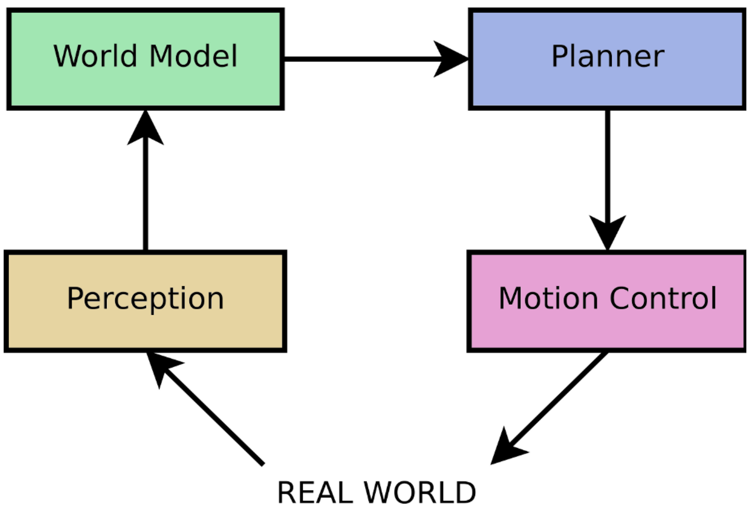
Simple Autonomous Robot Diagram



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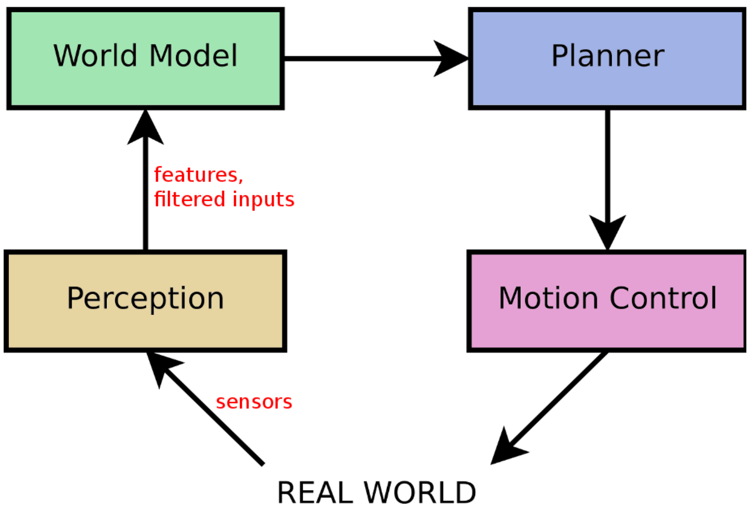

Perception Roadmap

- Sensors
  - Overview
  - Localization
  - Obstacle Distance
  - Vision

- Handling uncertainty, features

Sensors Overview

- Why should a robotics engineer know about sensors?

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  - They are the key technology for perceiving the environment
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  - Understanding the physical principle enables appropriate use

- Understanding the physical principle behind sensors enables us:
  - To properly select the sensors for a given application
  - To properly model the sensor system, e.g. resolution, bandwidth, uncertainties
  - To define the needs in collaboration with sensor system suppliers

Classification of Sensors

- What:
  - Proprioceptive sensors
    - measure values internally to the system (robot),
    -
  - Exteroceptive sensors
    - information from the robot's environment
    -
- How:
  - Passive sensors
    - energy coming for the environment
    -
  - Active sensors
    - emit their proper energy and measure the reaction
    - often better performance, but some influence on environment
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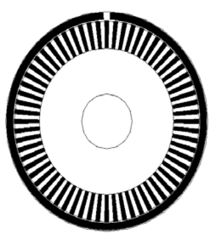
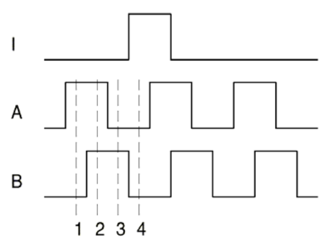
    - sonar, lidar

LECTURE 2: Localization Sensing Localization Sensors

Wheel sensors

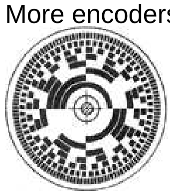
- measure position or speed of the wheels or steering
- optical encoders are proprioceptive sensors
  - thus the position estimation in relation to a fixed reference frame is only valuable for short movements.
- typical resolutions: 64 - 2048 increments per revolution.
- quadrature encoders are often used for higher resolution and/or directional information

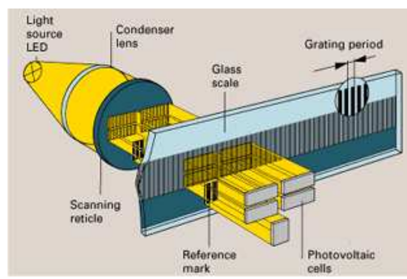




State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

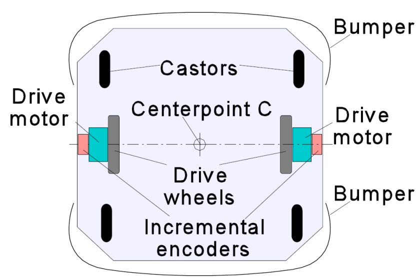
More encoders





Encoder counts to distance

- Integrate wheel movements over time to get an estimate of the position $\longrightarrow$ odometry
  - e.g., wheel circumference / encoder ticks per revolution = distance traveled per encoder tick
  - distance per tick / time between ticks = velocity
- For two wheeled, indoor robots, each wheel usually has its own motor /encoder
  - differential drive



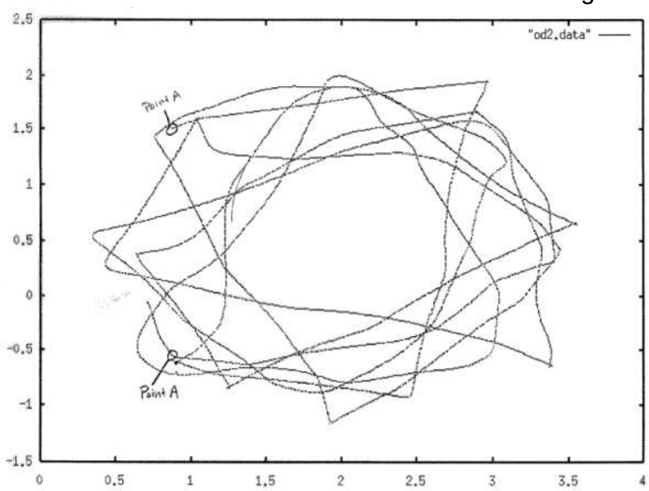
Calculating odometry for diff. drive robots

- For time interval I, each wheel has its own distance (+,-) traveled: ΔU_R and ΔU_L.
- The center point travels half the distance: $\Delta U = (\Delta U_R + \Delta U_L)/2$.
- The change in orientation is computed as $\Delta\theta = (\Delta U_R - \Delta U_L)/b$.
  - b is the wheelbase: distance between the wheels

- For the global, planar frame of reference, the robot's location at time t is calculated:
  - $\theta_t = \theta_{t-1} + \Delta\theta$
  - $x_t = x_{t-1} + \Delta U \cos(\theta_{t-1} + \Delta\theta/2)$
  - $y_t = y_{t-1} + \Delta U \sin(\theta_{t-1} + \Delta\theta/2)$
  - Why cos and sin?

Odometry is noisy!

Here a differential drive robot follows a $2m \times 3m$ rectangle 6 times.



Heading sensors

- Heading sensors can be proprioceptive () or exteroceptive ().
- Used to determine the robot's orientation (yaw) and inclination (pitch) and tipping (roll).

Heading sensors

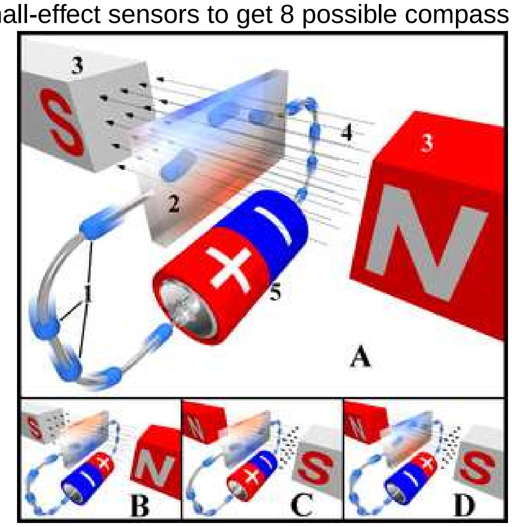
- Heading sensors can be proprioceptive (gyroscopes) or exteroceptive (compasses).
- Used to determine the robot's orientation (yaw) and inclination (pitch) and tipping (roll).

Compasses

- Used for navigation since before 2000 B.C., when Chinese suspended a piece of naturally magnetite from a silk thread and used it to guide a chariot over land.
- Exteroceptive
  - Magnetic field of Earth
  - absolute measure for orientation
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field (Hall-effect, fluxgate sensors)
- Major drawbacks
  - weakness of the earth field
  - easily disturbed by magnetic objects or electrical sources
  - slow to settle (mechanical, Hall-effect compasses)
  - expensive (fluxgate (electromagnet) compasses)

Hall-effect Overview

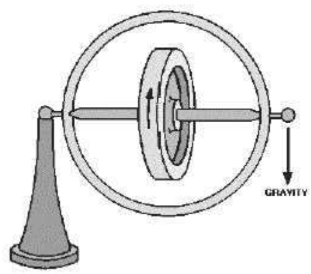
Need 2 hall-effect sensors to get 8 possible compass directions



Gyroscopes Heading sensors, that keep the orientation to a fixed frame

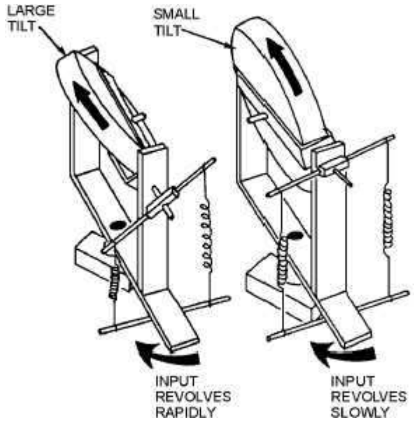
- precession-based measure for the heading of a mobile system
- Two categories, the mechanical and the optical gyroscopes

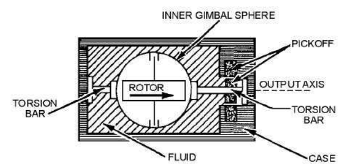
- Mechanical Gyroscopes: drift due to friction
  - Standard gyro (angle)
  - Rate gyro (speed)
- Optical Gyroscopes: more accurate, no mechanical parts
  - Rate gyro (speed)



Rate Gyroscopes

- Measures the rate of rotation in one dimension (e.g., heading)
- Angular velocity if proportional to precession



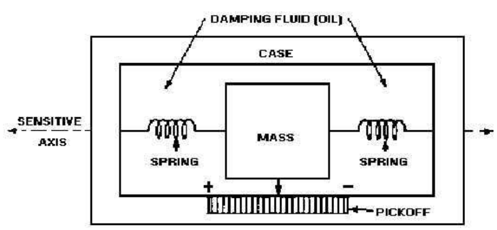


Optical Gyroscopes First commercial use started only in the early 1980 when they where first installed in airplanes.

- angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity of the cylinder

Accelerometers Spring mounted masses whose displacement under acceleration can be measured.

- Used to detect acceleration in a single dimension
- Based on Newtow's law $F = ma$ and the ideal spring-mass relation $F = kx$.
  - $a = kx/m$
- Usually, one accelerometer for each of 3 orthogonal axis is used
  - Detects acceleration in pitch, roll, and yaw
  - Integrated over time, can yield velocity and distance estimates in 3D space

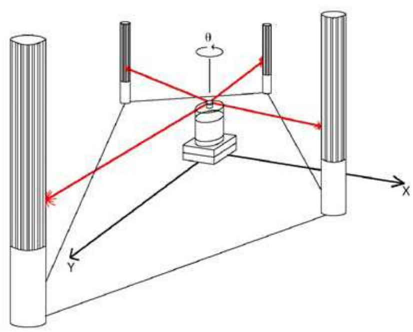


External Beacons

- “Elegant” way to solve the localization problem in mobile robotics
- Beacons are signaling guiding devices with a precisely known position
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses

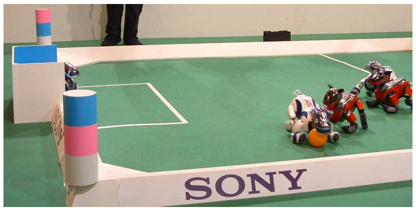
Major drawback with the use of beacons:

- Beacons require (costly) changes in the environment
- Limit flexibility and adaptability to changing environments



Beacon Examples

- Colored beacons used in Robocup (passive)
- Beacon for power docking (passive)
- Underwater beacons that send sonar chirps (active)
- GPS (active)
- Wifi signals (active)

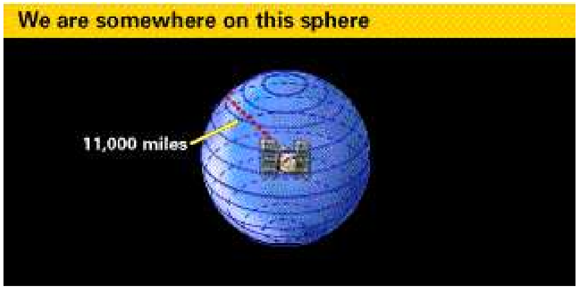


Global Positioning System

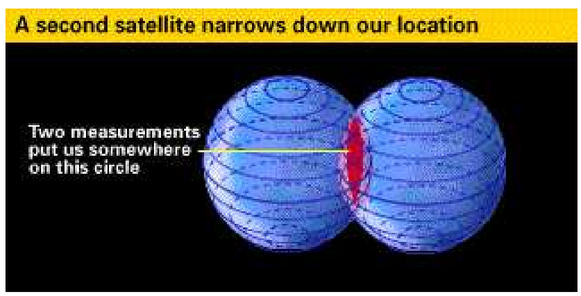
- Developed for military use (started in 1973, completed in 1995)
- Recently it became accessible for commercial applications
- 24 satellites (includes three spares) orbiting the earth every 12 hours at a height of 20,190 km.
- Four satellites are located in each of six planes inclined 55 degrees with respect to the plane of the Earth's equator
- Location of any GPS receiver is determined through a time of flight measurement (using 4 or more satellites)
- Technical challenges:
  - Time synchronization between the individual satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - Interferences with other signals

GPS Overview

- The basis of GPS is “trilateration” from satellites.
- A GPS receiver measures distance using the travel time of radio signals.
- To measure travel time, GPS needs very accurate timing which it achieves with some tricks
- Along with distance, you need to know exactly where the satellites are in space.
- Correct for any delays the signal experiences as it travels through the atmosphere

Trilateration Details 

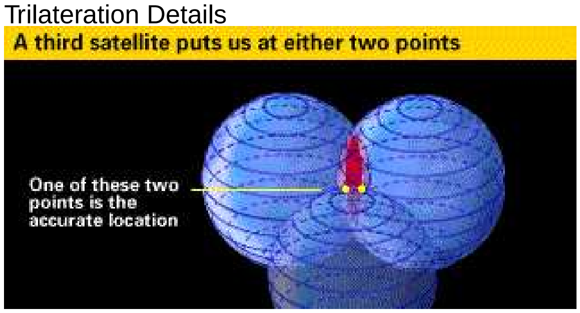
Knowing the distance to 1 satellite means we could be anywhere on a sphere.



Trilateration Details

With two satellites, two spheres intersect giving us a circle of locations that we could be located at.

Trilateration Details



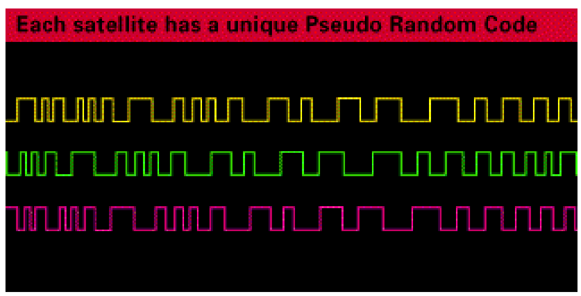
With a third circle, there are two points. One of the 2 points is usually nonsensical (not near the surface of the Earth).

Measuring Distance distance = velocity * time

- velocity = speed of light = 299,792.458 km/s
- For a satellite right above head $d \approx 20,190km$, so $t = 20190/299792.458 \approx 0.067s$
- The difference between the current receiver time and the time the satellite sent the signal gives the distance.
  - Clocks must be synchronized
  - Timing must be precise, even 0.001 seconds of timing error means 300 km of distance error.
  - Satellites all have atomic clocks.
  - Receivers do not (too expensive).

Timing

- At very fast, specified intervals each satellite sends a unique pseudo random code.
  - Each code modules at 1 MHz and repeats every 1023 bits



- A receiver is also generating these pseudo random codes at 1MHz.

Timing

- If the receiver assumes it generates the codes at the exact times of the satellites, then calculating the phase shift with 3 satellites will give a precise location (throwing away the bogus second hypothesis).
- The range measurements with four satellites allows to identify the correct position (x, y, z) and the clock correction ΔT.
  - Comparing to a fourth satellite, there will be an error (because the receiver most probably did not generate the codes at the exact same time as the atomic clock run satellites).
  - Since any offset between when the receiver creates codes and when the satellites created their codes will affect all four measurements, the receiver looks for a single correction factor that it can subtract from its time that would cause them all to intersect at a single point.
  - Once thus occurs, the receiver has a precise position AND an atomic accuracy clock.

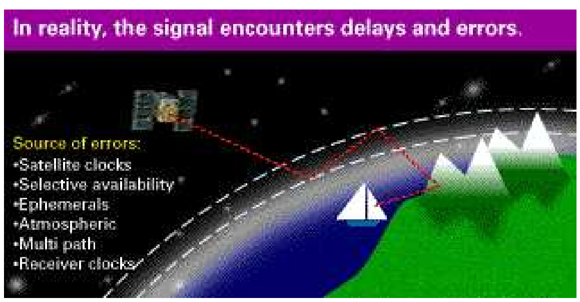
Satellite Locations

- Satellites are 20,190 km above the Earth for a reason.
  - High orbits are very predictable (no atmospheric effects)
- The DoD monitors each satellite from base stations and uploads corrections from the predicted orbit to each satellite.
- In turn, the satellite includes this info in its broadcast packet (along with the atomic clock time, the pseudo random code, etc.)
- Receivers use the current and predicted orbits to more quickly acquire satellites.

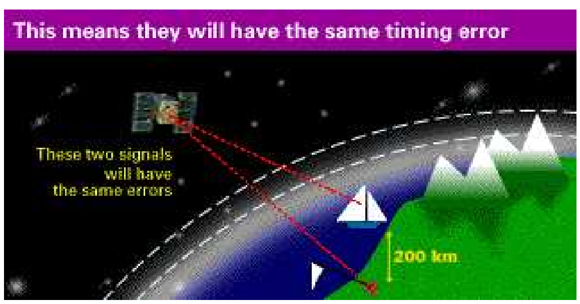
GPS Drawbacks

- Trees, buildings, mountains, etc. can block a number of satellites from view.
- Thus, GPS does not work in many cities with numerous large buildings.
- Does not work indoors, underwater, in caves, in forests, etc.
- General resolution of civilian GPS is usually between 3-15 m.
  - And that's without normal noise problems.
  - The ionosphere and troposphere can slow down and refract the radio signals.
  - Satellite clocks are very accurate, but still have some error.

GPS Noise Various satellite and atmospheric issues create errors in the GPS signals.



GPS Noise When these occur, GPS receivers in the same area on Earth will see the same delay in GPS signals.



DGPS Differential GPS or “DGPS” can yield measurements good to a couple of meters in moving applications and even better in stationary situations.

- By having a stationary base station, that knows its precise GPS coordinates, it can perform the GPS calculations backwards to find the timing errors for each satellite.
- We have one receiver measure the timing errors and then provide correction information to the other receivers (via radio signals) that are roving around.
- Not necessarily free, like GPS.
    - Subscription-based from OmniStar or similar (satellites; country wide access)
    - Free near some coast guard stations (radio towers)

RTK navigation Real Time Kinematic navigation uses the high frequency portion of the satellite signals for more accurate location.

- 1MHz pseudo random code means 300m wavelengths.
- Modern GPS receivers can sync their codes with the satellite code within 1% error: 3 meters (theoretically)
- Military uses a second, encrypted signal whose code is at 10MHz: 30 cm accuracy.
- Though the code of civilian GPS is 1MHz, the frequency of the carrier signal is 1575.42 MHz.
- Two nearby receivers determine their relative distances.
  - 1575 MHz signals at the speed of light have wavelength of 19cm.
  - By phase aligning its carrier signal with the carrier signal received by another GPS, a GPS receiver can determine its relative distance within centimeters.

Marvin's pose info Marvin has an Applanix POS-LV navigation system

- Integrates several sensors:
  - IMU (3 gyros and 3 accelerometers)
  - quadrature encoder on 1 wheel
  - D-GPS
  - RTK-based solutions during GPS outages
  - Information integrated with a Kalman filter (discussed later)
  - Approximate cost: $60,000

- Applanix gives:
  - Absolute locations
    - latitude & longitude (easily converted to x,y)
    - altitude (above sea level)
  - Orientations
    - heading/yaw (absolute)
    - roll
    - pitch
  - Speeds
    - forward/backward
    - sideways
    - up/down
    - turning, pitching, rolling

LECTURE 3: Distance Sensing

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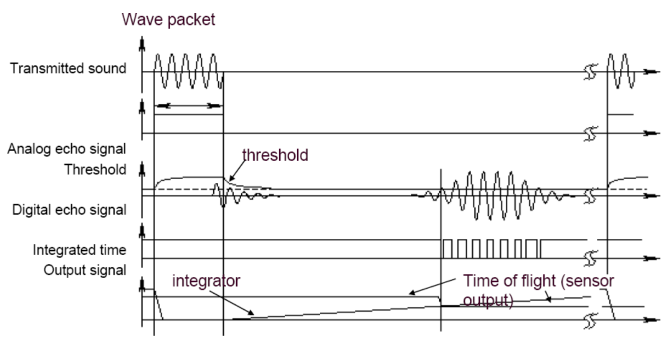
Time of Flight Range Sensors

- Long range distance measurement devices
  - Active measurement
- Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively.
- The traveled distance of a sound or electromagnetic wave is given by $d = c \cdot t$.
  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight

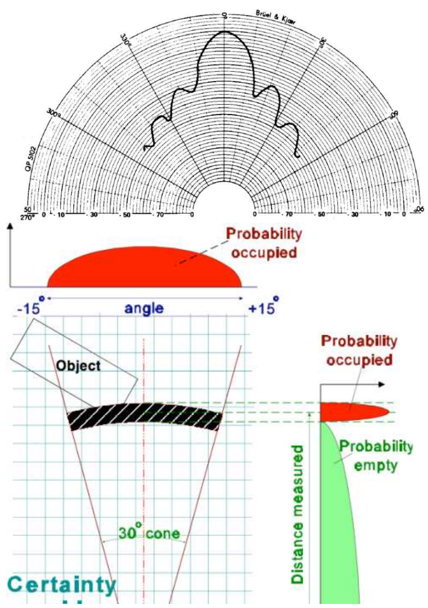
- Propagation speed of sound: 0.3 m/ms
- Propagation speed of of electromagnetic signals: 0.3 m/ns,
  - one million times faster.
- 3 meters
  - is 10 ms for an ultrasonic system
  - only 10 ns for a laser range sensor
  - time of flight with electromagnetic signals is not an easy task
  - laser range sensors expensive and delicate
- The 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 fight measure (laser range sensors)
  - Opening angle of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed (sound)
  - Speed of mobile robot and target (if not at standing still)

Ultrasonic Sensors

- Transmit a packet of (ultrasonic) 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: $d = c \cdot t/2$
- The speed of sound in 68° F air is about 343 m/s.



Ultrasonic Sensors



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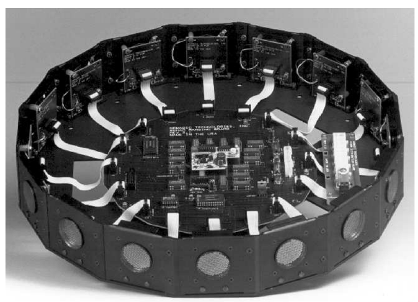
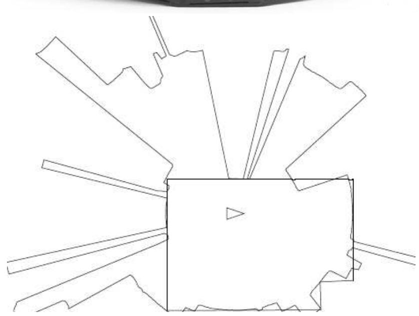
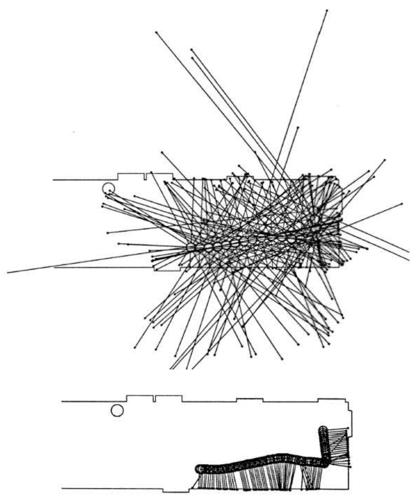




Ultrasonic Sensors



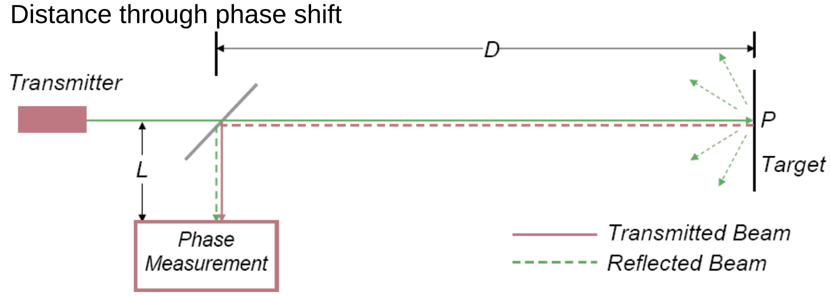
Ultrasonic Sensors

- Benefits:
  - Inexpensive
- Drawbacks:
  - Specular Reflections
  - Close (< 6 cm)/Far (> 3 m) objects are usually invisible
    - Close: ignores self-echos
    - Far: Amplitude degrades as per inverse square law
  - Certain objects (foam, fur, etc.) absorb sound
  - Speed of sound changes with altitude, humidity, etc.
  - Slow operating speed:
    - Sensing 3 meters away takes about 20 ms (50 Hz)
    - If we have 20 nearby sonars, they must fire sequentially
    - This means each one can fire about every 400 ms (2.5 Hz)

Laser Rangefinders

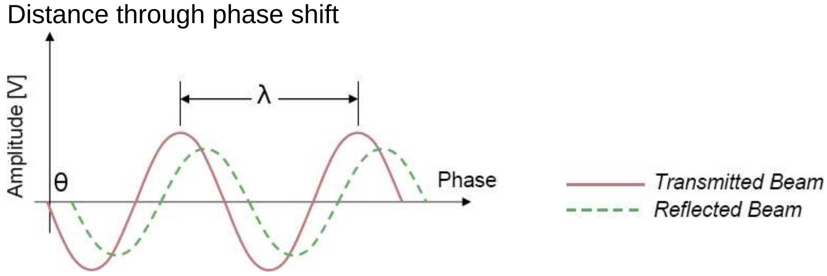
- By using electromagnetic laser beams instead of sound, we can get significant improvements in distance measurements.
- Lidar (light detection and ranging)
- Light reflects isotropically (in all directions) from surfaces having roughness greater than the light wavelength.
  - Light used in lidars is often around 824 nm (near-infrared)
  - All but the most shiny surfaces will be diffuse reflectors
  - Some light always reflects directly back to the transmission point
- Generally the phase shift from modulated light is measured, not time of flight directly
  - Speed of light is too fast.
  - Would need clocks capable of resolving picoseconds (one trillionth of a second).

Distance through phase shift



$D' = L + 2D$

Distance through phase shift



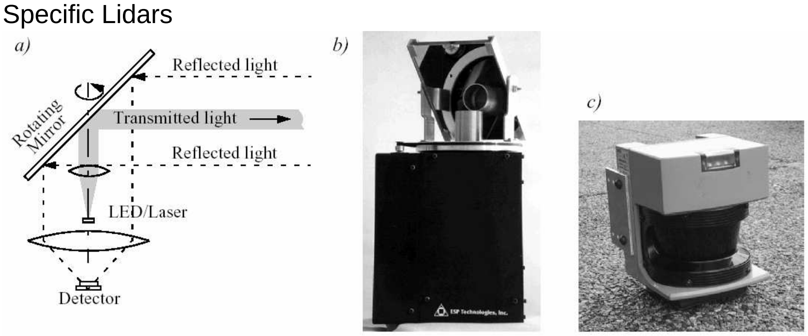
For amplitude modulated light:

- $c = f \cdot \lambda$, where f is the modulating frequency and λ the modulated wavelength.
- $L + 2D = L + \frac{\theta}{2\pi}\lambda$; $D = \frac{\theta}{4\pi}\lambda$
- Suppose f = 5 MHz, then λ = 60 m.
    - A target at range of 5 m, would have same phase shift as a target at 65 m.
    - Thus many lasers have maximum ranges of 60-120 m.

Lidar specifics

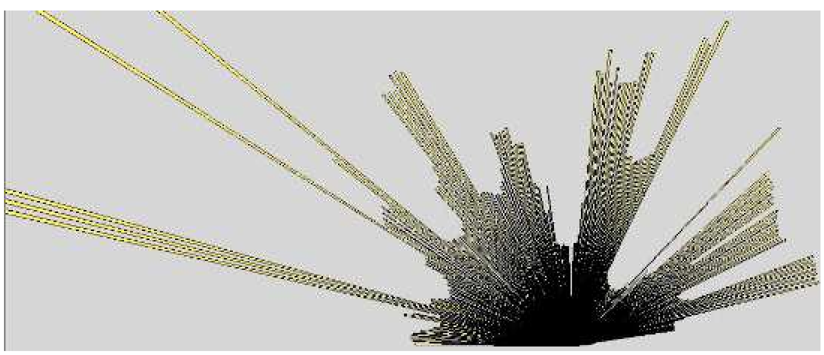
- Confidence in the range (phase/time estimate) is inversely proportional to the square of the received (modulated) signal amplitude.
  - Hence dark, distant objects will not produce such good range estimated as closer brighter objects.
  - Black velvet absorbs most light
  - Returned intensities may be useful
- Lidars cannot see glass (invisible) or mirrors (see reflected distances).
- Lidars can be dazzled by the sun
- Modern lidars with 80 m distance have about ± 1 cm of error
- Usually 1 distance measurement every .5 or 1°
- Usually give results at around 10Hz
- More expensive than sonar (planar units: \$2000-\$6000)

Specific Lidars



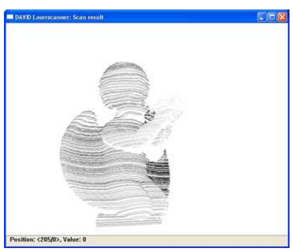
Lidar Returns

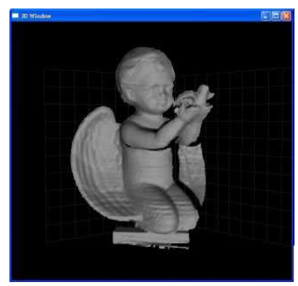
2D



Lidar Returns

2D to 3D

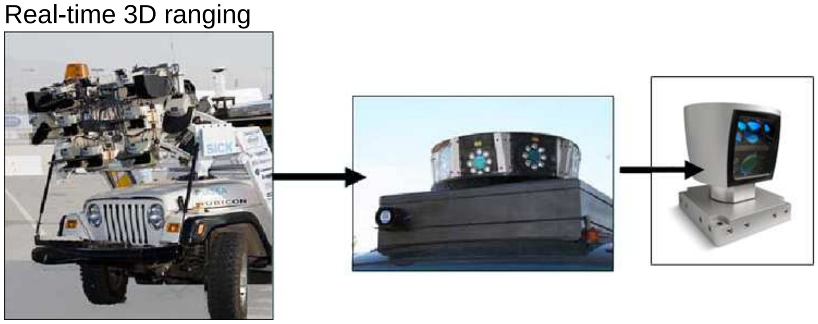




Lidar Returns

3D from 2D device mounted on its side on a spinning platform

Real-time 3D ranging



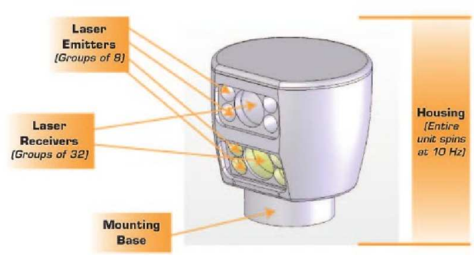
Velodyne HDL

- Created by a team from the 2005 Grand Challenge
- Most teams at the 2007 NQE had a Velodyne, but probably ¡ 100 exist
    - Older firmware buggy
    - Mostly works well these days
- 1,000,000 3D ranges a second; 100,000 at 10Hz
- Angled from from $+2^{\circ}$ to -24°.
- Ranges: Theoretical: 120 m; Practical: 50 m
- Accuracy: Theoretical $<$2 cm; Practical: 10cm
- Intensities: May be useful, but currently unused by ART
- Cost: Around $60,000

Velodyne details

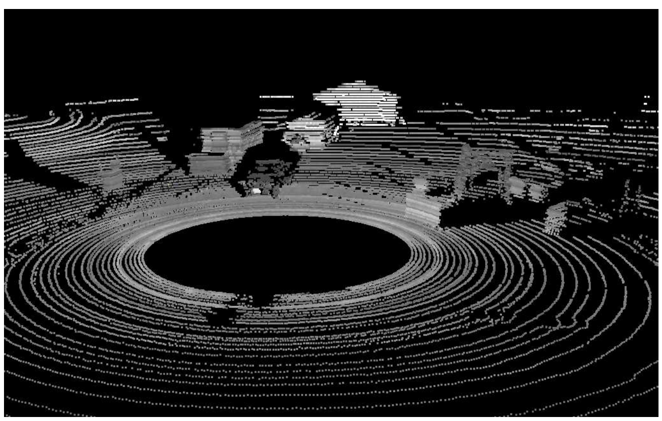
- Groups of lasers fire simultaneously as the unit spins
- Horizontal offset of laser is added to the heading of the cylinder when the reading was taken.
  - Laser returns have no fixed angular offsets with respect to straight-ahead
  - Vertical angle is fixed
- Data transmitted via UDP packets over Ethernet wire

High Definition Lidar
The HDL-64E features high definition 3 dimensional information about the surrounding environment.



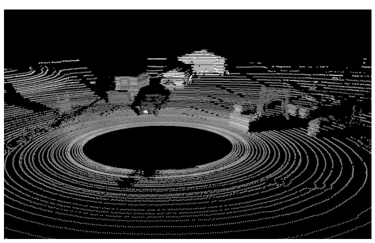
Velodyne Returns

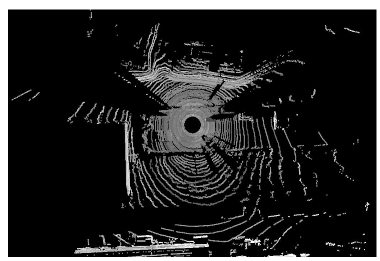
3D



Velodyne Returns

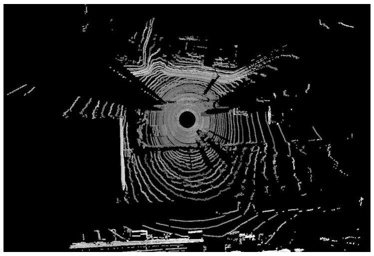
3D

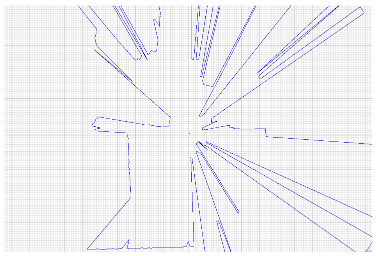




Velodyne Returns

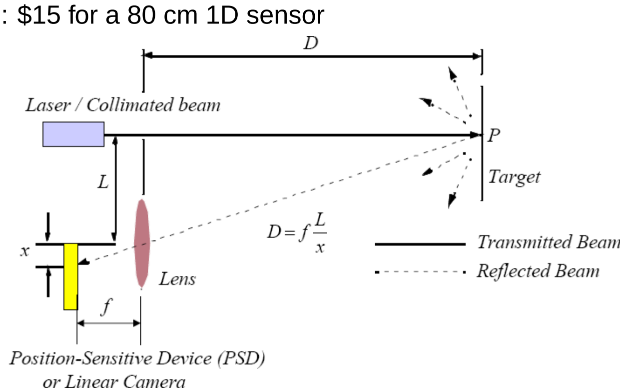
3D to 2D





1D Optical Triangulation

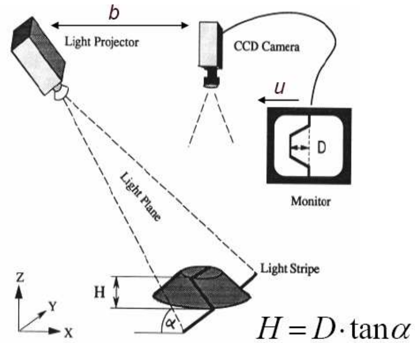
- Instead of laser phase being examined, the position of the laser after it reflects and passes through a lens in measured.
- Position from middle of lens x is inversely proportional to distance D.
- Usually works from 8 cm to 2 m.
- Inexpensive: $15 for a 80 cm 1D sensor



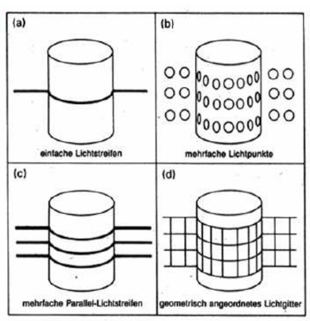
2D Optical Triangulation

- Same principle as 1D approach but with a line (2D) or pattern (3D) instead of a beam of light.
- 2D/3D approach is called structured light
- Surpassed by modern lidar units
- Still studied in vision research

a



b



Radar

- Radar is very much like sonar, but uses electromagnetic radio waves (e.g., microwaves)
- Can see through many surfaces (e.g., fog, dust, but also certain walls)
- Different surfaces changes the waves in predictable ways
- Many of the same problems as sonar
  - specular reflection
  - large footprint
- Usually have a range of about 150 m, but only work at around 2 Hz
- Accurate to within 1 km/hr from 0 to 160 km/hr
- Relatively expensive for robotics applications

Doppler Effect

- Radar and Sonar devices that can measure the speed of objects (not just distance)
- The frequency of waves from a stationary transmitter is lower than when the transmitter moves toward the receiver.
  - And higher than when it moves away from the receiver.
  - This is why an ambulance sounds higher pitched (higher frequency) moving towards you than when moving away.
- $v = \frac{\Delta f \cdot c}{2 f_t \cos \theta}$
  - Δf = frequency shift between transmitted and received wave; $f_t - f_r$
  - θ = relative angle in direction of motion and beam axis
  - Positive v is velocity away from source

Marvin's ranging info

- 2 SICK-brand lidars
  - 180° f.o.v.
  - 80 meter range
  - 1cm accuracy
  - 1 on front bumper
    - used for short range sensing
    - car pitching can see ground further than about 8 m.
  - 1 on rear bumper
- 1 Velodyne HDL
  - used for 8m to 50 m obstacle detection
  - mostly just senses ground
- Multiple SICK lidars in storage
  - Intensities can detect road stripes