Introduction to Mobile Robotics

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LEDs

Light emitting diodes - LEDs

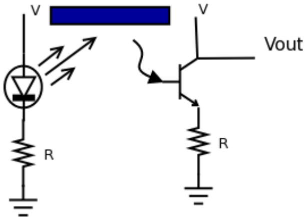
These are diodes which emit at specific EM bands.

LEDs have a variety of operating specs.

Assume we have one that operates in the 3-6 volt range and current level is 20mA. If we select $V = 5$ then the resistor should be $R = V/I = 5/.02 = 250$. Since 250 is not a standard value, we select $R = 270$ ohms.

LEDs and obstacle detection

LEDs can emit in non-visible ranges as well - UV or IR. They can be used for simple object detection in combination with a phototransistor:



This system can be used for simple occupancy detection or close obstacle detection.

Encoders

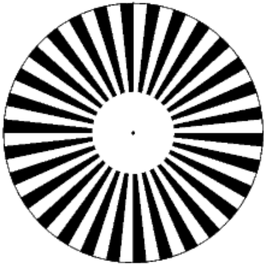
Wheel encoders
Navigation and localization can be challenging problems in mobile robotics. One approach to measuring motion is to measure the amount of rotation of a wheel.

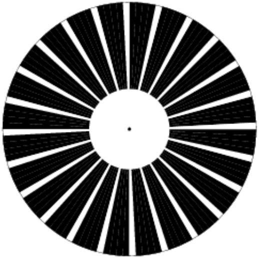
- Measure position or speed of a wheel or dial.
- One may then integrate to get an estimate of the position: odometry.
  - Really this is a summation.
  - Rather error prone and methods are needed to correct it.
- Optical encoders are proprioceptive sensors
  - the position estimate in relation to a fixed reference frame is only valuable for short movements.
- typical resolutions: 64 - 2048 increments per revolution

Encoders

Two elements are required: an encoder and a detector.

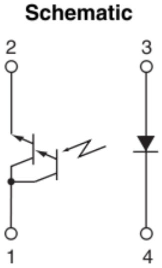
An encoder pattern may be attached (glued) to the inside of a robot wheel. Simple encoder patterns are just alternating black and white radial stripes. Two examples are

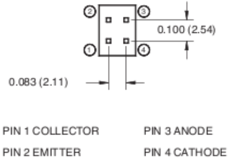


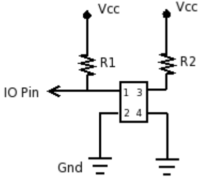


Encoder wiring

To read the encoder, you will need an optical sensor. Typically one uses an IR LED (IR light emitting diode) and phototransistor pair.



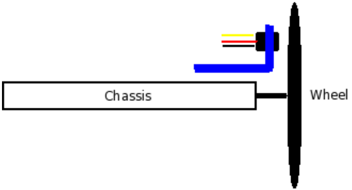




These are packaged in single units, for example the Fairchild QRD1313. This has the LED and the phototransistor packaged into a unit that is 6.1mm x 4.39mm x 4.65mm (height).

Encoder mounting

Glue the encoder pattern to the inside of the wheel and mount the detector:

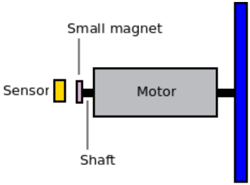


Compass

- Used for over 4000 years
  - Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land
- Magnetic field on earth
  - absolute measure for orientation
  - special property of the liquid iron core
  - pole reversals occur
- Large variety of solutions to measure the earth's magnetic field
  - mechanical magnetic compass
  - direct measure via Hall-effect or magnetoresistive sensors
- Major drawbacks
  - weakness of the earth's field
  - easily disturbed by magnetic objects or other sources
  - not always good indoors or on planets without significant fields

Magnetic encoding

It is possible to use Hall-effect or other similar devices to do encoding.



Orientation

Gyroscopes

- Heading sensors that keep the orientation to a fixed frame
  - absolute measure for the heading of a mobile system
- Two categories
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)
  - Optical Gyroscopes
    - Rate gyro (speed)

Acceleration

Accelerometers: Measures acceleration in a particular direction.

- IMU - Inertial Measurement Unit
  - 3 - Accelerometers, 3 - Gyroscopes $\Rightarrow$ 6DOF
  - 3 - Accelerometers, 3 - Gyroscopes, 3 axis compass $\Rightarrow$ 9DOF
- Basis for AHRS: Attitude and Heading Reference System

Inclineometer: tilt sensor

These devices often have serial (or USB) connections and return text strings of data at some Hz.

AHRS: Attitude and Heading Reference System

AHRS consist of either solid-state or MEMS gyroscopes, accelerometers and magnetometers on all three axes.

The key difference between an IMU and an AHRS -

is the addition of an on-board processing system in an AHRS which provides solved attitude and heading solutions versus an IMU which just delivers sensor data to an additional device that solves the attitude solution.

AHRS - Filtering

A form of non-linear estimation such as a Kalman filter is typically used to compute the solution from these multiple sources.

AHRS differs from traditional inertial navigation systems (INS) by attempting to estimate only attitude (i.e. roll, pitch, yaw a.k.a heading) states, rather than attitude, position and velocity as is the case with an INS.

Beacons

- Elegant way to solve the localization problem
- Beacons are signaling systems with known positions
- Beacon base navigation is very old
  - Natural beacons: stars, mountains, sun
  - Artificial beacons: lighthouses
- GPS, Global Positioning System, revolutionized navigation
  - One of the key sensor systems in mobile robotics
  - Outdoor only
- Indoor beacon systems require
  - Modify the environment
  - Limited flexibility to changing conditions

GPS

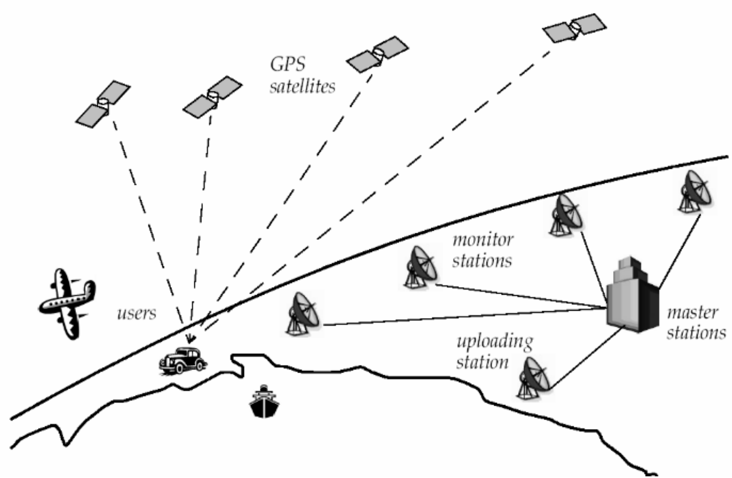
Overview

- Developed for military use
- Recent availability for non-military
- 24 satellites (with 3 spares) orbiting the earth every 12 hours at an altitude of 20,190 km
- Four satellites in each of the six planes inclined 55 degrees with respect to the plane of the earth's equator
- Location of a GPS receiver is determined by a time of flight measurement

Challenges

- Time synchronization between satellites and GPS receiver
- Real time update of exact location of the satellite
- Precise measurement of time of flight
- Interference with other signals

GPS


GPS
satellites
monitor
stations
users
master
stations
uploading
station

GPS Details

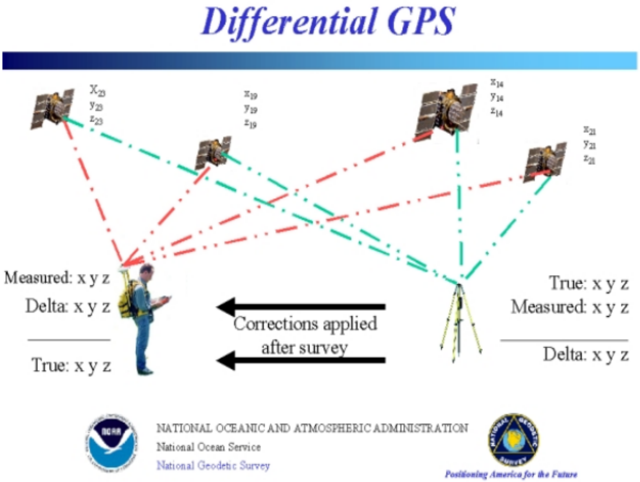
- Time synchronization:
  - atomic clocks on each satellite
  - monitoring them from different ground stations
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed - 0.3m per nanosecond
  - position accuracy proportional to precision of time measurement
  - relativistic effects mean that time passes more quickly for the satellites than it does for a receiver on the ground.
- Real time update of exact location of the satellites
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyzes all the measurements and transmits the actual position (of each) to each of the satellites.

GPS Details

- Exact measurement of the time of flight
  - the receiver correlates a pseudocode with the same code coming from the satellite
  - the delay time for the best correlation represents the time of flight
  - quartz clock on gps receivers are not very precise
  - the range measurement with four satellites allows one to identify the three values (x, y, z) for the position and the clock correlation Δt.
- Commercial GPS receivers allows position accuracies down to a couple of meters.

Differential GPS

- position accuracies in sub-meter to cm range



Partial Worked Example

Assume that you have four beacon towers located in roughly a square over a 10km x 10km patch of land. You place a coordinate system on the land and measure the beacon locations.

The locations in meters are B1 (0,0), B2 (56, 9752), B3 (9126, 7797), B4 (9863, 218).

If the beacons transmit a packet with a time stamp, then a mobile system with an accurate clock can determine its location in the instrumented area.

Determine locations if t1 = 17608 ns, t2 = 16815 ns, t3 = 22933 ns, t4 = 25370 ns.

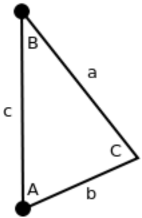
Example

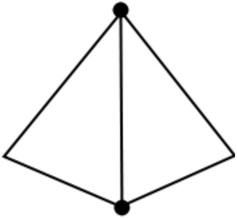
Since this is strictly a 2D problem (over 10km the curvature of the earth is not a significant issue), we can use trig, specifically the law of cosines, to solve the problem.

The distances are found via $d = ct$: $d_1 = 5282m$, $d_2 = 5045m$, $d_3 = 6880m$, $d_4 = 7611m$.

From the figure below we have that

$$b^2 = a^2 + c^2 - 2ac\cos(B), \quad a^2 = c^2 + b^2 - 2cb\cos(A).$$

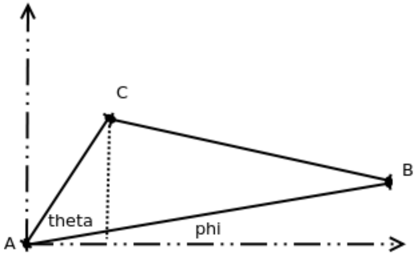




Example

The right figure shows the basic dual solution. Using the region of interest we can eliminate one point. Using the figure below, we can compute ϕ from beacon location data.

We already computed θ from the law of cosines. This tells us the actual angle off of the axis $\theta + \phi$.



Example

We know the distance of the segment AC which is the basic range data (call this R).

Using

$$x = R\cos(\theta + \phi)$$

$$y = R\sin(\theta + \phi)$$

We obtain a location (x, y). This can be repeated for the three other beacon pairs. Take the three closest points and average their values.

Example

There are plenty of other ways to treat this problem.

One may intersect two circles to provide the location of the two intersecting points and then proceed over all combinations.

An image processing approach akin to the Hough Transform (with voting) would also work.

It is also possible to lay down a grid and then just step through each grid point.

If any grid cell gets two or more beacons that are the correct distance, then it is the location. See if you can come up with other approaches.

Range Sensors

- Large range distance measurement called *range sensors*
- Short range measurements sometimes known as proximity detectors
- Range information:

  key element for localization and environment modeling
- Ultrasonic sensors and many laser range sensors make use of propagation speed of sound or light respectively.
- Some laser sensors use triangulation.
- The traveled distance of a sound wave or light wave is given by

$$d = c \cdot t$$

- where
  - d is the distance traveled (round trip)
  - c is the speed of the wave
  - t is the time of flight

Range Sensors

Some details ...

- Speed of sound: 0.3 m/ms
- Speed of light: 0.3 m/ns (10^6 times faster than sound)
- 3 meters
  - is 10 ms for an ultrasonic system
  - is 10 ns for a laser range sensor
  - time of flight with electromagnetic signals is not easy
  - laser rangers are 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 flight measurement
- Opening angle of transmitted beam
- Interaction with the target
- Variation of the propagation speed
- Speed of robot and target

Sonar

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:

$$d = \frac{c \cdot t}{2}$$

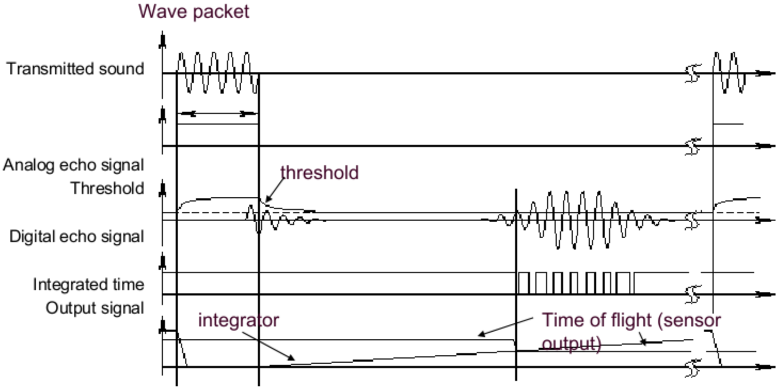
The speed of sound, c (about 340 m/s), in air is given by

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

where

- γ adiabatic index
- R gas constant
- T gas temperature in Kelvin

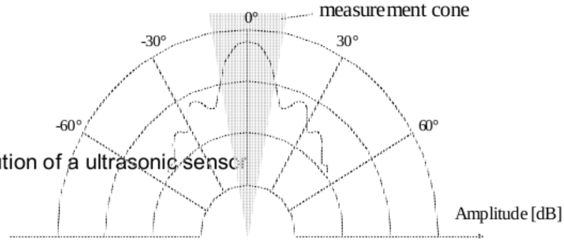
Sonar Echos



Signals of an ultrasonic sensor

Sonar Details

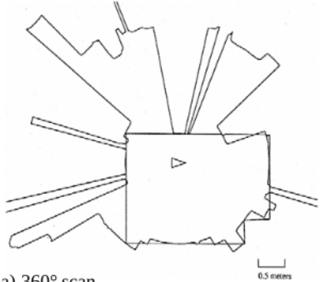
- Typical frequency: 40 - 180 KHz
- Generation of sound waves via a Piezo transducer
  - transmitter and receiver separated or not
- Sound beam propagates in a cone (approx)
  - opening angles around 20 to 40 degrees
  - regions of constant depth
  - segments of an arc (sphere for 3D)



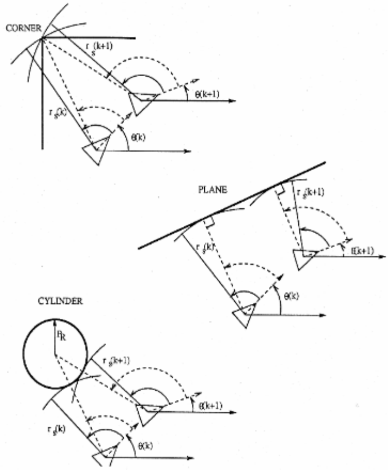
Typical intensity distribution of a ultrasonic sensor

Sonar Reflection

- Other problems for ultrasonic sensors
  - soft surfaces that absorb most of the sound energy
  - surfaces that are fare from being perpendicular to the direction of the sound -> specular reflection

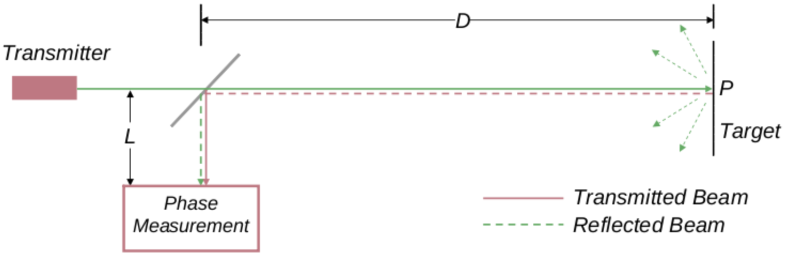


a) 360° scan



b) results from different geometric primitives

Laser Ranging



- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated beam (laser)
- Receiver detects the time needed for round trip
- A mechanical mechanism with mirror sweeps (2D or 3D).

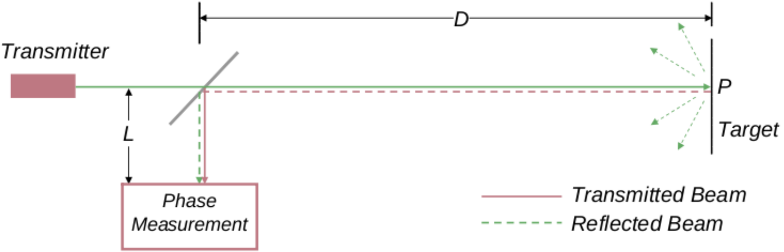
LIDAR

Time of flight measurement

- Pulsed laser (current standard)
  - measurement of elapsed time
  - resolving in picoseconds
- Beat frequency between a frequency modulated continuous wave and its received reflection
- Phase shift measurement to produce a range estimation
  - technically easier than the previous methods

LIDAR

- *Phase-Shift Measurement*



$$D' = L + 2D = L + \frac{\theta}{2\pi}\lambda \qquad \lambda = \frac{c}{f}$$

Where:
c is the speed of light, f is the modulating frequency, D' is the distance covered by the beam.

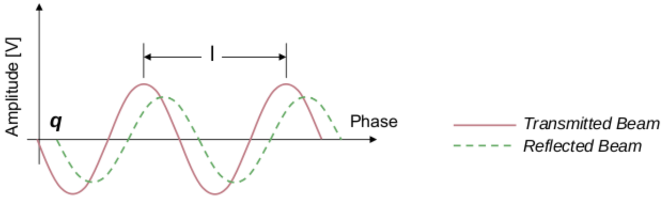
Note: if $f = 5$ Mhz then $\lambda = 60$ meters.

LIDAR

- Distance D, the distance between the beam splitter and the target,

$$D = \frac{\lambda}{4\pi}\theta$$

  where θ is the phase difference between the transmitted and reflected beam
- Range estimate is not unique,
  for example if $\lambda = 60$ then a target at 5, 35, 65, ... meters give the same phase shift.



Example

Assume you are using a laser diode to build a distance sensor.

- What is the wavelength of the modulated frequency of 12MHz?
- If you measure a 20 degree phase shift, this value corresponds to what distances?
- What other modulation frequency would be a good choice to isolate the value? (show this)
- How would you do the modulation and phase shift measurement?

Example

Wavelength $= \lambda = c/f = 3(10^8)/(12(10^6)) = 25$ meters.

A 20 degree shift is $(20/360)$ of the wavelength, so we get

$$25/18 \approx 1.389m$$

The actual distance is $1/2$ due to the round trip: 0.6945m.

Focus on the full trip. This would correspond to

$$1.389 + 25n \text{ for } n = 0, 1, 2, 3...$$

Example

As long as our values are relatively prime, frequency selection is pretty open. Factors of 12 are 2, 3, 4.

So 5 Mhz would work (as would 17 Mhz and many others) for some distance. Using 5Mhz, we have a wavelength of 60 meters.

If the distance was actually 26.389, then the 5Mhz would produce

$$26.389 + 60m, \quad m = 0, 1, 2...$$

as values. To find where the wavelengths give the same value, set

$$1.398 + 25n = 26.389 + 60m,$$

and obtain

$$m = 5(n-1)/12.$$

Example

We thus need $5(n-1)/12$ to be an integer for these two to agree.

Also, one wants the smallest value. This will allow one to determine the region that you can determine distance.

Step up the values: $n = 0, 1, 2, 3...$ and see when you get an integer for m.

```
#include<stdio.h>

int main()
{
  int i,j;
  float x;

  for(i=0; i<20; i++)
    {
      x = 5.0*(i-1)/12;
      printf("%d,   %f\n", i, x);
    }
 }
```

Example

```
2,    0.416667
3,    0.833333
4,    1.250000
5,    1.666667
6,    2.083333
7,    2.500000
8,    2.916667
9,    3.333333
10,    3.750000
11,    4.166667
12,    4.583333
13,    5.000000
```

Example

So $m = 5$.

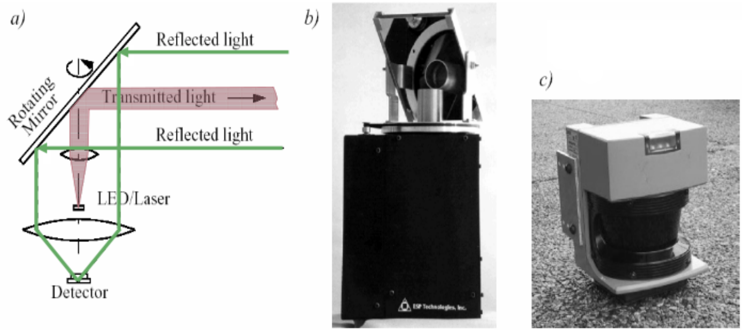
This gives isolation out to about 165 meters using two waves with a much shorter wavelength.

Modulation and phase shift?

How about trying a PWM unit and some gpio.

LIDAR Hardware

- Confidence in the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
- Dark distant objects do not produce as good of range estimate as closer brighter objects.



LIDAR Map Construction

Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.