right) \\ \frac{\Delta s_r - \Delta s_l}{2L} \end{bmatrix}$$

Modeling Motion

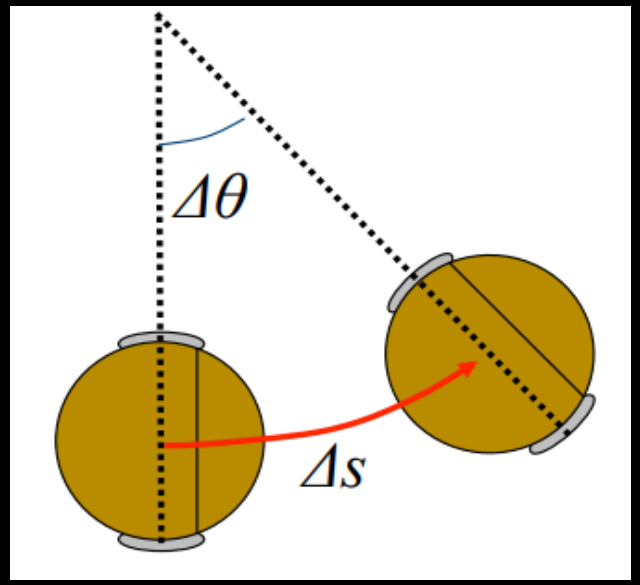
- How do wheel rotation errors propagate into positioning errors?
  - $\Delta s = d + e_s$
    - $\Delta x = \frac{\Delta s_l + \Delta s_r + e_s}{2} cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right)$
    - $\Delta y = \frac{\Delta s_l + \Delta s_r + e_s}{2} sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right)$

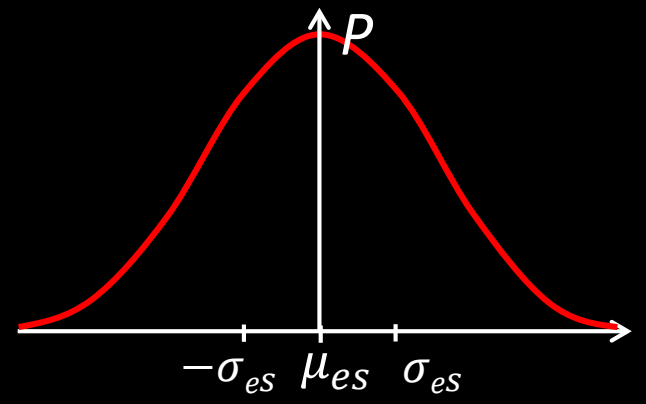


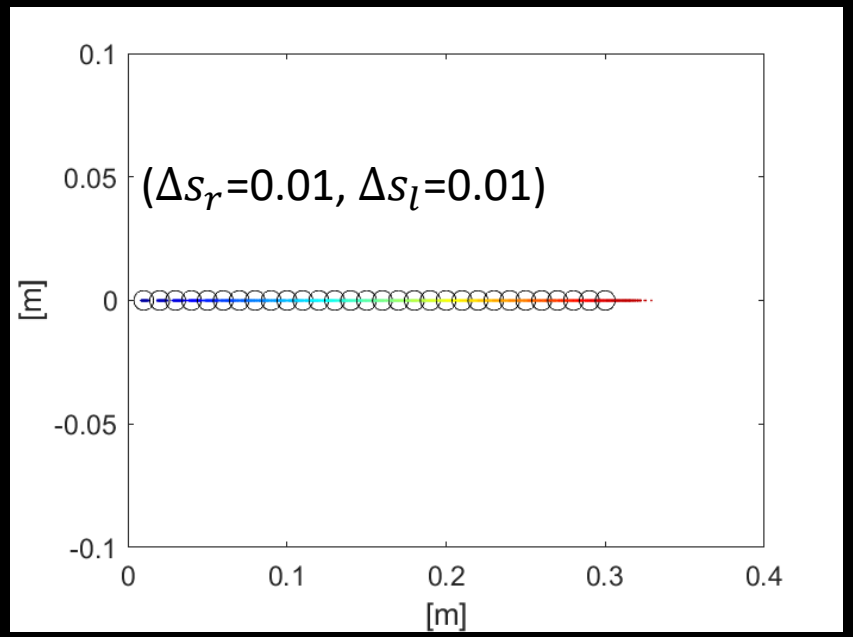


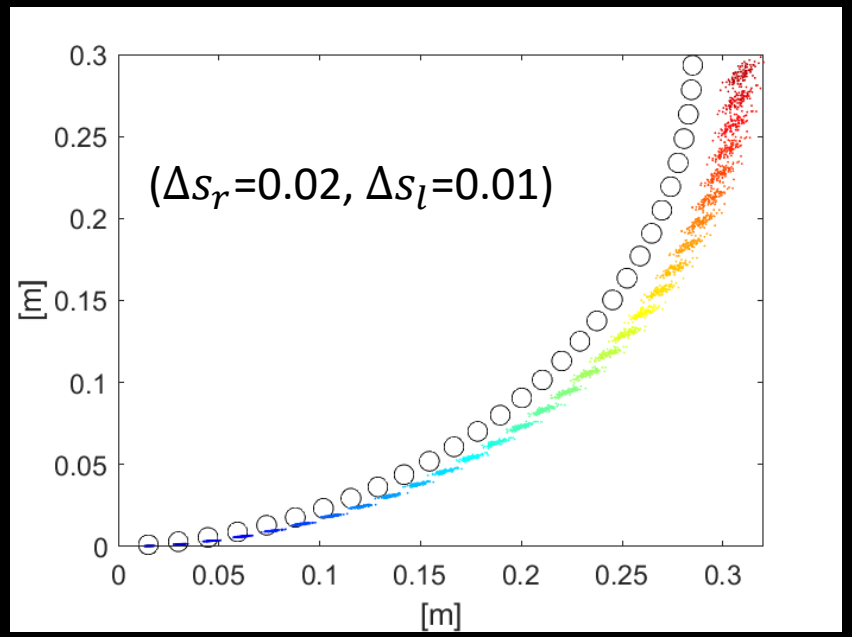
Modeling Motion

- How do wheel rotation errors propagate into positioning errors?
  - $\Delta s = d + e_s$
    - $\Delta x = \frac{\Delta s_l + \Delta s_r + e_s}{2} cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right)$
    - $\Delta y = \frac{\Delta s_l + \Delta s_r + e_s}{2} sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right)$
    - e_s (μ_{es}= 1mm, σ_{es}= 2mm)



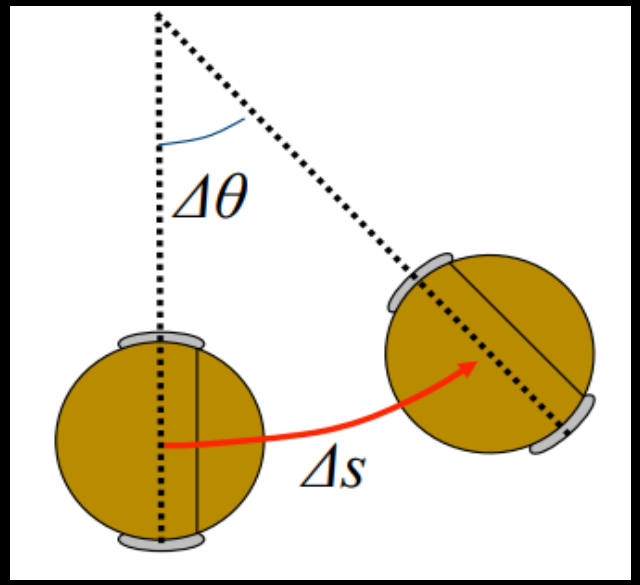


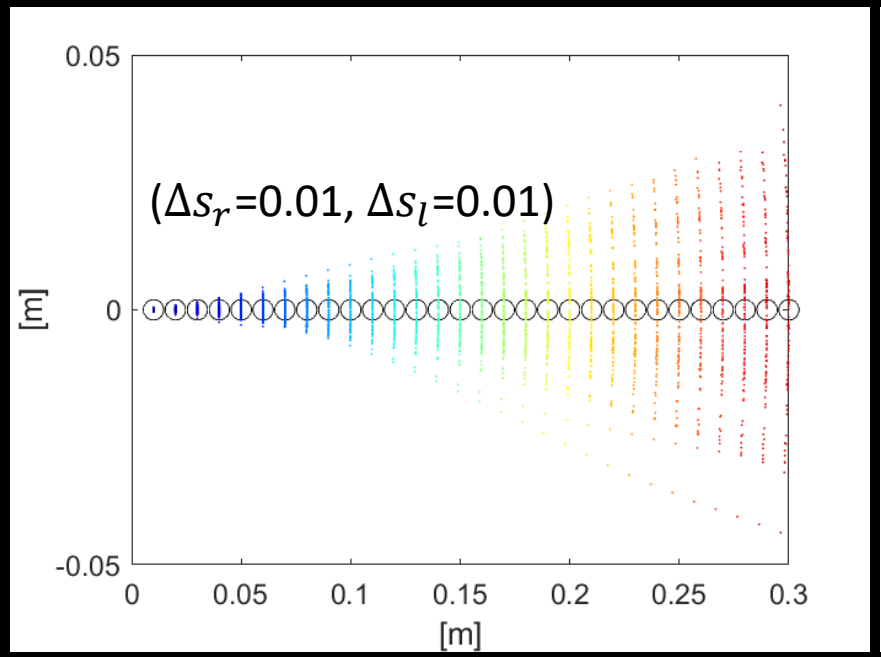


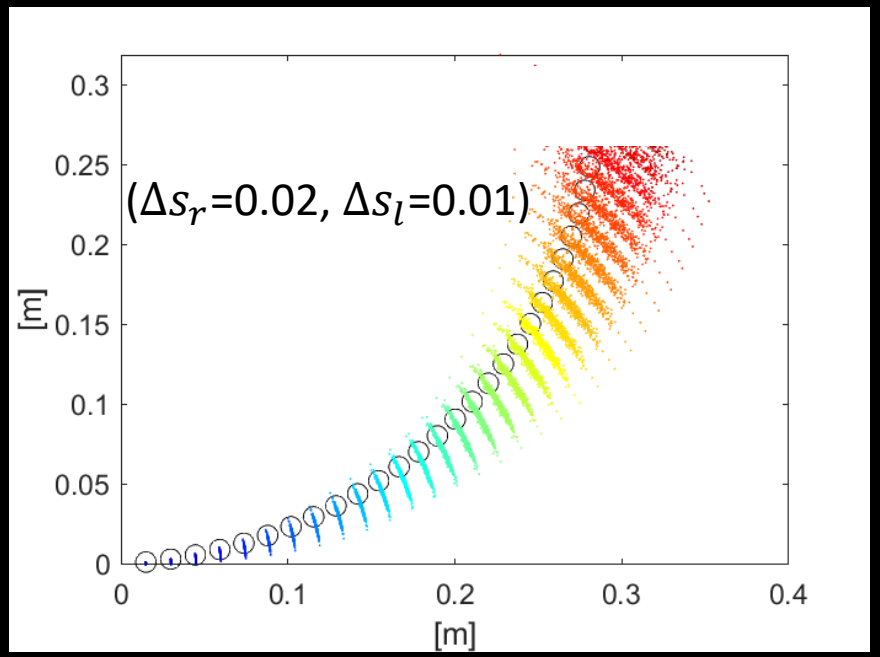


Modeling Motion

- How do wheel rotation errors propagate into positioning errors?
  - $\Delta\theta = \beta + e_\theta$, e_θ = 1°
    - $\Delta x = \Delta s \cos\left(\theta + \frac{\beta}{2} + e_\theta\right) = 0.1000m$
    - $\Delta y = \Delta s \sin\left(\theta + \frac{\beta + e_\theta}{2} + e_\theta\right) = 0.0175m$
    - e_θ ($\mu_{e\theta}$= 0°, $\sigma_{e\theta}$= 1°)







Prof. Kirstin Hagelskjær Petersen
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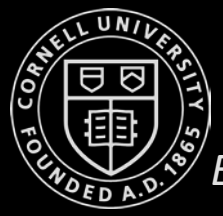
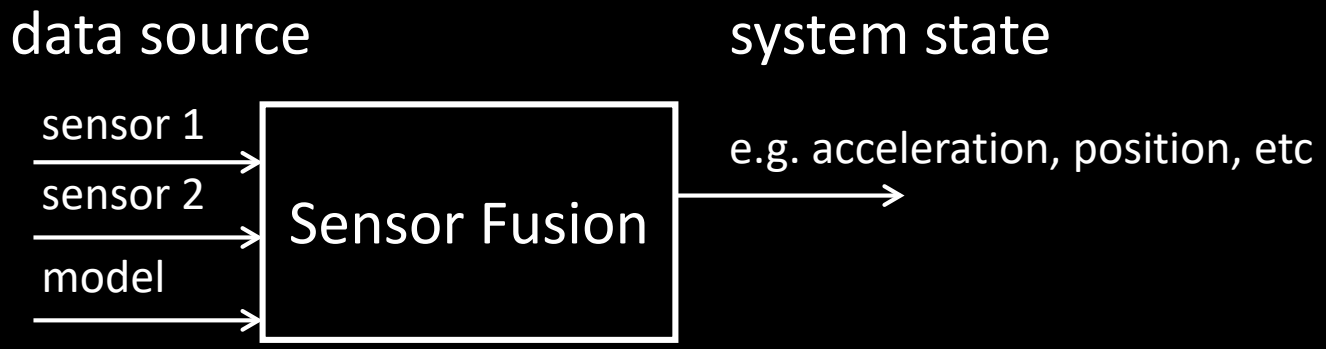
WHY SENSOR FUSION?



Intro to Sensor Fusion

- Combine two or more data sources in a way that generates a “better” understanding of the system
  - More consistent signal over time
  - More accurate signal over time
  - More dependable



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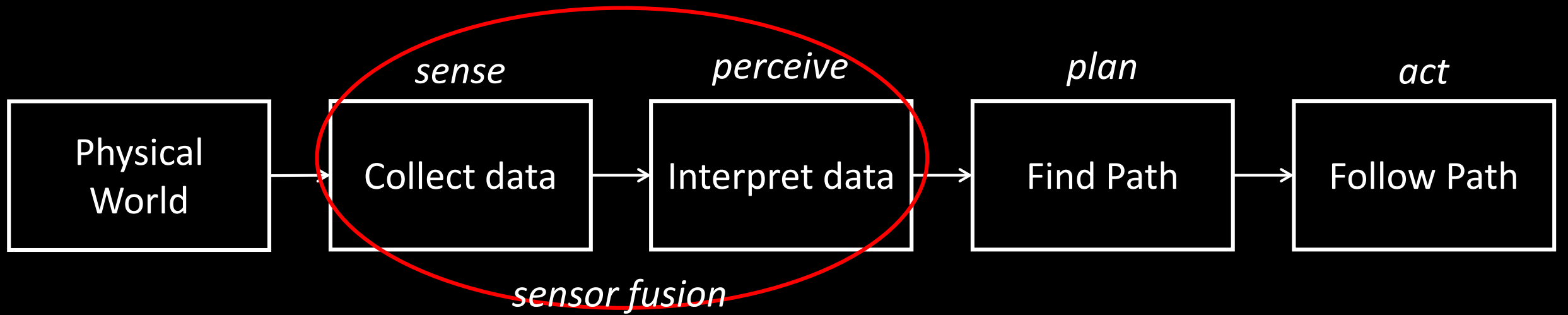
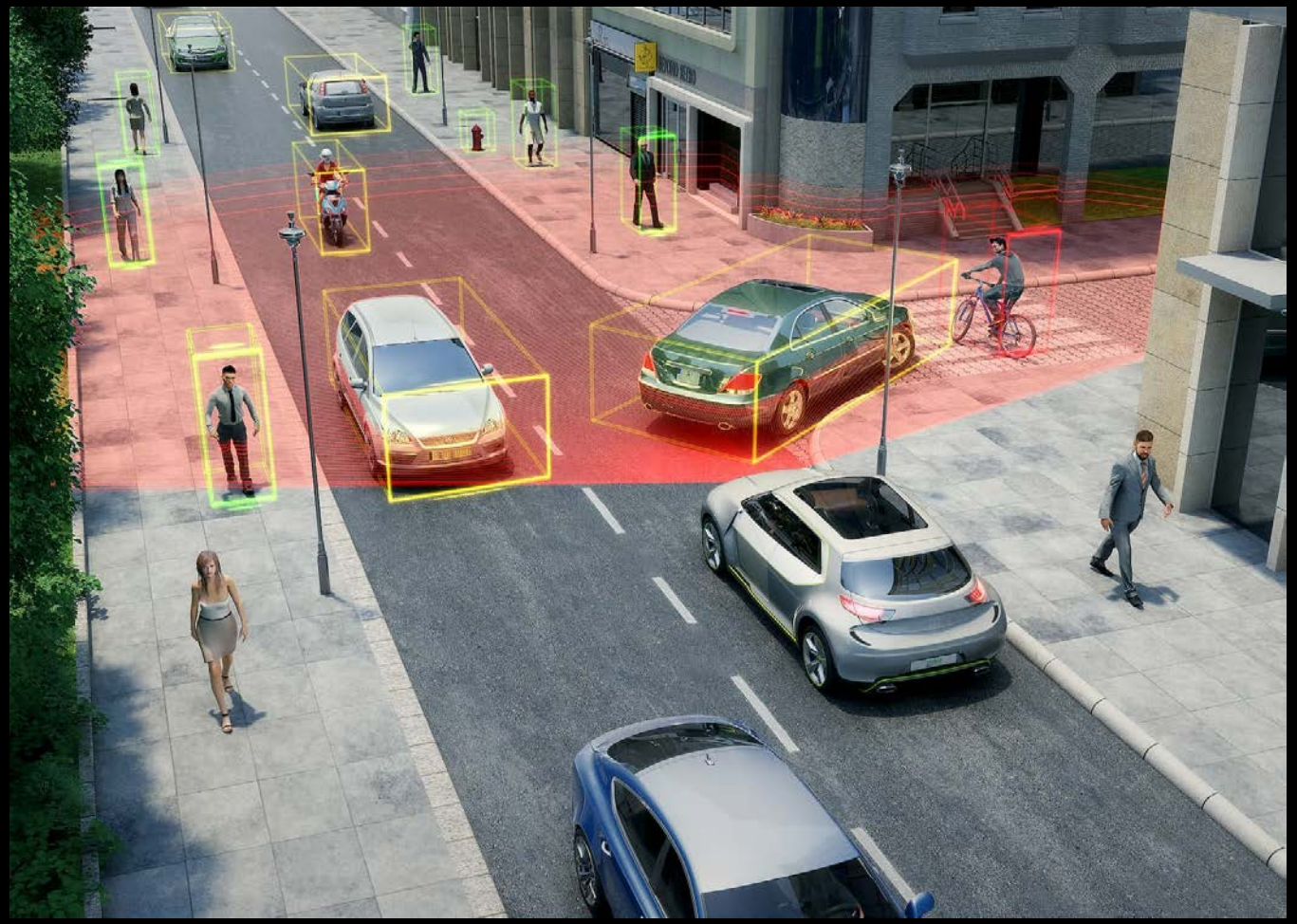


Responsibility:

- Self-awareness (where am I? what am I doing? what is my state?)
- Situational awareness (detection/tracking)

Intro to Sensor Fusion

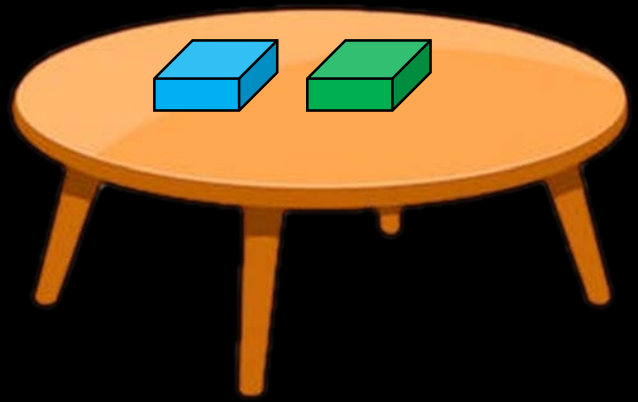
- Example of situational awareness:

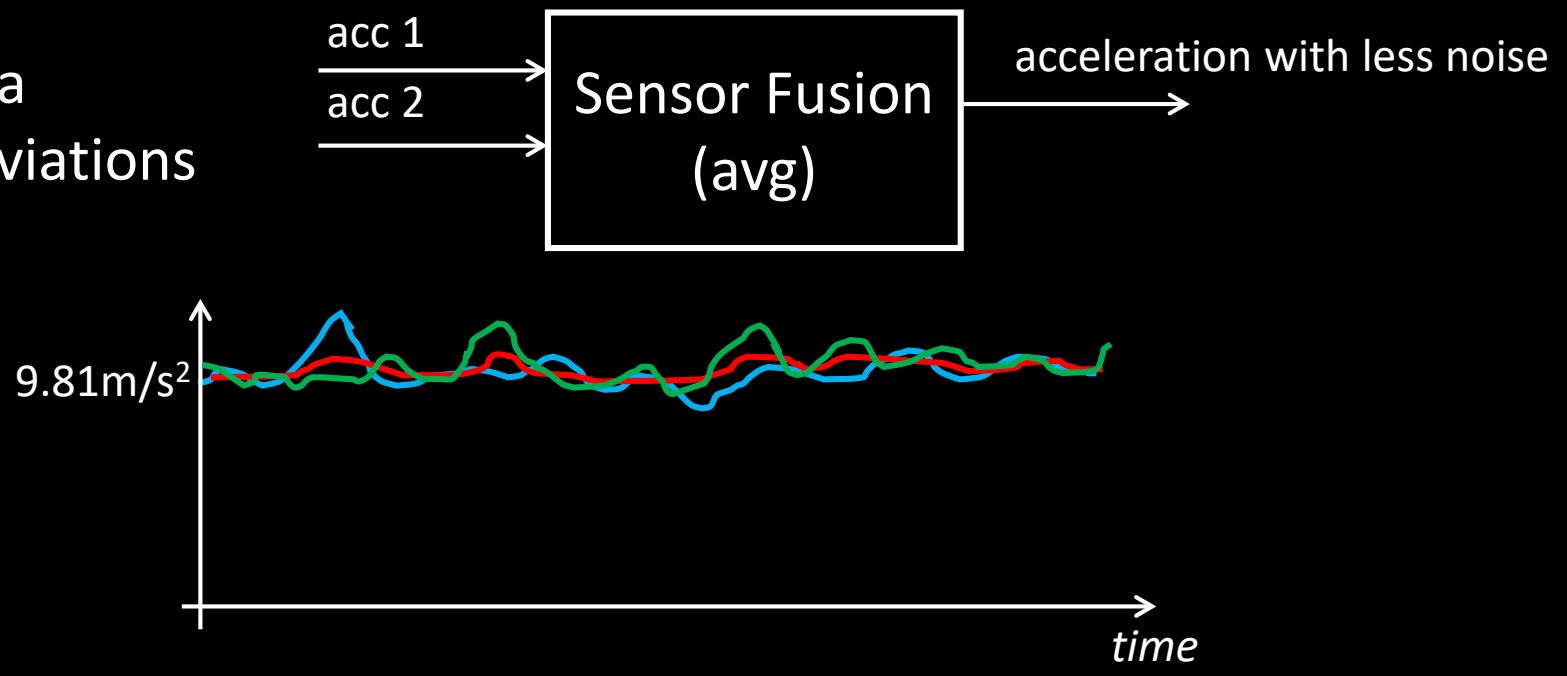


Valeo's LIDAR

Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations





- Adding sensors lowers noise: n =1/(√N)
  - 4 identical sensors = ½ noise
    - (Only if the noise is not correlated!)

Intro to Sensor Fusion

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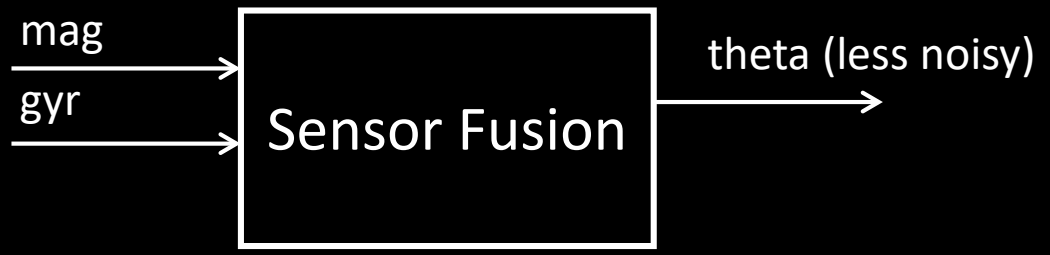
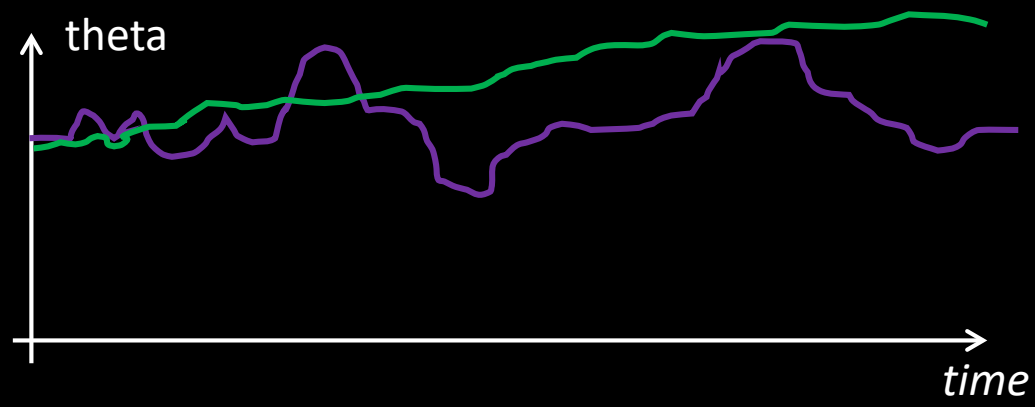
   - Less noise, uncertainty, deviations

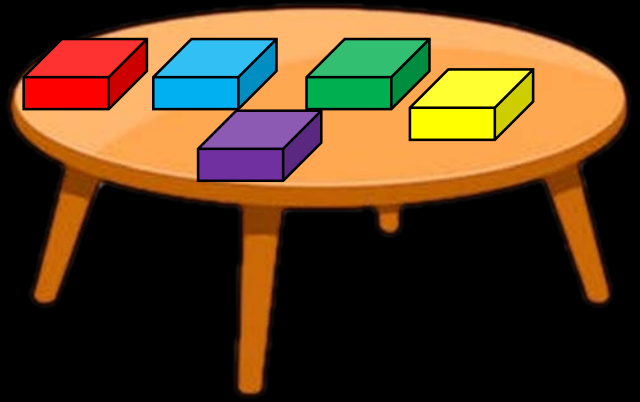


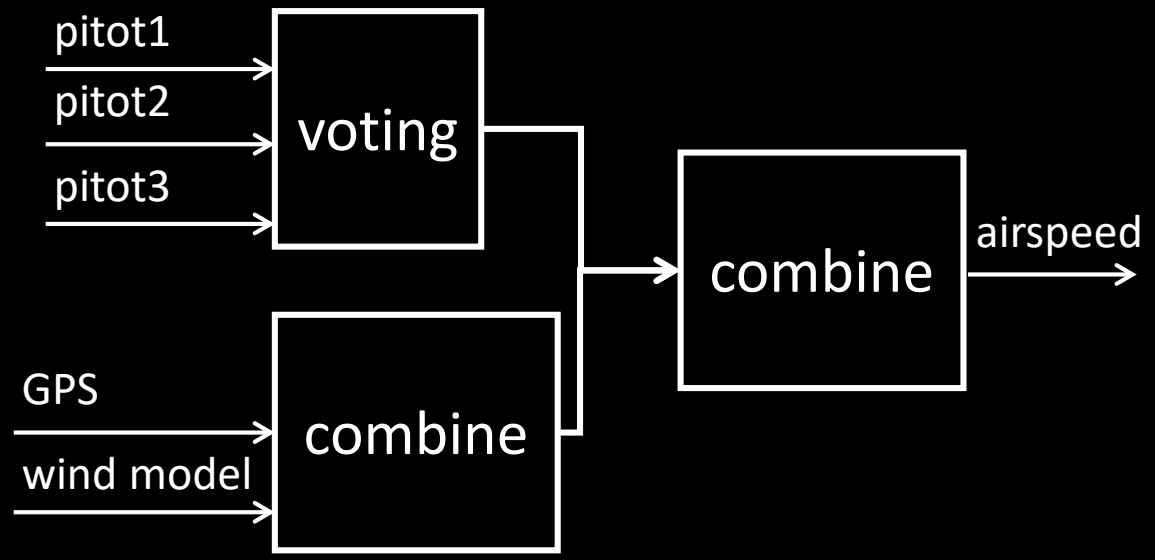


- You can add a 2nd magnetometer to decrease noise
- But some of the noise is correlated
  - Magnetic fields
- Sol 1: Move the sensor away from the magnetic field
- Sol 2: Low pass filter (introduces lag)
- Sol 3: Fuse the mag data with gyr data

Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability





Intro to Sensor Fusion

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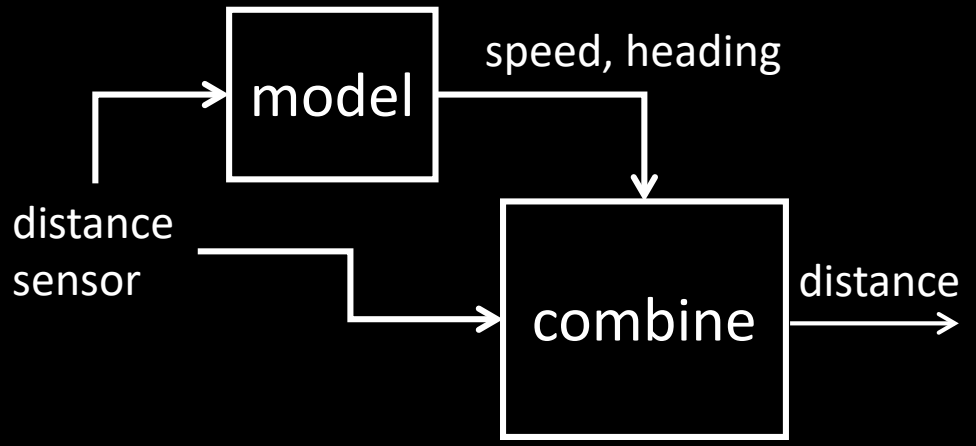
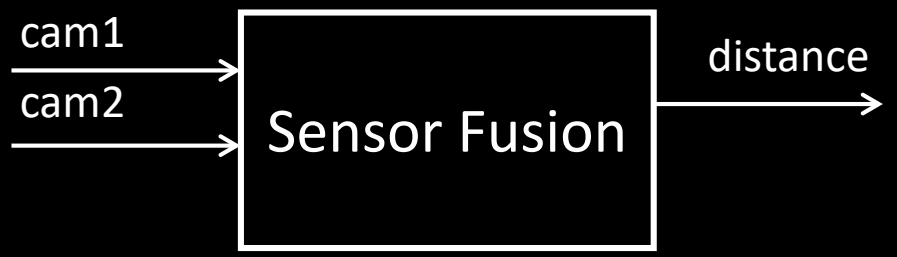
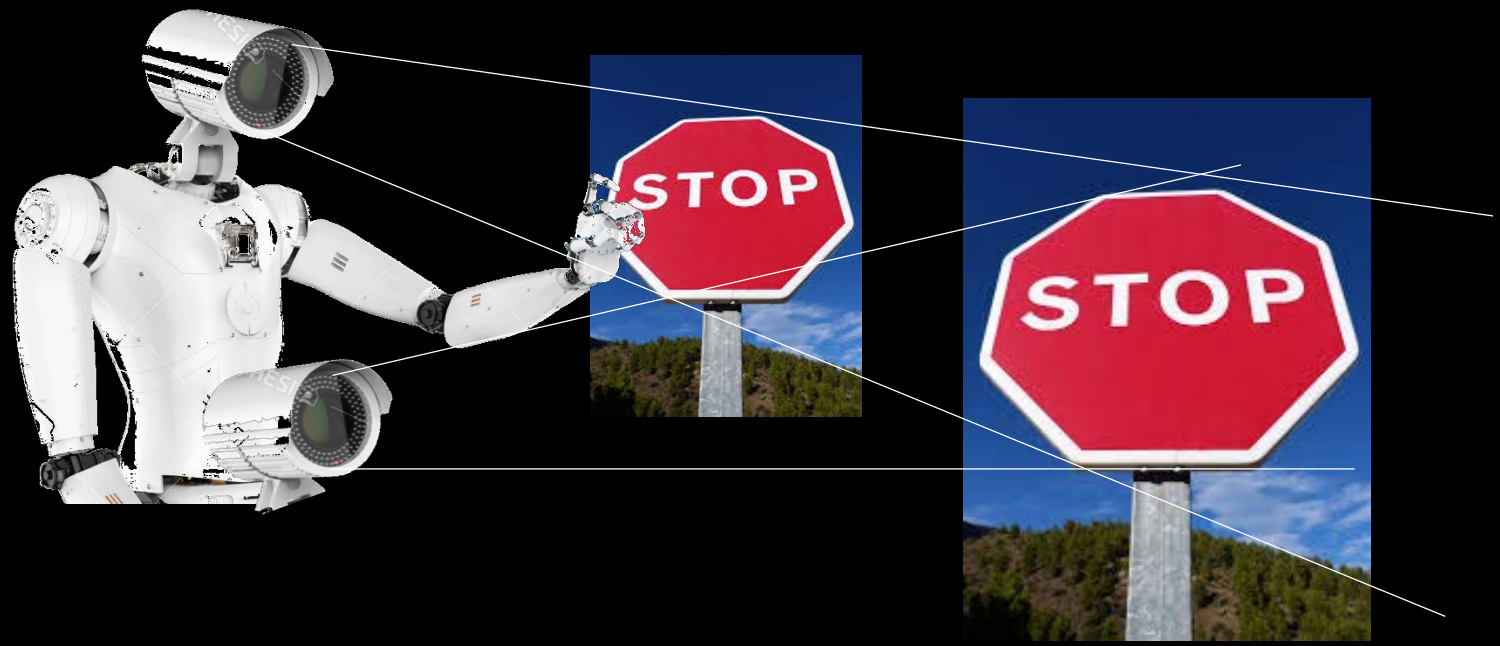


Intro to Sensor Fusion

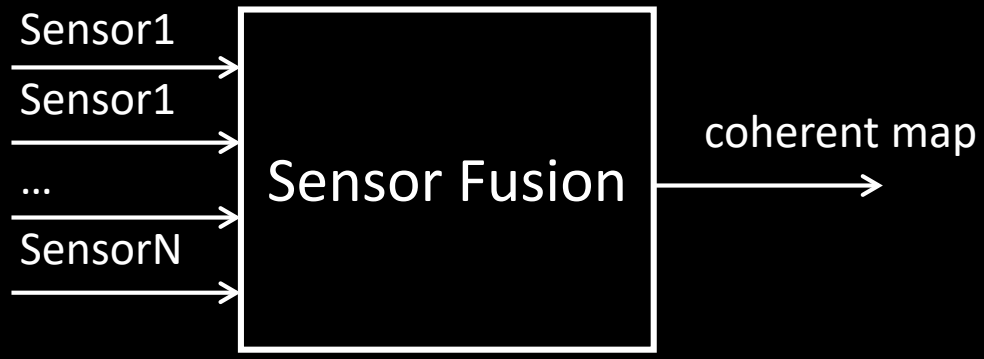
1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability
3. You can measure unmeasured states

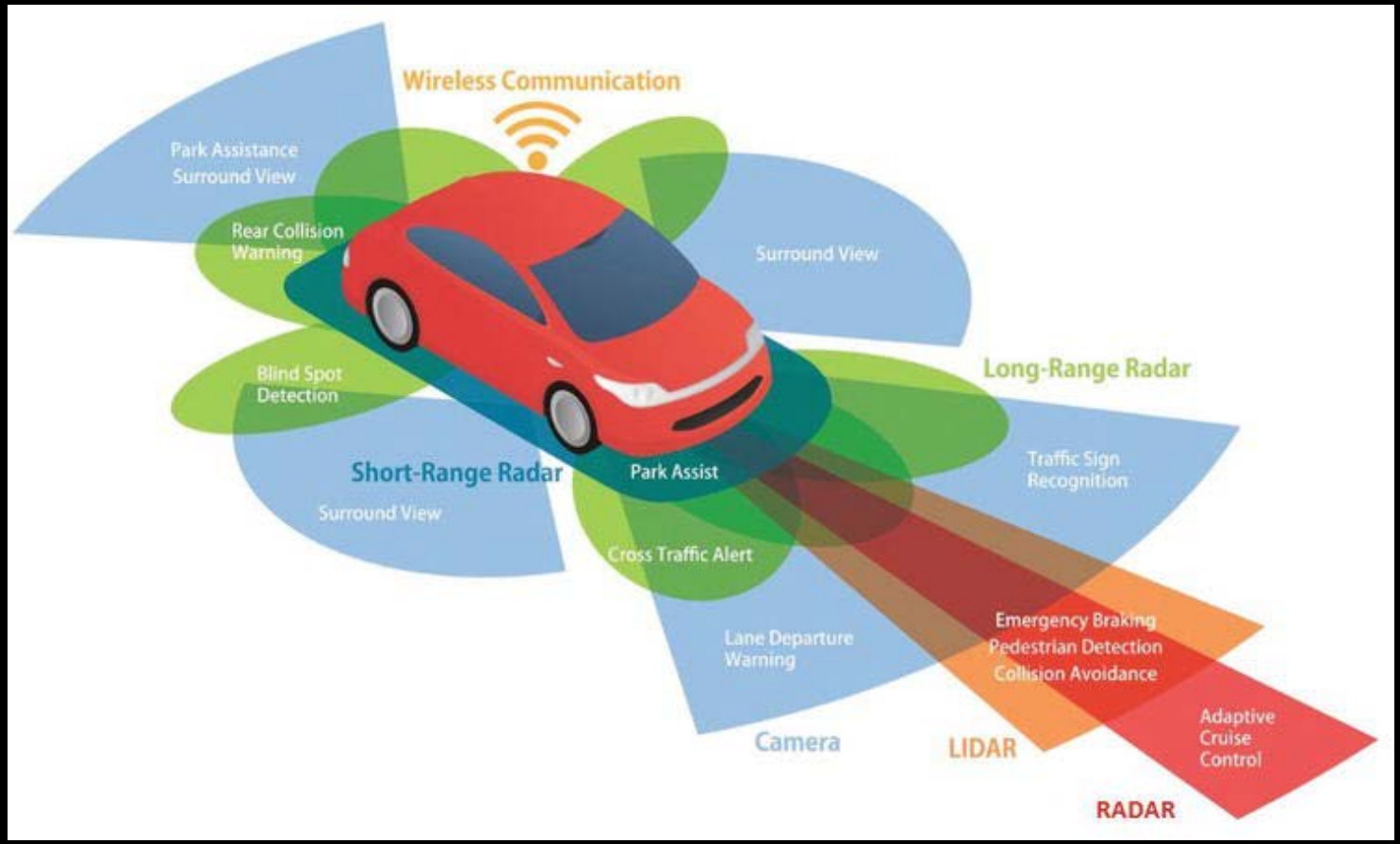




Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability
3. You can measure unmeasured states
4. Increase the coverage area





Sources and References

- http://www.cs.cmu.edu/~rasc/Download/AMRobots4.pdf
- https://www.ti.com/lit/ug/sbau305b/sbau305b.pdf?ts=1599417595209&ref_url=https%253A%252F%252Fwww.google.com%252F
- https://hmc.edu/lair/ARW/ARW-Lecture01-Odometry.pdf
- Matlab Tech Talks on Sensor Fusion (https://www.youtube.com/watch?v=6qV3YjFppuc)