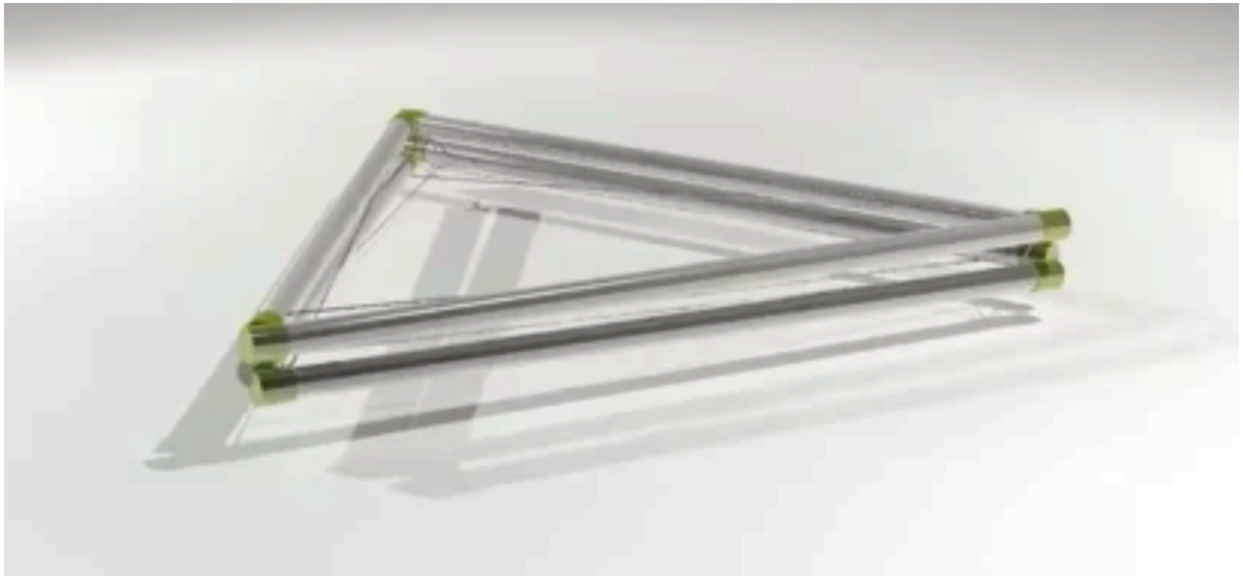
E160 – Lecture 5
Autonomous Robot Navigation

Instructor: Chris Clark

Semester: Spring 2016

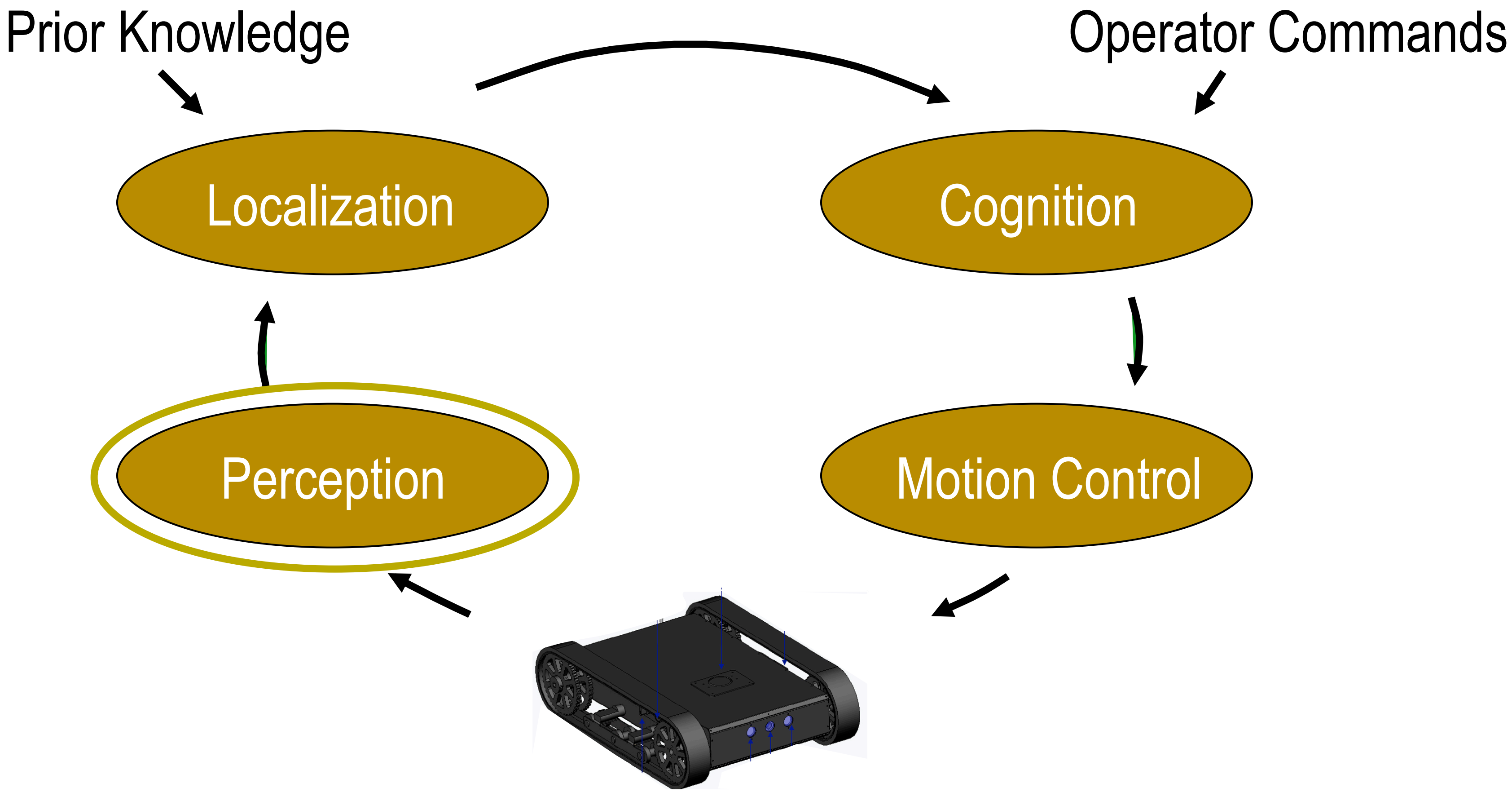
Figures courtesy of Siegwart & Nourbakhsh

Superball



https://www.youtube.com/watch?v=ZBSRdGlAh5s

Control Structures
Planning Based Control



Prior Knowledge

Operator Commands

Localization

Cognition

Perception

Motion Control

Sensors

IMU
Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders

Omnidirectional Camera

Pan-Tilt Camera

Sonar Sensors

Laser Range Scanner

Bumper

Courtesy of Siegwart & Nourbakhsh

Sensors: Outline

1. Sensors Overview
    1. Sensor classifications
    2. Sensor characteristics
2. Sensor Uncertainty
3. Sensor Examples

Sensor Classifications

- **Proprioceptive/Exteroceptive Sensors**
  - Proprioceptive sensors measure values internal to the robot (e.g. motor speed, heading, …)
  - Exteroceptive sensors obtain information from the robots environment (e.g. distance to objects)

Sensors

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Inertial Measurement Unit

Emergency Stop Button

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Bumper

Courtesy of Siegwart & Nourbakhsh

Sensor Classifications

- **Passive/Active Sensors**
  - Passive sensors use energy coming from the environment (e.g. temperature probe)
  - Active sensors emit energy then measure the reaction (e.g. sonar)

Sensors

IMU
Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders

Omnidirectional Camera

Pan-Tilt Camera

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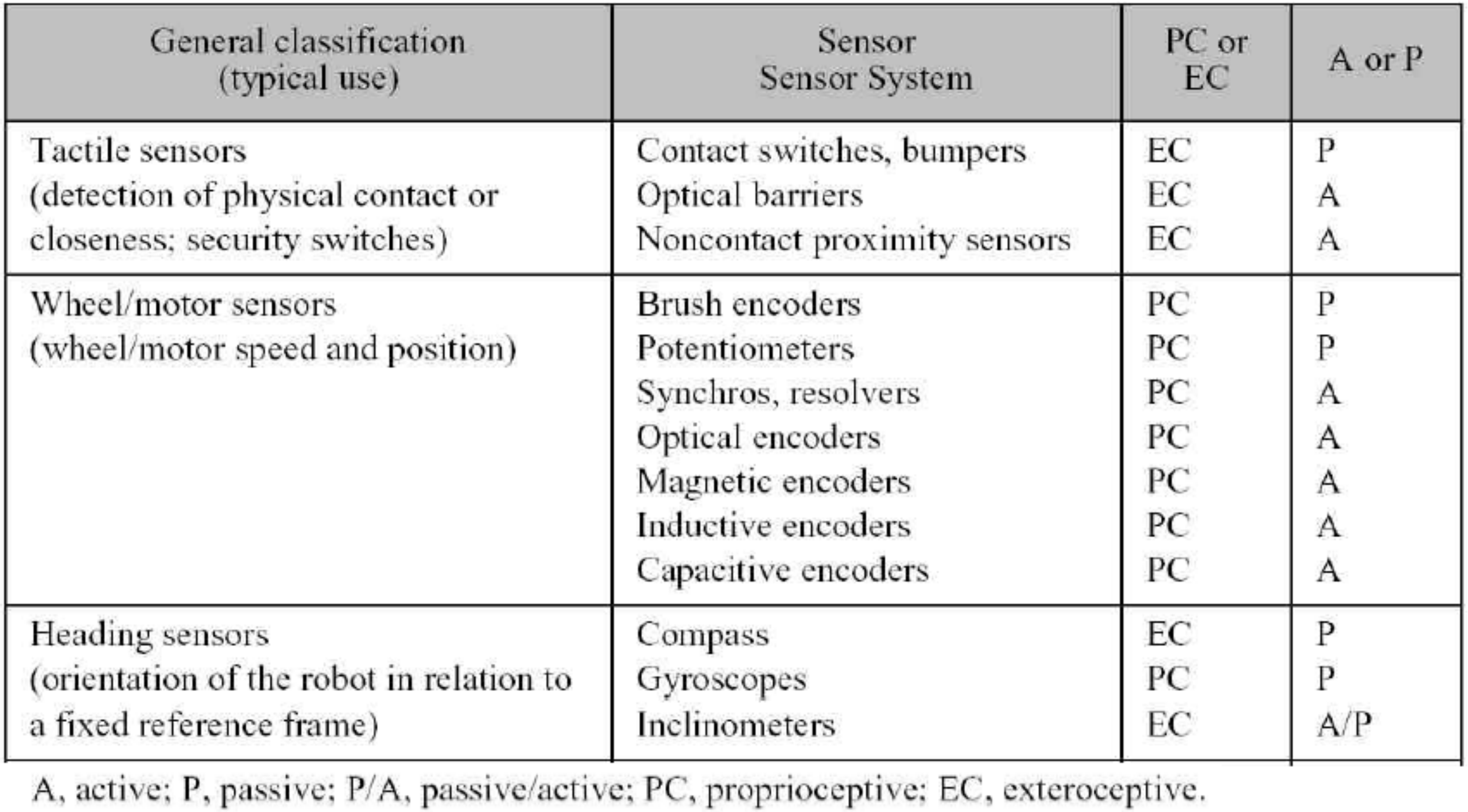
Courtesy of Siegwart & Nourbakhsh

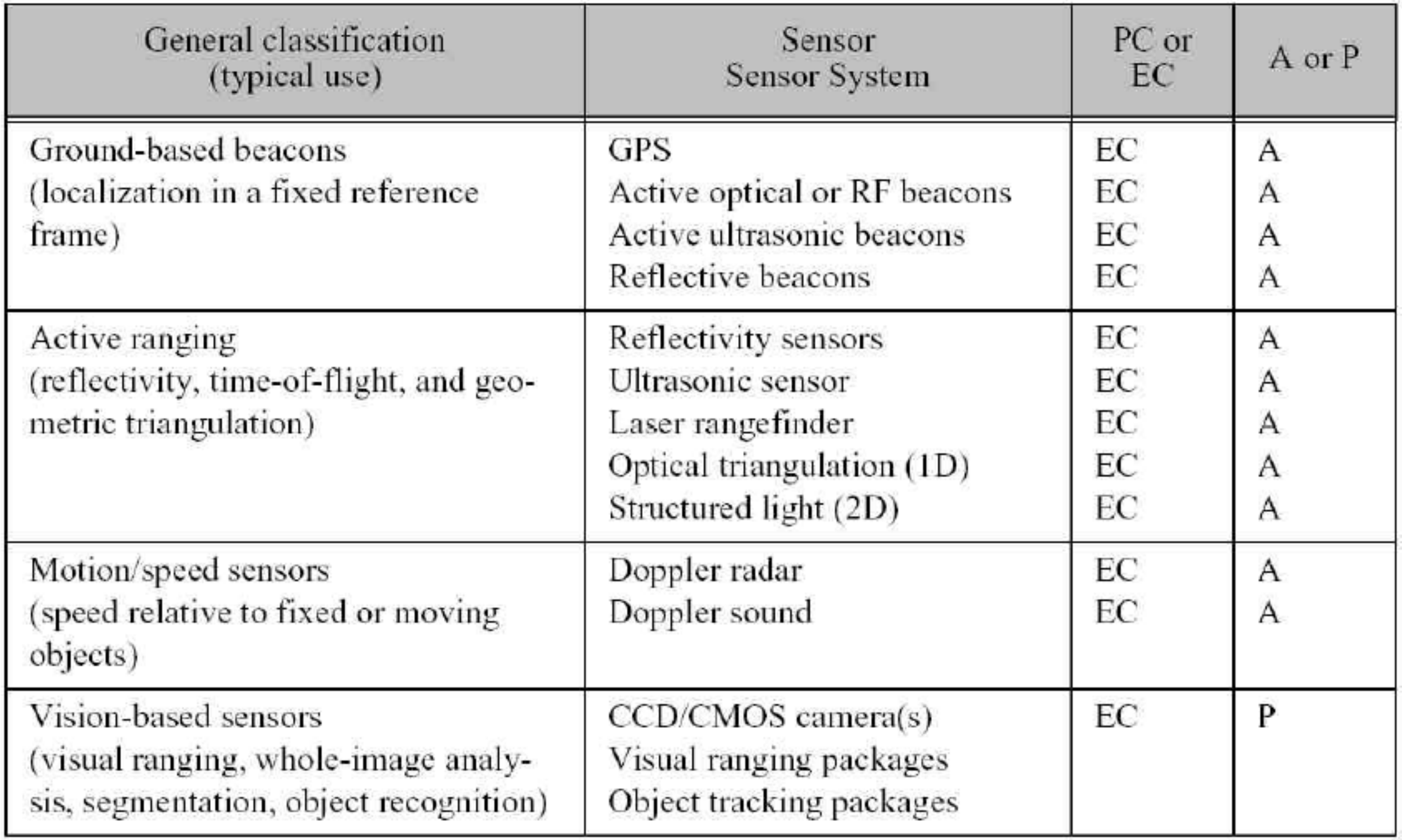
Sensor Classifications



General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

Sensor Classifications



General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Sensors: Basic Characteristics

- **Range**
  - Lower and upper limits
  - E.g. IR Range sensor measures distance between 10 and $80\ cm$.
- **Resolution**
  - minimum difference between two measurements
  - for digital sensors it is usually the A/D resolution.
    - e.g. $5V / 255\ (8\ bit) = 0.02\ V$

Sensors: Basic Characteristics

- **Dynamic Range**
  - Used to measure spread between lower and upper limits of sensor inputs.
  - Formally, it is the ratio between the maximum and minimum measurable input, usually in decibals (dB)

$$\text{Dynamic Range} = 10 \log[\, \text{UpperLimit} / \text{LowerLimit} \,]$$

  - E.g. A sonar Range sensor measures up to a max distance of 3m, with smallest measurement of 1cm.

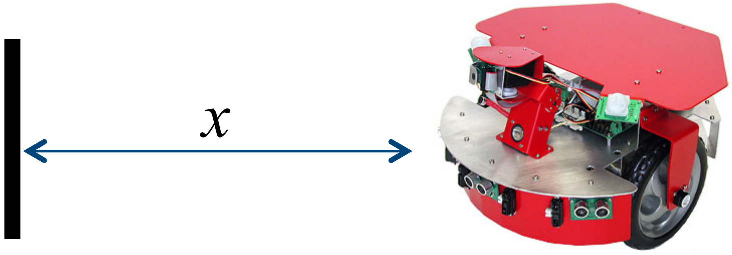
$$\begin{aligned} \text{Dynamic Range} &= 10 \log[\, 3 / 0.01 \,] \\ &= 24.8 \text{ dB} \end{aligned}$$

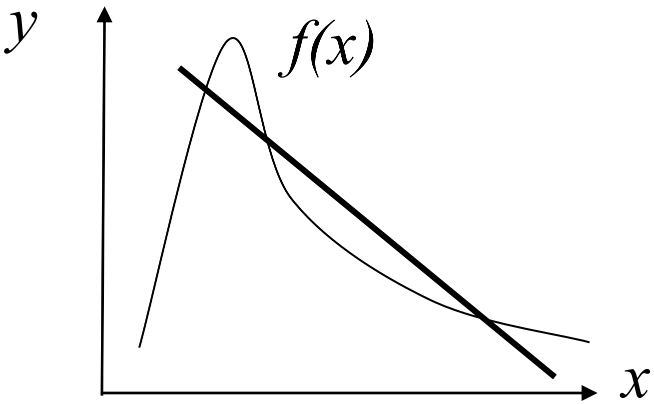
Sensors: Basic Characteristics

- **Linearity**
  - A measure of how linear the relationship between the sensor’s output signal and input signal.
  - Linearity is less important when signal is treated after with a computer

Sensors: Basic Characteristics

- **Linearity Example**
  - Consider the range measurement from an IR range sensor.
  - Let x be the actual measurement in meters, let y be the output from the sensor in volts, and $y = f(x)$.





Sensors: Basic Characteristics

- **Bandwidth or Frequency**
    - The speed with which a sensor can provide a stream of readings
    - Usually there is an upper limit depending on the sensor and the sampling rate
        - E.g. sonar takes a long time to get a return signal.
    - Higher frequencies are desired for autonomous control.
        - E.g. if a GPS measurement occurs at 1 Hz and the autonomous vehicle uses this to avoid other vehicles that are 1 meter away.

Sensors: In Situ Characteristics

- **Sensitivity**
  - Ratio of output change to input change
    - E.g. Range sensor will increase voltage output 0.1 V for every cm distance measured.
  - Sensitivity itself is desirable, but might be coupled with sensitivity to other environment parameters.

- **Cross-sensitivity**
  - Sensitivity to environmental parameters that are orthogonal to the target parameters
    - E.g. some compasses are sensitive to the local environment.

Sensors: In Situ Characteristics

- **Accuracy**
  - The difference between the sensor's output and the true value (i.e. $error = m - v$).

$$accuracy = 1 - \frac{|m - v|}{v}$$

m = measured value

v = true value

Sensors: In Situ Characteristics

- **Precision**
  - The reproducibility of sensor results.

$$precision = \frac{range}{\sigma}$$

$$\sigma = standard\ deviation$$

Sensors: In Situ Characteristics

- **Systematic Error**
  - Deterministic
  - Caused by factors that can be modeled (e.g. optical distortion in camera.)
- **Random Error**
  - Non-deterministic
  - Not predictable
  - Usually described probabilistically

Sensors: In Situ Characteristics

- Measurements in the real-world are dynamically changing and error-prone.
  - Changing illuminations
  - Light or sound absorbing surfaces

- Systematic versus random errors are not well-defined for mobile robots.
  - There is a cross-sensitivity of robot sensor to robot pose and environment dynamics
  - Difficult to model, appear to be random

Sensors: Outline

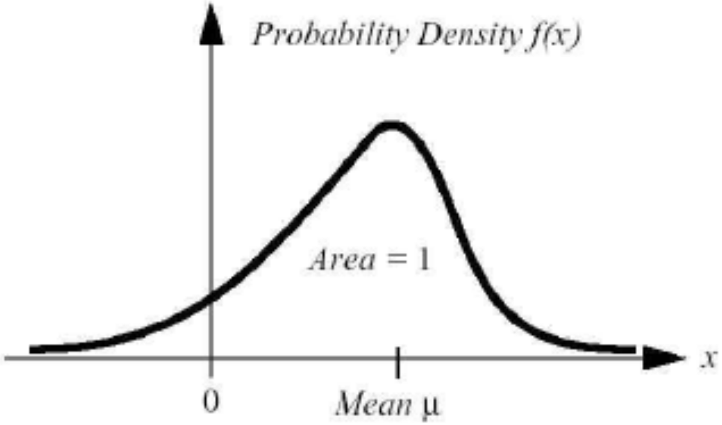
1. Sensors Overview
2. Sensor Uncertainty
3. Sensor Examples

Sensor Uncertainty

- **How can it be represented?**
    - With probability distributions ...

Sensor Uncertainty

- **Representation**
  - Describe measurement as a random variable X
  - Given a set of n measurements
  - Characterize statistical properties of X with a *probability density function f(x)*



Sensor Uncertainty

- Expected value of X is the mean μ

$$\mu = E[X] = \int_{-\infty}^{\infty} x f(x) dx$$

- The variance of X is σ^2

$$\sigma^2 = Var[X] = \int_{-\infty}^{\infty} (x - \mu)^2 f(x) dx$$

Sensor Uncertainty

- Expected value of X is the mean μ

$$\mu = E[X] = \frac{1}{n}\sum_{i=1}^{n} x_i$$

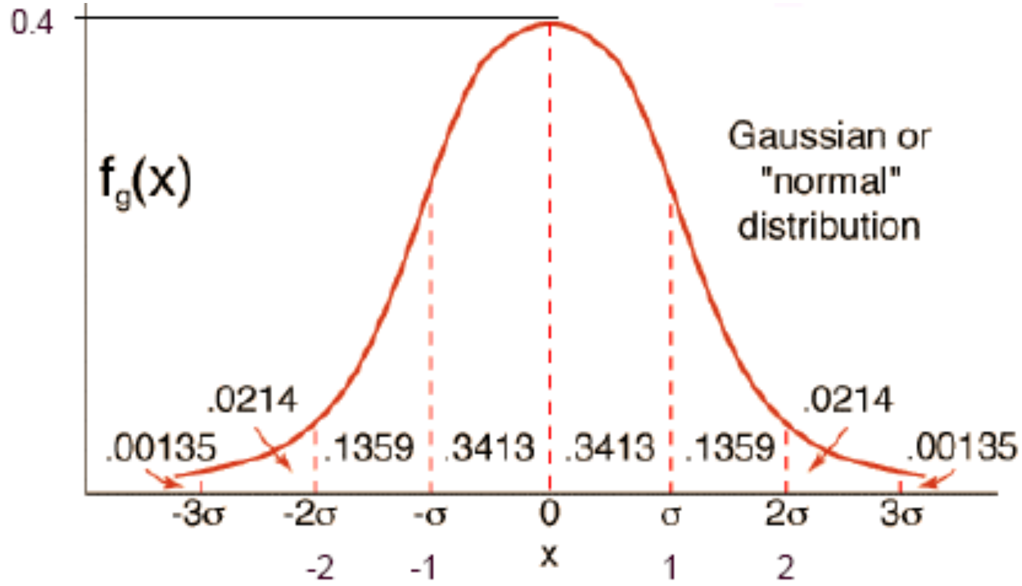
- The variance of X is σ^2

$$\sigma^2 = Var[X] = \frac{1}{n}\sum_{i=1}^{n} (x_i - \mu)^2$$

Sensor Uncertainty

- Use a Gaussian Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$



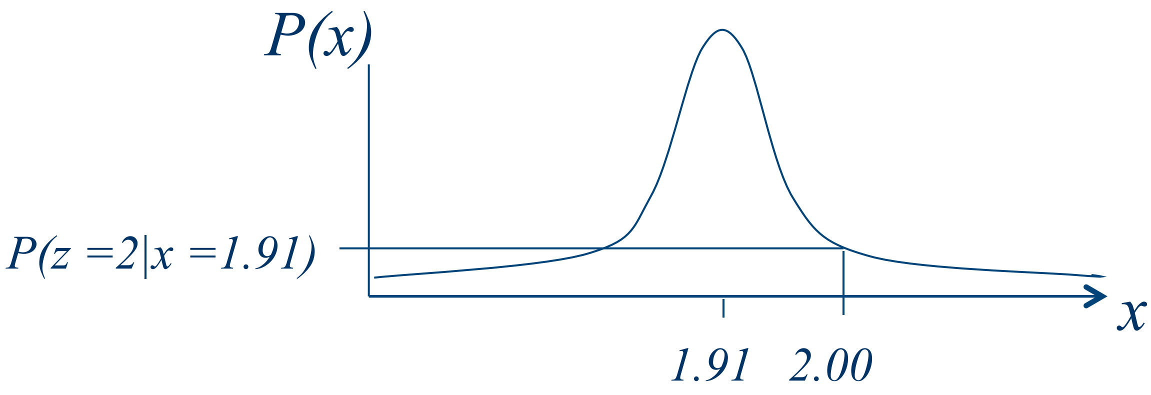
Sensor Uncertainty

- **How do we use the Gaussian?**
  - Learn the variance of sensor measurements ahead of time.
  - Assume mean measurement is equal to actual measurement.

- Example:
  - If a robot is 1.91 meters from a wall, what is the probability of getting a measurement of 2 meters?

Sensor Uncertainty

- **Example cont':**
  - Answer – if the sensor error is modeled as a Gaussian, we can assume the sensor has the following probability distribution:
  - Then, use the distribution to determine $P(z = 2|x = 1.91)$.



Sensors: Outline

1. Sensors Overview
2. Sensor Uncertainty
3. Sensor Examples
    - Encoders
    - Range Sensors

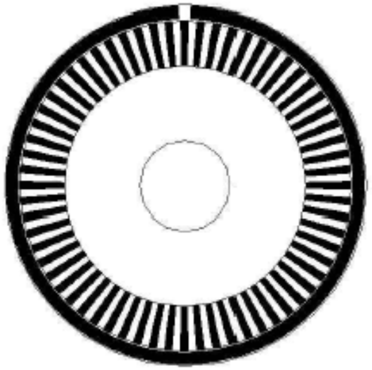
Sensors: Encoders

- A digital optical encoder is a device that converts motion into a sequence of digital pulses. By counting a single bit or by decoding a set of bits, the pulses can be converted to relative or absolute position measurements.

  - Optical encoders are Proprioceptive sensors
  - Can integrate signal to obtain robot position

Sensors: Encoders

- Most encoders are composed of a glass or plastic code part with a photographically deposited pattern organized in tracks. As lines in each track interrupt the beam between a photoemitter-detector pair, digital pulses are produced.



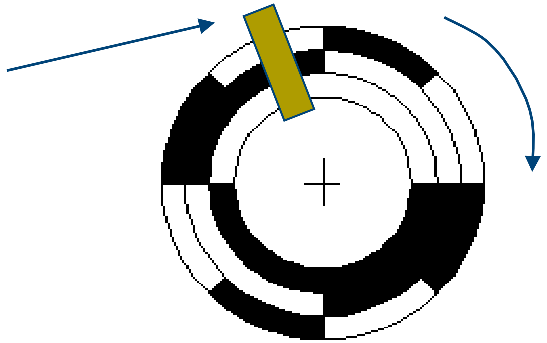
Sensors: Encoders

- **There are two main types**

1. Absolute encoders – which measure the current orientation of a wheel.
2. Incremental encoders – which measure the change in orientation of a wheel.

Sensors: Encoders

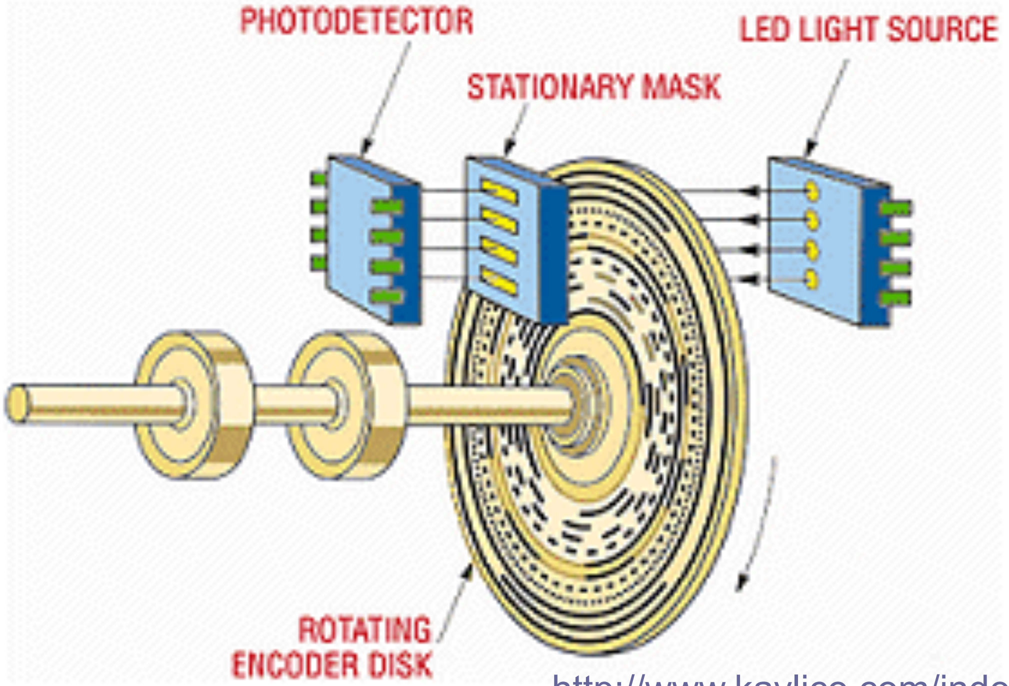
- **Absolute Encoder**
  - The optical disk of the absolute encoder is designed to produce a digital word that distinguishes *N* distinct positions of the shaft.



Checks each track E.g. 101

Sensors: Encoders

- **Absolute Encoder**
  - 12 track example:



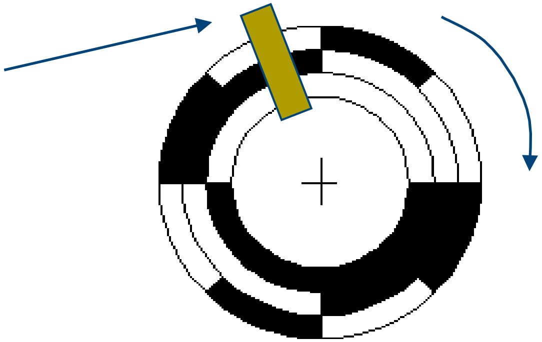
http://www.kavlico.com/index_home.html

Sensors: Encoders

- **Absolute Encoder**
    - The resolution of the encoder will depend on the number of tracks. Each track is either clear or black (1 or 0), giving 2^T possible combinations for T tracks.

Sensors: Encoders

- **Absolute Encoder**
  - For the example above, there are *3* tracks, yielding *8* possible combinations of track readings. Divided among *360* degrees, this leaves a resolution of *360/8* = *45* degrees.



Checks each track E.g. 101

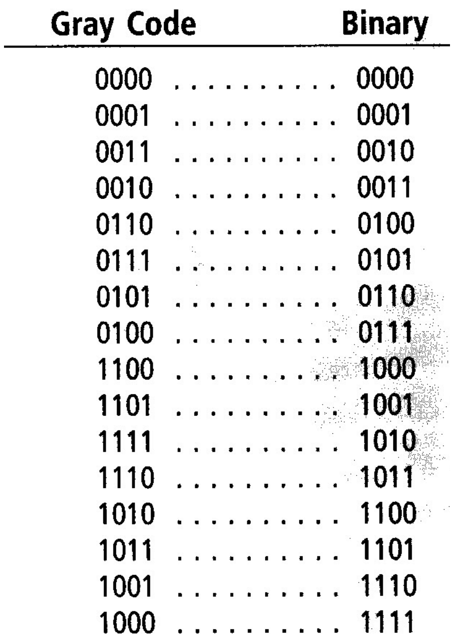
  - *Note*: Needs a larger disk or strip for higher resolution

Sensors: Encoders

- **Gray Code:**
  - The most common types of numerical encoding used in the absolute encoder are gray and binary codes
  - Gray code uses an ordering of binary numbers such that **only one bit changes from one entry to the next**.
  - Gray codes for *4* or more bits are not unique.

Sensors: Encoders

- **Gray Code:**



Gray Code	Binary
0000	0000
0001	0001
0011	0010
0010	0011
0110	0100
0111	0101
0101	0110
0100	0111
1100	1000
1101	1001
1111	1010
1110	1011
1010	1100
1011	1101
1001	1110
1000	1111

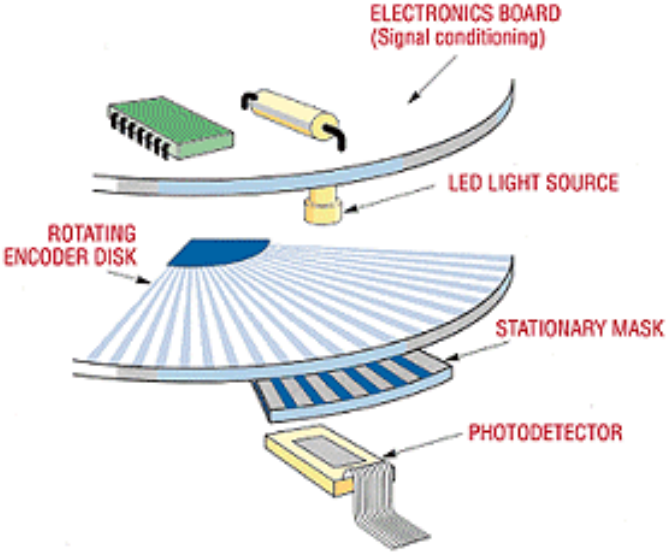
  - Gray codes for *4* or more bits are not unique

Sensors: Encoders

- **Why Gray Code?**
  - Gray code is used is to eliminate errors that occur due to timing inconsistencies.
  - When a disk moves from one position to the next, the different bit flips will occur at different times.
  - Example:
    - When changing from 0011 to 0100, three different bits get flipped. If these happen at different times, the encoder could spit out 0011, 0111, 0101, 0100. This gives 2 erroneous measurements.

Sensors: Encoders

- **Incremental Encoders**
  - Incremental encoders operate by means of a grating moving between a light source and a detector.



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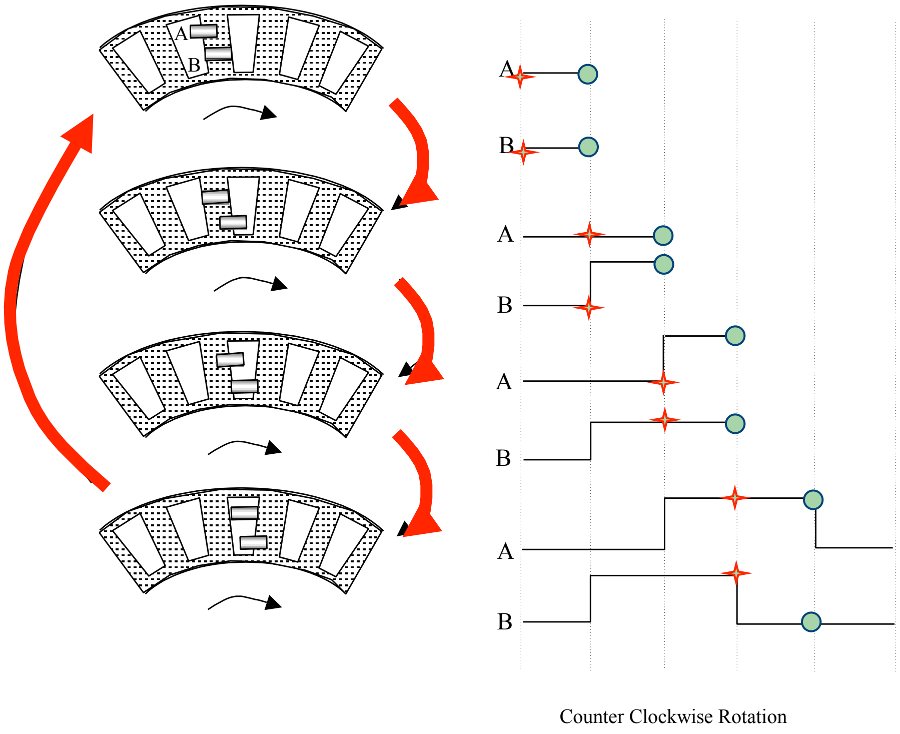
Sensors: Encoders

- **Incremental Encoders**
  - They need a reference for position measurement.
  - Higher resolution can be obtained more easily.
  - Needs a decoder to detect direction and position/ velocity.

Sensors: Encoders

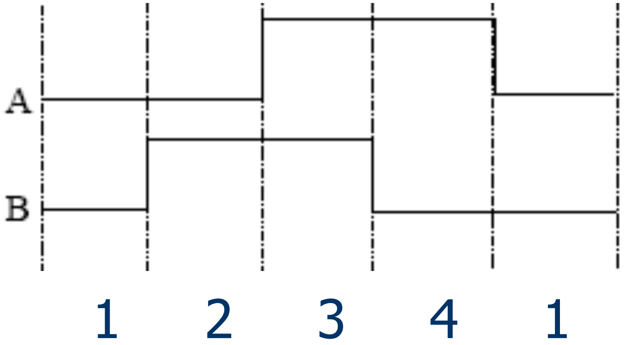
- **Incremental Encoders**
  - 4X Decoding:



Counter Clockwise Rotation

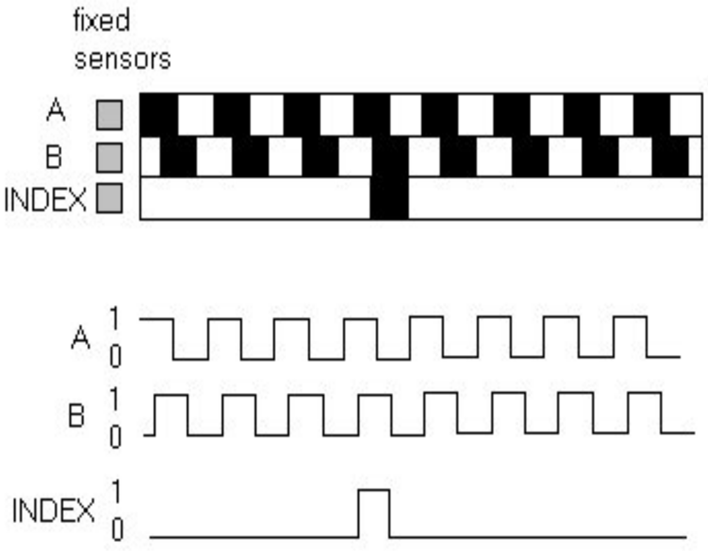
Sensors: Encoders

- **Incremental Encoders**
  - *4X* Decoding: Resolution is $360/4N$, where N is the number of gratings.



Sensors: Encoders

- **Incremental Encoders**
  - Example:
    - Encoder with 2 tracks instead of 2 sensor positions.
    - Home position track.



Sensors: Outline

1. Sensors Overview
2. Sensor Uncertainty
3. Sensor Examples
    - Encoders
    - Range Sensors

Sensors: Range Sensors

- Range sensors make use of propagation speed of sound or electromagnetic waves respectively.
- Distance traveled by a wave is given by:

$$d = c\,t$$

d = distance traveled

c = speed of wave propagation

t = time of flight

Sensors: Range Sensors

- For sound, $v = 0.3\ m/ms$
- For electromagnetic signals, $v = 0.3\ m/ns$
- If distance = $3\ m$:
  - $t_{ultrasonic} = 10\ ms$
  - $t_{laser} = 10\ ns$
  - t_{laser} *is difficult to measure, laser range sensors are expensive and difficult*

Sensors: Range Sensors

- **Quality depend on:**
  - *Uncertainties of time of arrival of reflected signal*
  - *Inaccuracies in time of flight measure (laser)*
  - *Opening angle of transmitted beam (sound)*
  - *Interaction with the target (specular reflections)*
  - *Variation of propagation speed*

Sensors:
Ultrasonic Range Sensors

- Sensor transmits a packet of ultrasonic pressure waves

$$d = c\, t / 2$$

- The speed of sound c $(340\ m/s)$ in air is:

$$c = \sqrt{\gamma R T}$$

γ = ratio of specific heats

R = gas constant

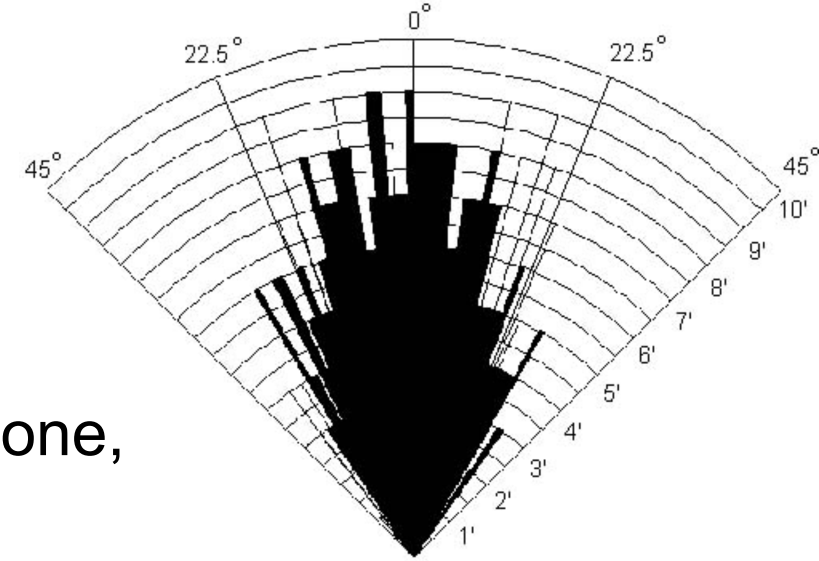
T = temperature in Kelvin

Sensors:
Ultrasonic Range Sensors

Signals of an ultrasonic sensor

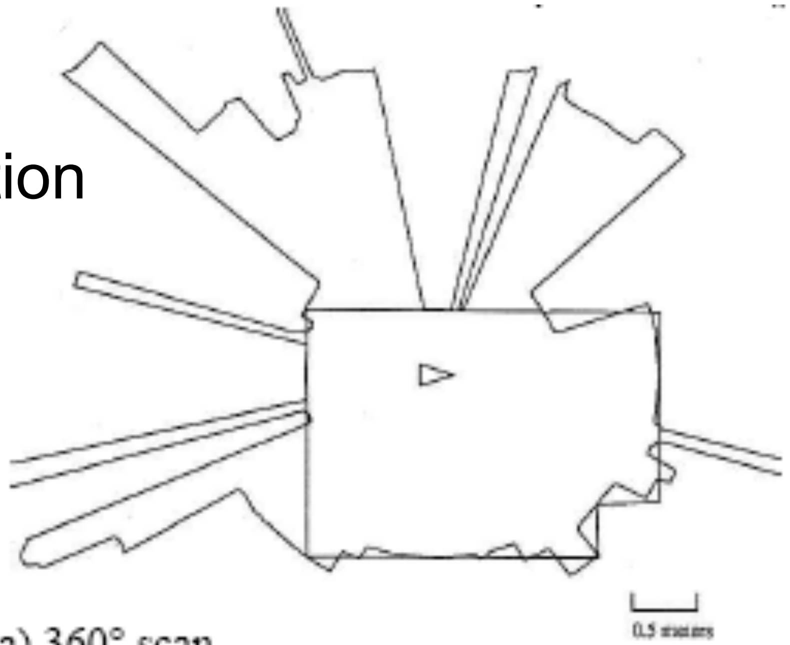
Sensors:
Ultrasonic Range Sensors

- Frequency typically 40 – 180 kHz
- Wave generated by piezo transducer
- Receiver may coincide with transmitter
  - Problem with objects too close, Blanking time!
- Sound beam propagates in cone, not points



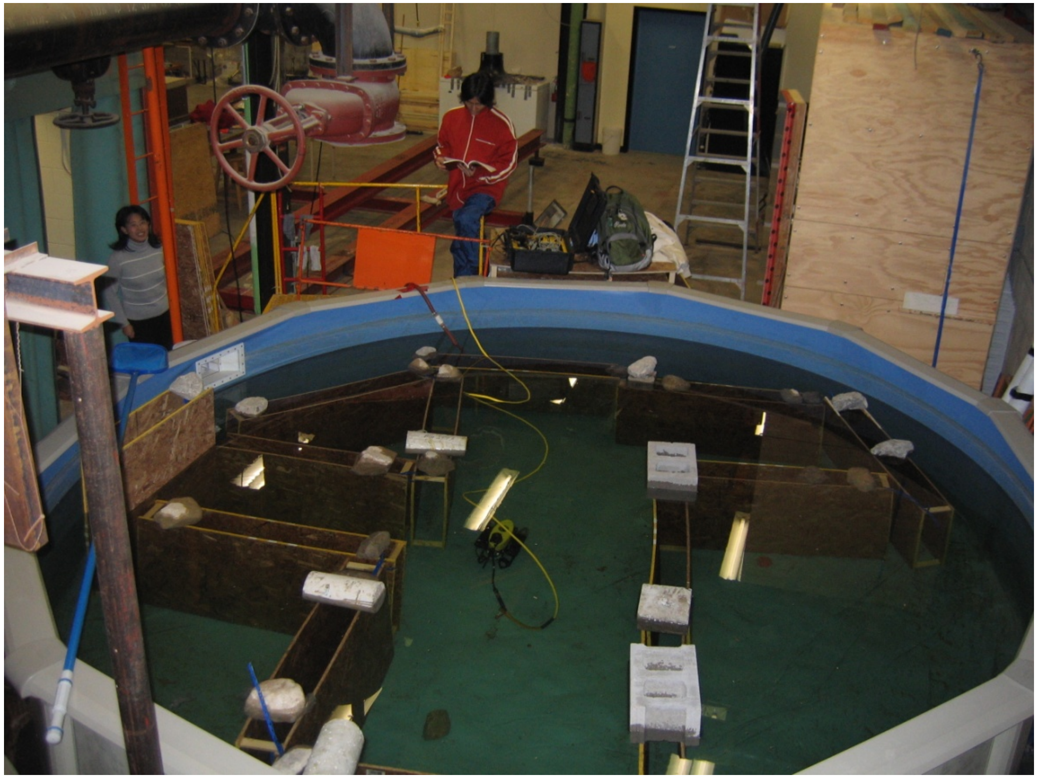
Sensors:
Ultrasonic Range Sensors

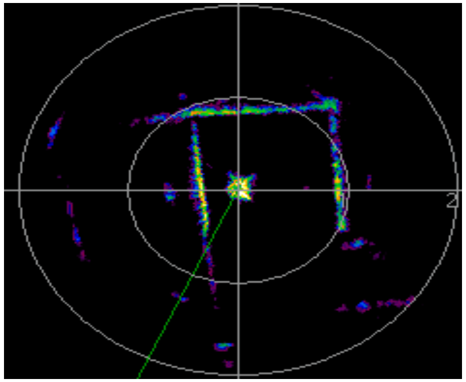
- Other problems
  - Soft surfaces that absorb most of sound energy
  - Surfaces that are not perpendicular to the direction of sound, get specular reflection
  - Low Bandwidth



a) 360° scan

Sensors:
Example Application 1

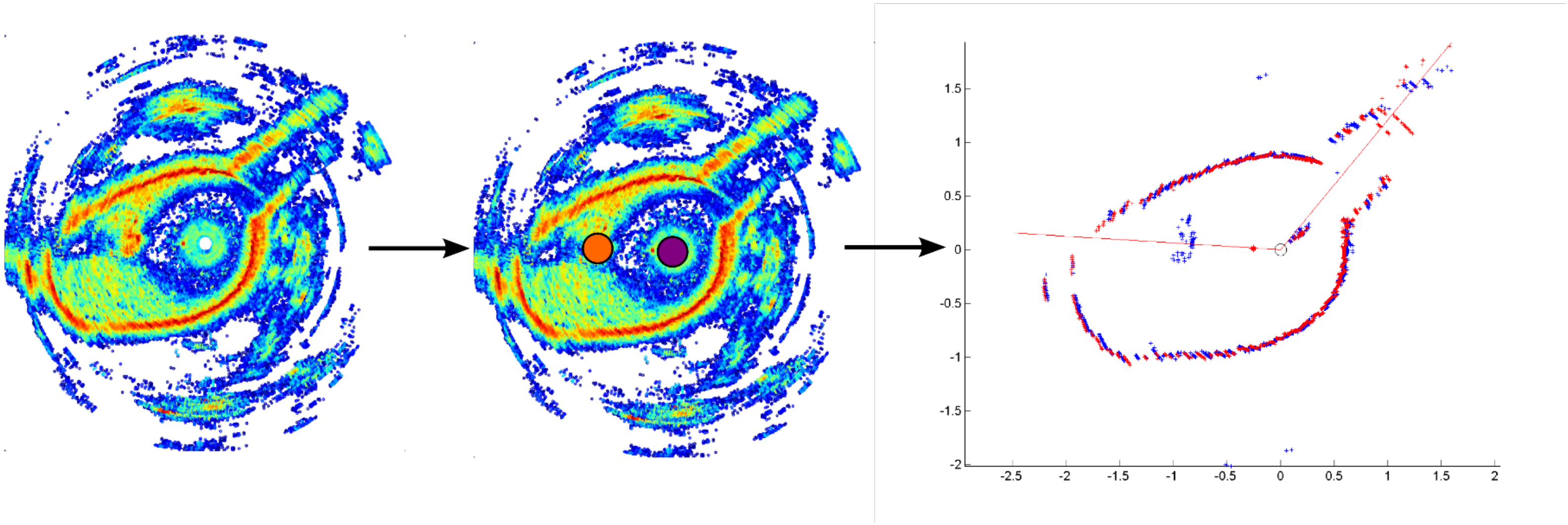




Clark, Cal Poly SLO

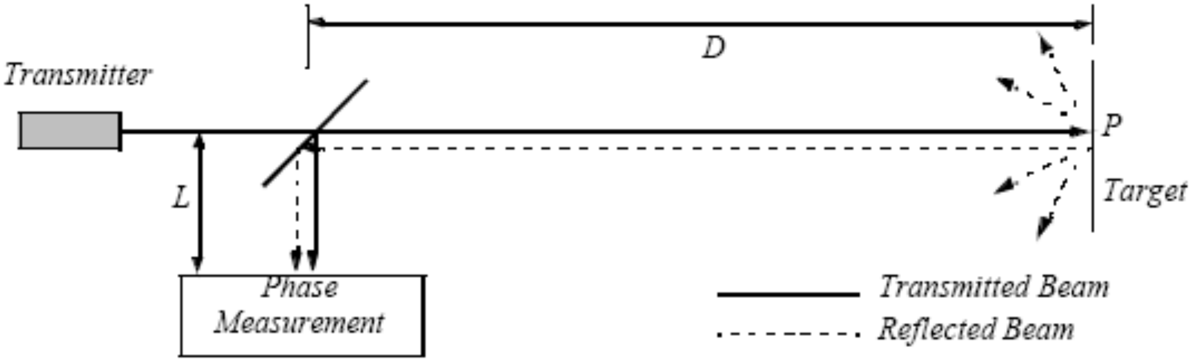
Dual Robot Deployments

- leap-frog scanning



Sensors:
Laser Range Sensors

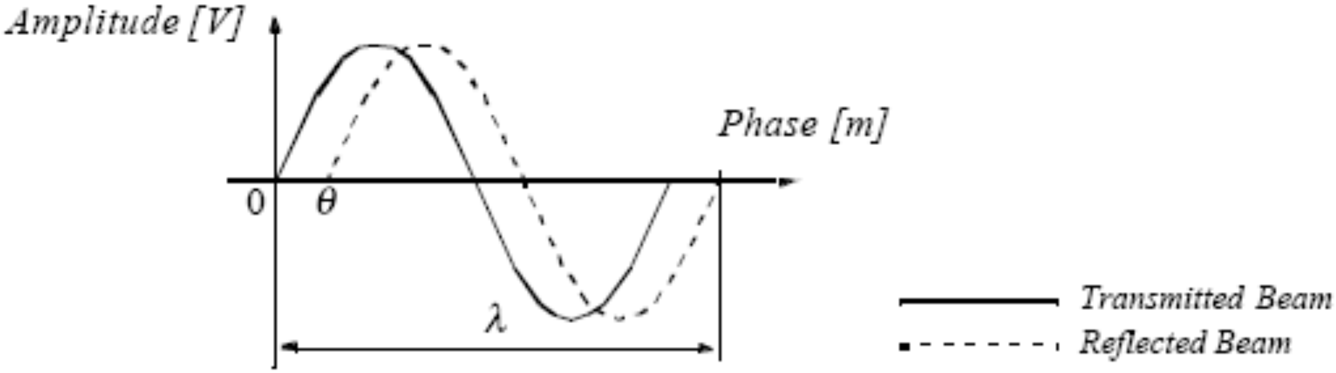
- Transmitted and received beams coaxial
- Transmitter illuminates target with beam
- Receiver detects time needed for round-trip



Sensors:
Laser Range Sensors

- Methods for measuring time of flight:
  - Use pulsed laser and measure time of flight directly

    OR
  - Measure the phase shift



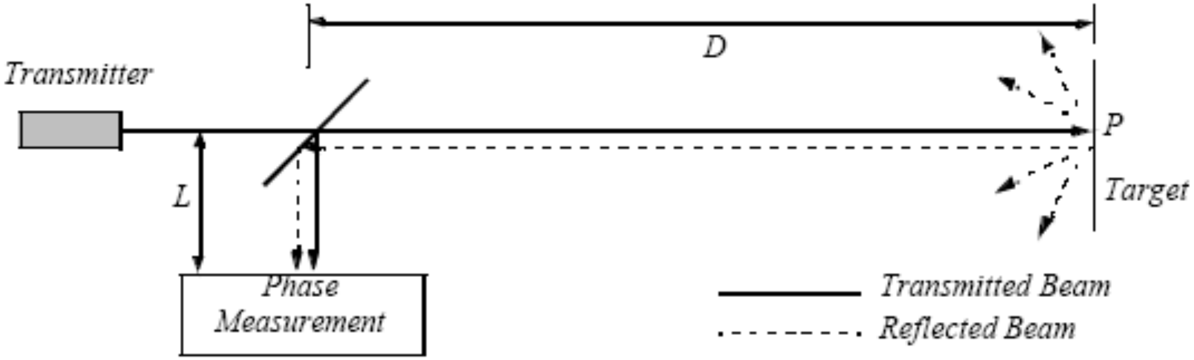
Sensors:
Laser Range Sensors

- Phase Shift Measurement:
  - Wavelength λ relates to modulating freq. f as:

$$\lambda = c/f$$

  - Total distance is:

$$D' = L + 2D$$

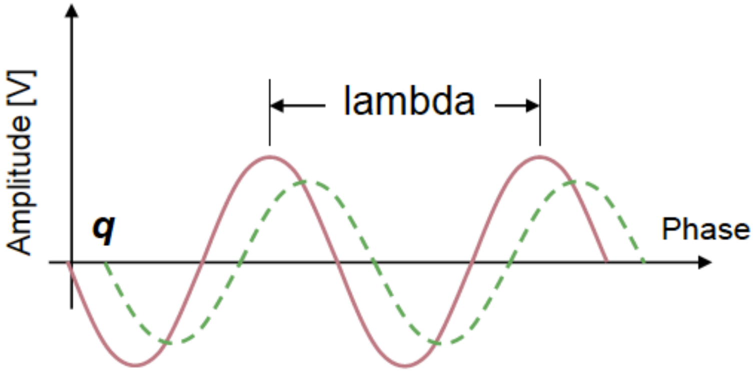


Sensors:
Laser Range Sensors

- We want to measure the distance to target

$$2D = \lambda\, \theta / 2\pi$$

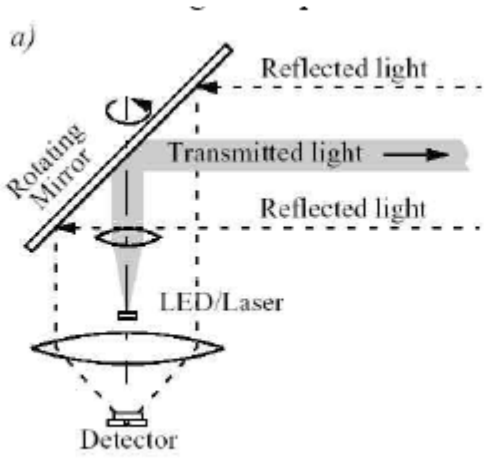
  - Where θ is the phase difference between the transmitted and received beams.



  - Note there is theoretical ambiguity in range estimates

Sensors:
Laser Range Sensors

- Schematic and examples:



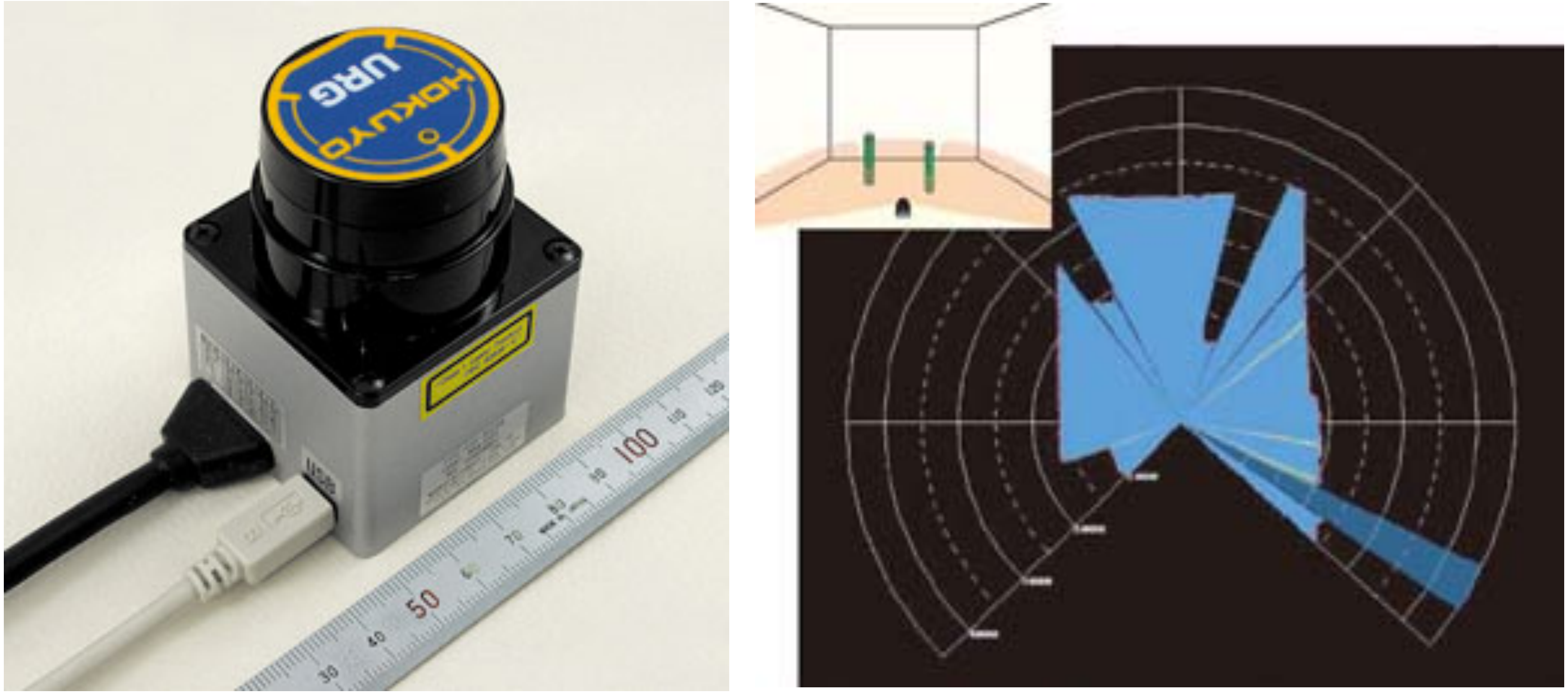
a) Schematic

b) EPS Technologies

c) SICK

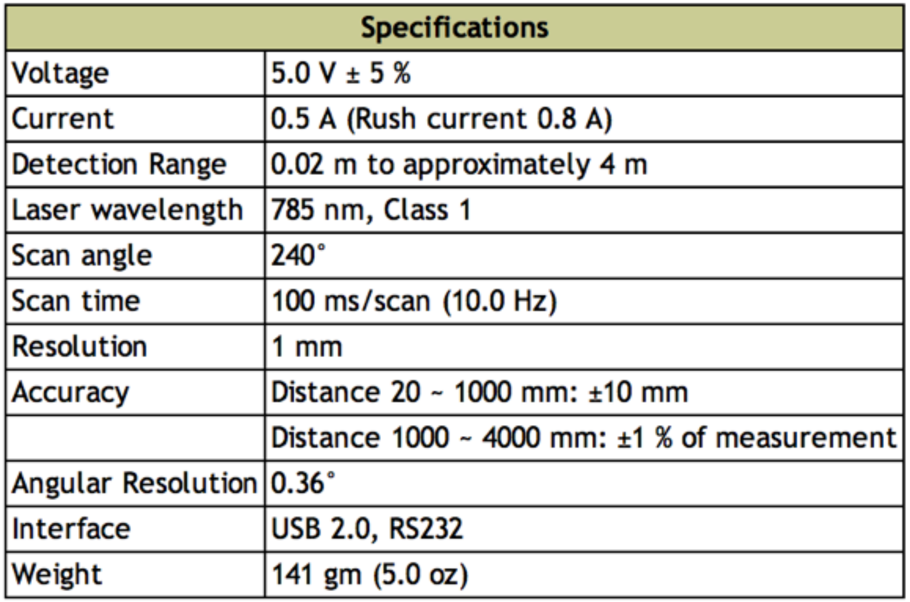
Sensors:
Laser Range Sensors

- Schematic and examples (cont’):



d) Hokuyo URG Scanning laser range finder

Sensors:
Laser Range Sensors

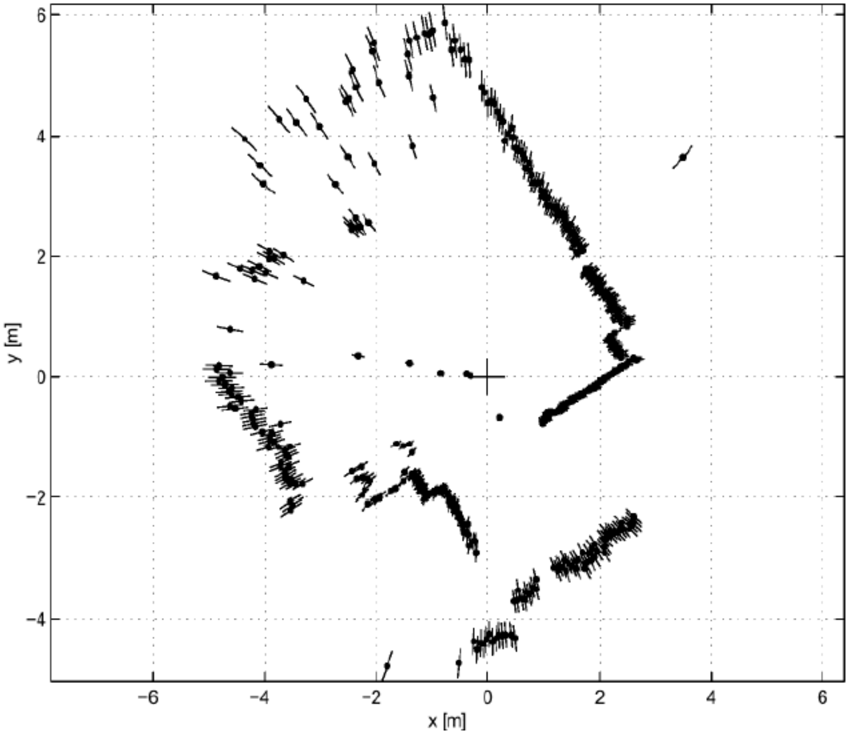


Specifications	
Voltage	5.0 V ± 5 %
Current	0.5 A (Rush current 0.8 A)
Detection Range	0.02 m to approximately 4 m
Laser wavelength	785 nm, Class 1
Scan angle	240°
Scan time	100 ms/scan (10.0 Hz)
Resolution	1 mm
Accuracy	Distance 20 ~ 1000 mm: ±10 mm
	Distance 1000 ~ 4000 mm: ±1 % of measurement
Angular Resolution	0.36°
Interface	USB 2.0, RS232
Weight	141 gm (5.0 oz)

d) Hokuyo URG Scanning laser range finder

Sensors:
Laser Range Sensors

- Uncertainty
  - Uncertainty of the range is inversely proportional to the square of the received signal amplitude.
  - Dark, distant objects will not produce such good range estimated as closer brighter objects …



Sensors:
Laser Range Sensors

- Schematic and examples (cont’):

e) SICK in 3D scanning configuration

Sensors: Triangulation Laser Range Sensors

- Distance is inversely proportional to x

$$D = f L / x$$