• Lab 2
  – Installing all the packages

• Logistics & Travel
  – Makeup class
  – Recorded class
  – Class time to work on lab
  – Remote class
Classification of Sensors

• Proprioceptive sensors
  – internal to robot

• Exteroceptive sensors
  – information from robot’s environment

• Passive sensors

• Active sensors
Wheel Encoders, Beacon Systems
“Indoor GPS”

• Sound

• Wi-Fi
  – RSSI (Received Signal Strength Indication)
  – Fingerprinting (lookup table)
  – Angle of arrival
  – Time of Flight
Neato

• On-board Room Positioning System (RPS) technology

• Maps with only one projector!
Neato

- [https://www.researchgate.net/publication/221070323_Vector_field_SLAM](https://www.researchgate.net/publication/221070323_Vector_field_SLAM)
(From 2011)
So Far...

• Compass
• Wheel encoders
• Gyroscope
  – v.s. Accelerometer?
• GPS
  – Beacons
  – Sound
  – WiFi
  – Etc.
Range Sensors

• How do “time of flight” sensors work?
• What problems would there be?
• Differences between using sound vs. light?
Range Sensors (time of flight) (1)

• Large range distance measurement: *range sensors*

• Range information:
  – key element for localization and environment modeling
  – Ultrasonic sensors: Sound
  – Laser sensors: electromagnetic waves
Range Sensors (time of flight) (2)

- Propagation speed $v$ of sound: 0.3 m/ms
- Propagation speed $v$ of electromagnetic signals: 0.3 m/ns, one million times faster
- Time of flight $t$ with electromagnetic signals is not an easy task
  - Laser range sensors expensive and delicate
- Quality of time of flight range sensors mainly depends on:
  - Uncertainties about the exact time of arrival of the reflected signal
  - Inaccuracies in the time of flight measure (laser range sensors)
  - Opening angle of transmitted beam (ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed
  - Speed of mobile robot and target (if not at standstill)
Ultrasound Sensor (1)

- Transmit packet of (ultrasound) pressure waves
- Distance $d$ of the echoing object can be calculated based on the propagation speed of sound $c$ and the time of flight $t$

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

where

$\gamma$: ratio of specific heats
$R$: gas constant
$T$: temperature in degree Kelvin
Ultrasonic Sensor (2)

Analog Signal

Threshold

Integrated Input
Ultrasonic Sensor (3)

Threshold: high initially (avoid ringing) then decreases over time

Very close objects = trouble!
Ultrasonic Sensor (4)

- typically a frequency 40 - 180 kHz
- generation of sound wave: piezoelectric transducer
  - Early application: WWI sonar
- sound beam propagates in a cone-like manner
  - opening angles around 20 to 40 degrees
  - segments of an arc (sphere for 3D)

Typical intensity distribution of an ultrasonic sensor

Amplitude [dB]

measurement cone
Ultrasonic Sensor (5)

- Soft surfaces that absorb most of the sound energy
- Surfaces far from perpendicular to the direction of sound: specular reflection

360° scan 0.5 meters
Speed of Light

Fizeau apparatus
Speed of Light

Fizeau apparatus
Foucault apparatus
Laser Range Sensor (1)

• Transmitted and received beams coaxial
• Transmitter illuminates a target with a collimated beam
• Received detects the time needed for round-trip
• A mechanical mechanism with a mirror sweeps
  – 2 or 3D measurement
Laser Range Sensor (2)

- **Pulsed laser**
  - measurement of elapsed time directly
- **Beat frequency**
  - between a frequency modulated continuous wave and received reflection
Laser Range Sensor (3)

Phase-Shift Measurement (easier than other 2 methods)

\[ \lambda = \frac{c}{f} \]

\[ L + 2D = L + \frac{\theta}{2} \]

c: speed of light; f: modulating frequency, \( \theta \): phase measurement

for \( f = 5 \text{ Mhz} \), \( \lambda = 60 \text{ meters} \)
Example Laser Range Sensor

Length of lines through the measurement points indicate the uncertainties

http://www.youtube.com/watch?v=NC1F0TwJ_Q8
Structured Light Projection

- What if you projected a pattern instead of a point. How would this be useful?
Triangulation Ranging

- Geometrical properties of image establish a distance measurement
- Project a well defined light pattern (e.g. point, line) onto the environment
  - Reflected light captured by a photo-sensitive line or matrix (camera) sensor device
  - Triangulation establishes distance
Structured Light (vision, 2 or 3D)

- Eliminate correspondence problem by projecting structured light on the scene
- Slits of light / emit collimated light (laser) by means of rotating mirror
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

\[ H = D \cdot \tan \alpha \]
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Doppler Effect Based (Radar or Sound)

a) between two moving objects

transmitter is moving

receiver is moving

Doppler frequency shift

\[ f_r = f_t \left(1 + \frac{v}{c}\right) \]

Doppler effect

\[ \Delta f = f_t - f_r = \frac{2f_t v \cos \theta}{c} \]

relative speed

\[ v = \frac{\Delta f \cdot c}{2f_t \cos \theta} \]

b) between a moving and a stationary object

transmitter/ receiver

Object