Aalto University
School of Electrical Engineering

Sensing and Perception

ELEC-E8111 Autonomous Mobile Robots

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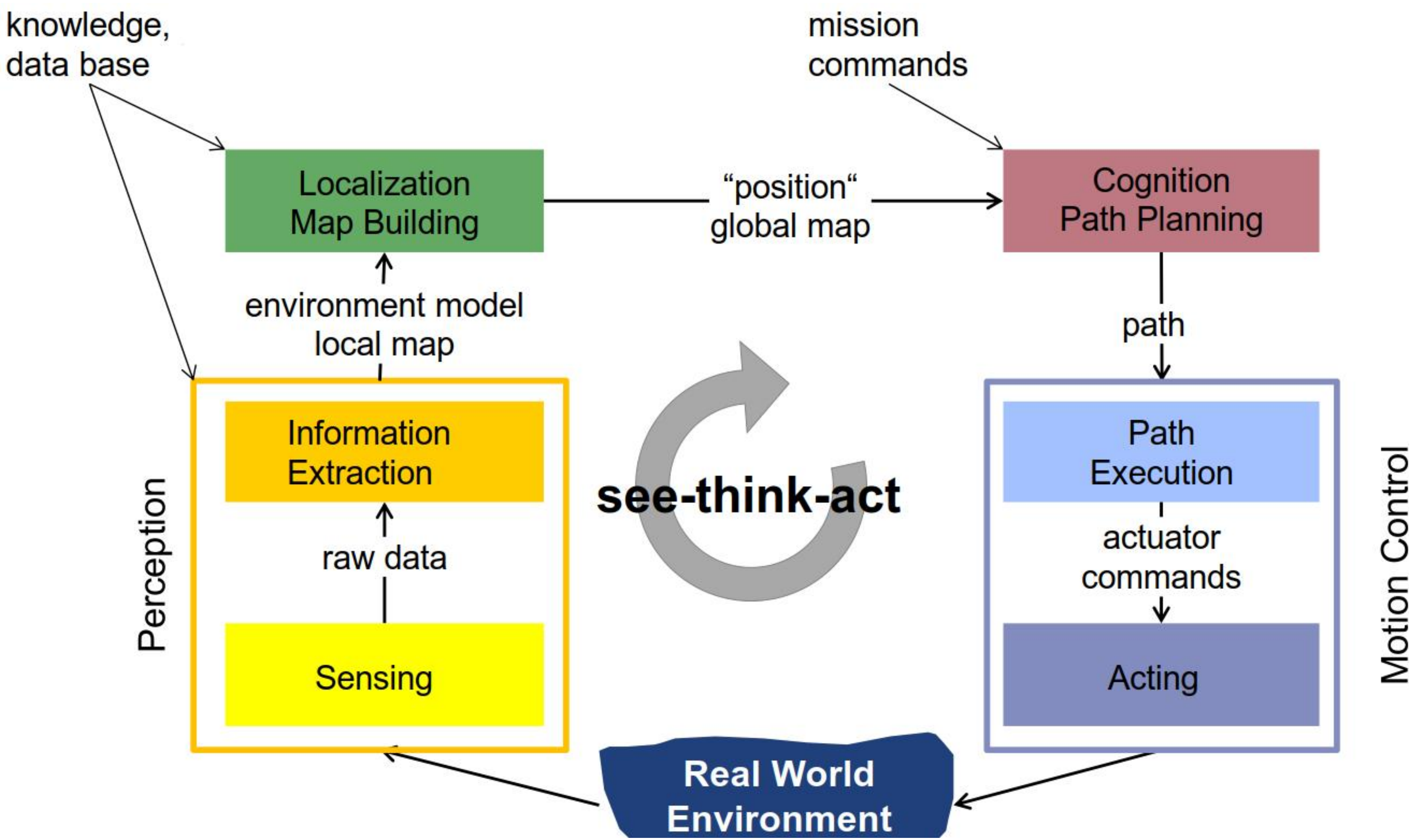
Sensing and perception in context



Overview

- Characterizing sensors
- Classification of sensors
- Sensor types for mobile robots
- Perception in mobile robotics

Characterizing sensors

- Sample rate
- Bandwidth
- Range
- Resolution
- Accuracy
- Precision

Can you explain these?

Characterizing sensors

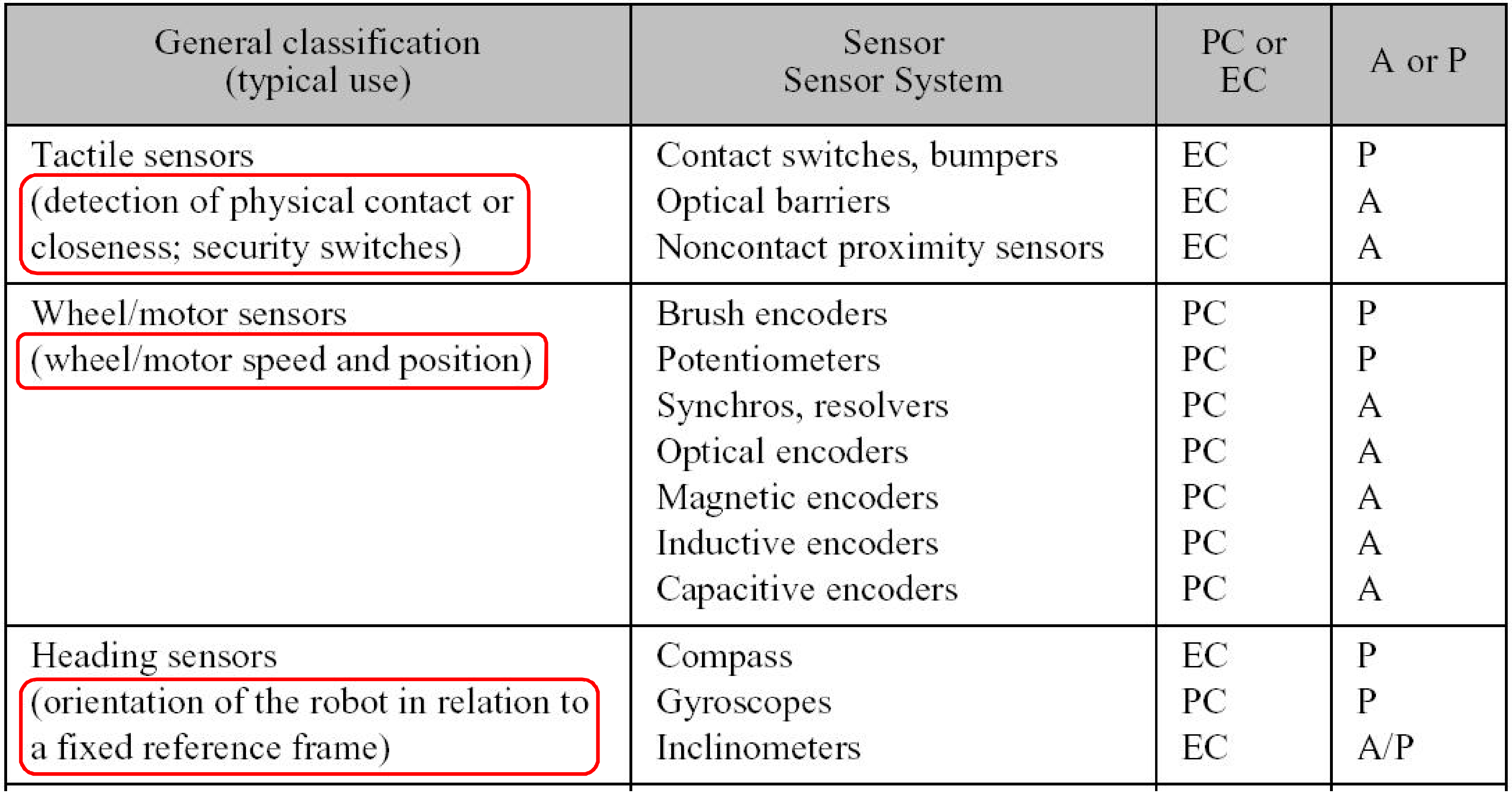
- Bandwidth – rate of measurements, Hz
- Range – lower and upper limit
- Resolution – minimum measurable difference
- Accuracy – difference to true value
- Precision – reproducibility of measurements
- Precision and accuracy are separate!
  - Precision depends on random errors
  - Accuracy depends on both random and systematic errors
  - Systematic errors can be decreased by modeling/calibration.

Classification of sensors

- Sensing target
  - Proprioceptive
    - measure internal state
    - e.g. motor/wheel speed, joint angles, battery status
  - Exteroceptive
    - measure external environment
    - e.g. distances to objects, light intensity
- Method of operation
  - Passive
    - Measure energy from environment
  - Active
    - Emit energy and measure reaction

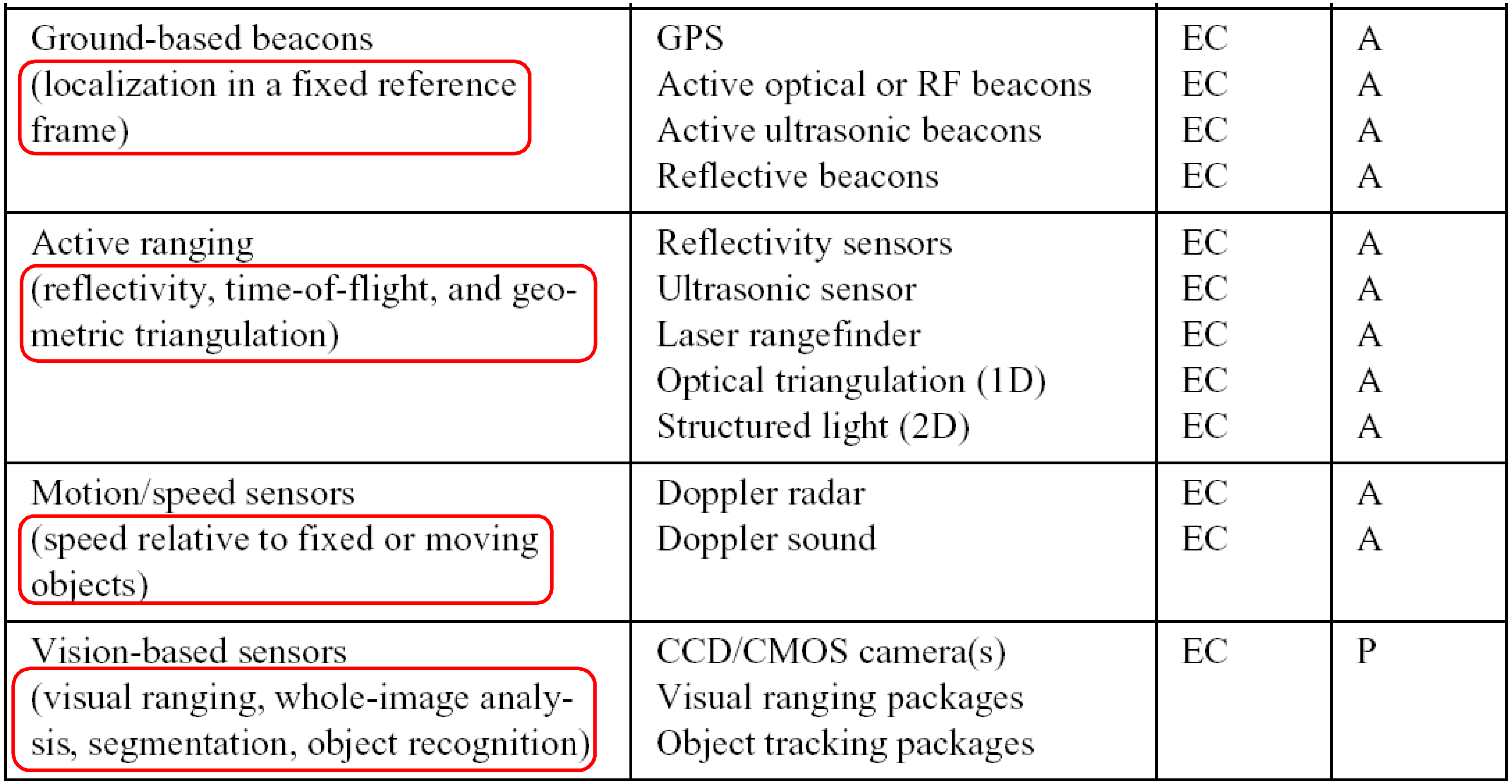
What kind of quantities need to be measured in a mobile robot?

Sensor types and sensing targets



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	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

Sensor types and sensing targets



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

Sensors on this course

- Optical encoders
- Heading sensors
- Accelerometers
- Inertial measurement units (IMUs)
- Global positioning system (GPS, Glonass, Galileo, Beidou)
- Range sensors, LiDAR
- And later a bit about vision

Navigation (internal) Sensors

- **To sense robot’s own state**
- Magnetic compass (absolute heading)
- Gyro (angular speed => change of heading)
- Acceleration sensors (acceleration)
- **tako, encoder (speed, distance)**
- **syncro, resolver (speed, position)**

Dead-reckoning

- Maritime term from deduced reckoning
- ”Murtoviivasuunnistus” in Finnish
- The position is calculated on the basis of previous position, heading and travelled distance
- No external beacons needed
- Very sensitive to the heading measurement!
- **Error is accumulating all the time!!**
- With ”basic sensors” a very low cost alternative à do always!
- High accuracy costs a lot!

Dead-reckoning

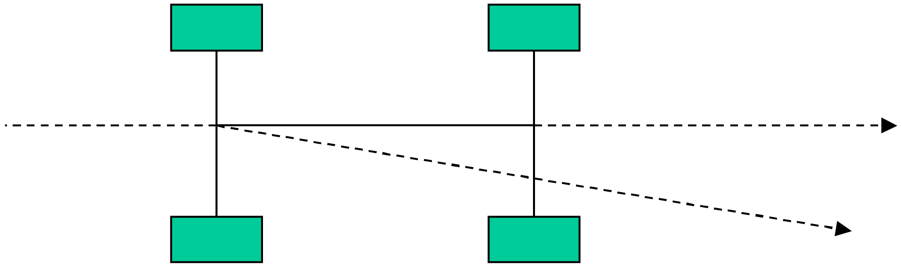
- The distance is measured with odometry
  - easy with wheels and tracks
  - difficult with legs and in maritime and airborne applications
- The heading can be defined by using:
  - Measurements and vehicle kinematics
    - steering angle + odometry measurement (ackermann)
    - Odometry (skid steering)
  - Direct measurement
    - compass
    - gyro
    - etc.

Error accumulation

Distance error from slippery etc. incrementally moves the calculated final position

Heading error from steering, gyro, etc. has much bigger effect

à heading is critical!!



Odometers

tachometer (DC motor)
potentiometer
synchro
resolver
optical encoder
magnetic encoder
inductive encoder
kapasitive encoder

The most used odometers are:

optical encoders
resolvers
potentiometers

Potentiometer

low-cost, easy to use

resistace/voltage proportional to the **absolute angle/position**

not for continuous rotation, mechanical wearing, nonlinear in accurate measurements

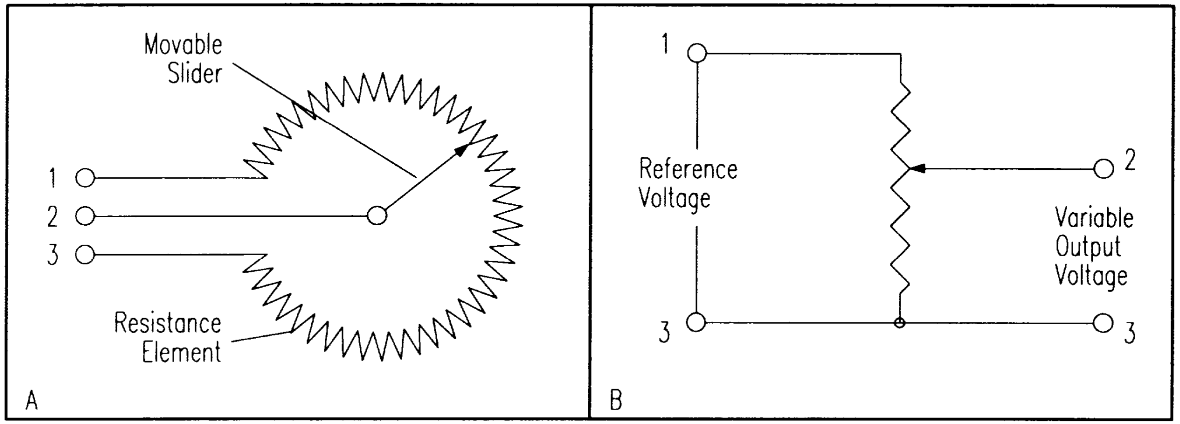


Figure 2-1. For a linear-taper pot, the output voltage V_o is directly related to the ratio of actual to full scale displacement.

DC-Tachometer

- Like normal DC-motor (DC with brushes, AC without)
- Output voltage proportional to the **rotation speed**
- cheap, output also in low speeds
- wearing brushes (not in brushless), analog output

Synchro

Electro mechanical system which transfers the angle information with high accuracy

Based on coupling of the magnetic flux

The receiver rotor will follow the transmitter rotor when same alternating voltage is supplied to both rotors

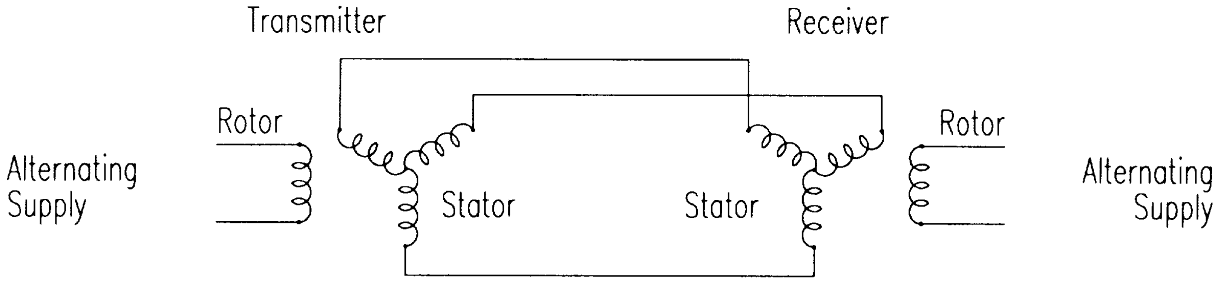


Figure 2-3. Schematic diagram of a typical remote-indicating synchro configuration (adapted from Schwartz & Graftstein, 1971).

Resolver

Special configuration of synchro

The output phase is proportional to **shaft absolute angle** and output (amplitude)/frequency is proportional to the **shaft speed** (ideal feedback sensor for brushless DC-motors)

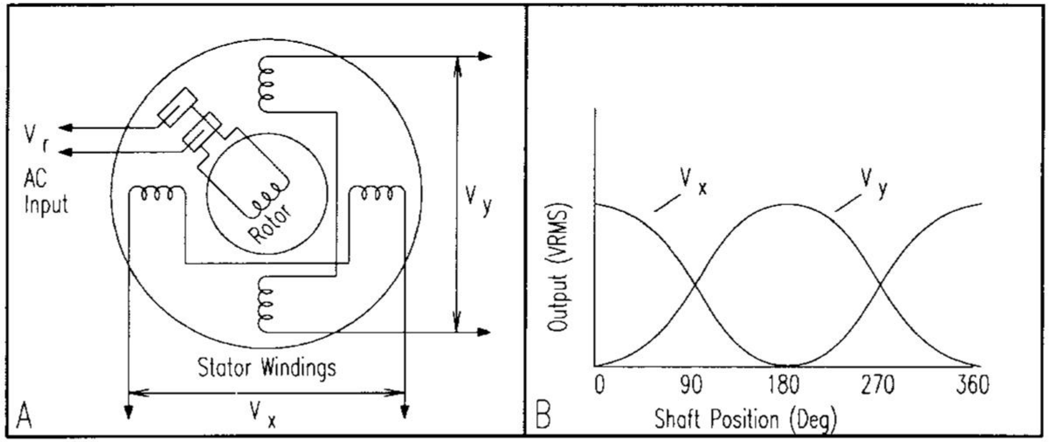


Figure 2-4. The outputs of the two orthogonal stator windings in a *resolver* are proportional to the sine and cosine of the applied rotor excitation (adapted from Tiwari, 1993).

Variable reluctance resolver

Rotor consists of only electro-magnetic steel sheets

One-phase of exciting coil and two-phase output coils are wound on the stator core

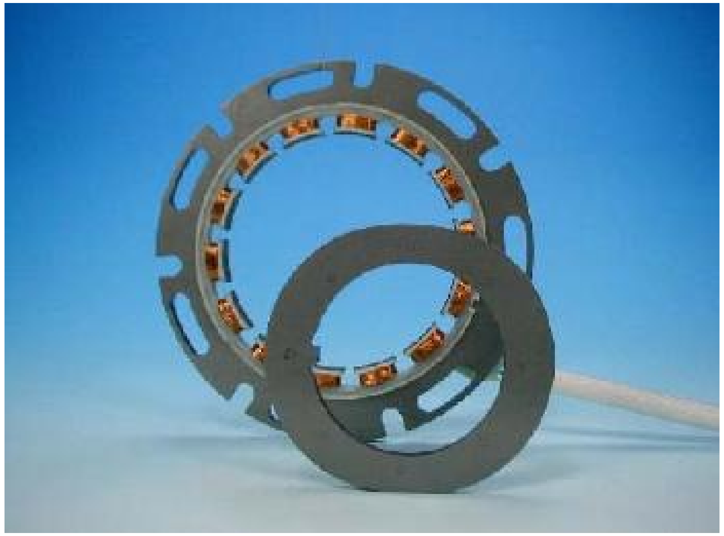
The contour of rotor is made as ellipsoid i.e. air-gap between the stator and rotor is varied in sinusoid depending on the shaft angle

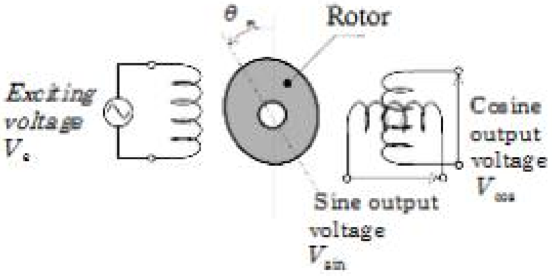
No brushes or sliprings

Extremely robust

Both speed and absolute angle output

Used in Toyota Prius

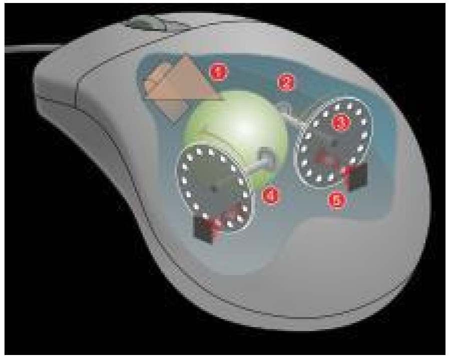




Structure of 2X-VR Resolver

http://www.scribd.com/doc/38612704/Tamagawa

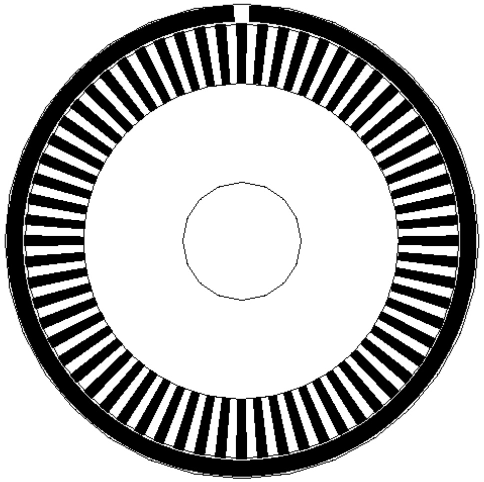
Encoders

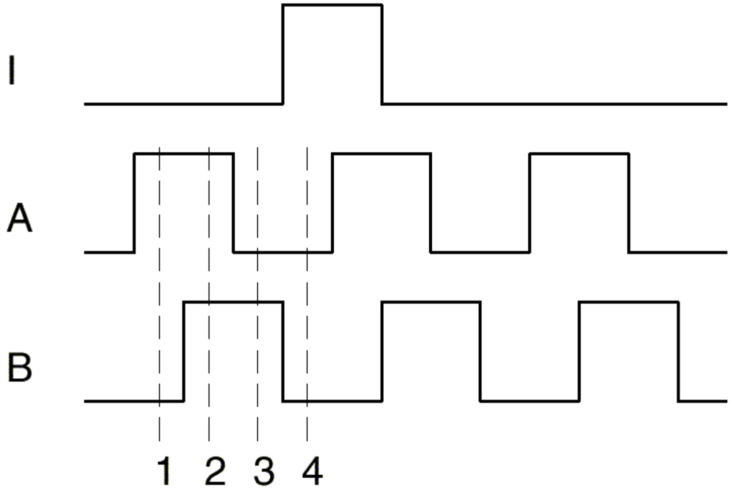


- Electro-mechanical devices that convert position into electrical signal
  - Measure either linear or angular motion
- Measure e.g. position of wheels and steering in mobile robots
- Operation principle
  - Optical sensor measures incremental changes
  - Typical resolution 64-2048 steps per rev
  - Counter used to accumulate steps
  - Interpolation can be used for higher resolution

Encoders - operation

- *Quadrature measurements* often used to sense the direction of motion.
  - Two sensors in quadrature phase shift.
  - Ordering of pulses determines direction of motion.





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

Absolute Encoder

Measures the **absolute position/angle**

More expensive than incremental one

Best for slow rotations with high accuracy

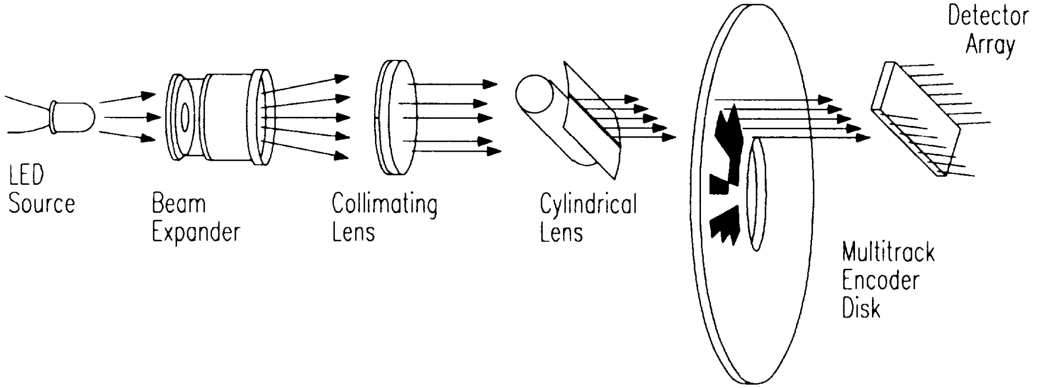


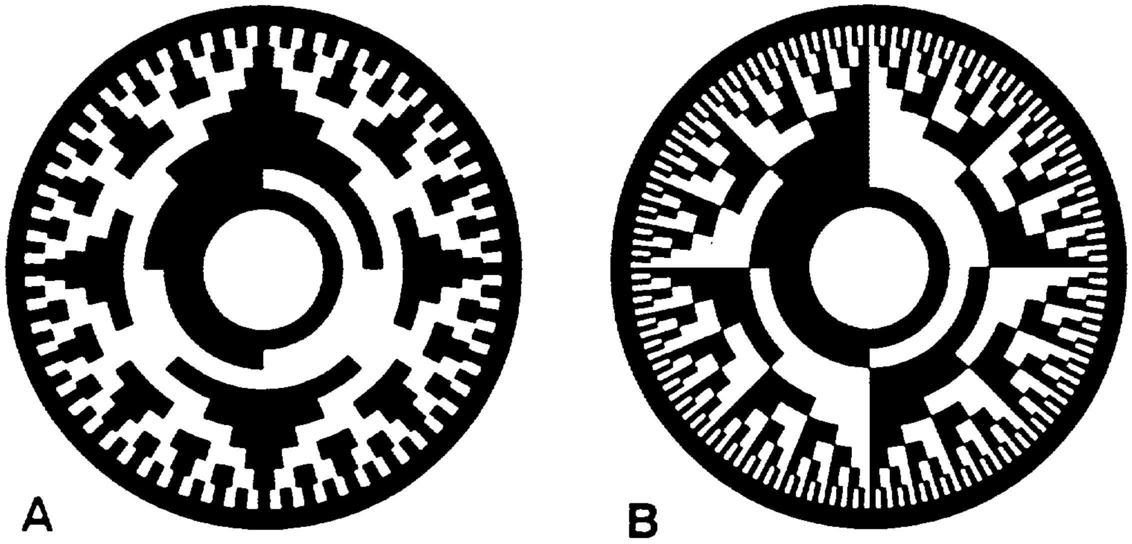
Figure 2-8. A line source of light passing through a coded pattern of opaque and transparent segments on the rotating encoder disk results in a parallel output that uniquely specifies the absolute angular position of the shaft (adapted from Agent, 1991).

Absolute Encoder

The most used configurations are:

A: Gray-code

B: Binary code



Ground Speed Radar

The wheels and tracks always slide => odometry is not accurate

Doppler radar gives the real groung speed, proportional to the speed difference between the radar and the target

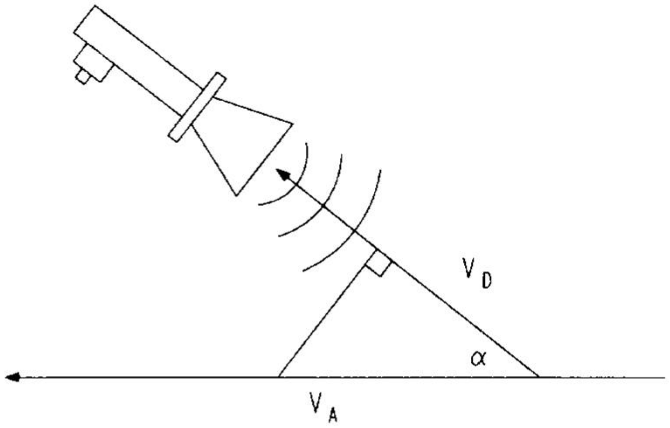


Figure 2-11. A Doppler ground speed sensor inclined at an angle α as shown measures the velocity component V_D of true ground speed V_A (adapted from Schultz, 1993).

Compasses, magnetometer

- Earth's magnetic field is an absolute reference.
- Approaches
  - Mechanical magnetic compasses
  - Direct measurement of magnetic field (e.g. Hall effect)
  - Gyrocompass (spinning wheel and friction, exploits gyroscopic forces caused by rotation of Earth, especially in ships)
- Drawbacks
  - Magnetic compasses easily disturbed by objects affecting the magnetic field
    - Not suitable for indoors for absolute orientation

What affects?

Magnetic Compasses

- Based on the detection of earth’s magnetic field~60mT
- Absolute heading, coarse accuracy
- Available magnetic compasses:
  - Mechanical magnetic compasses
  - Fluxgate compasses
  - Magnetoinductive compasses
  - Hall-effect compasses
  - Magnetoresistive compasses
  - Magnetoelastic compasses

Magnetic Compasses

- Magnetic field ~ 60mT
- About from south to north
- Declination = the angle between true and magnetic north
- Deviation = the angle between the indicated and actual bearing to magnetic north
- Inclination = the vertical component of the magnetic field (magnetic dip)
- Variation = local errors

Mechanical Magnetic Compasses

- Marine navigation device (the first written reference: China 2634BCE, commonly in use 1300)
  - Fluid damping and gimbal mounting is adequate for marine applications
  - problems in rough terrain
- ‘Starguide’ miniatyre compass
  - permanent-magnet rotor
  - low-friction jeweled bearing
  - internal damping
  - 8 led display or analog output

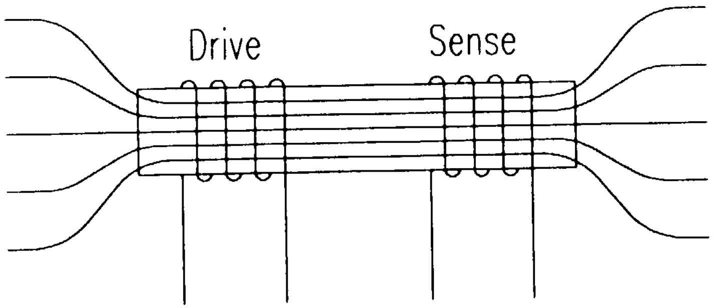
Fluxgate-Compass

Fluxgate = trade name of the first commercial *saturable-core magnetometer*

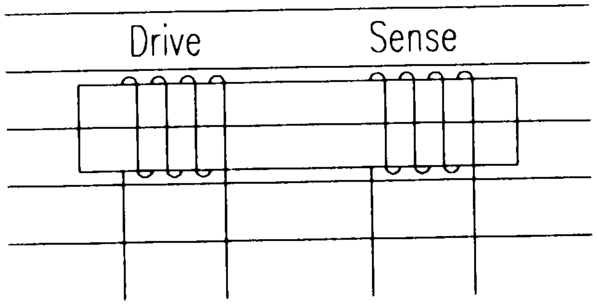
High permeability core non-saturated (A) and saturated (B) controls the magnetic flux

Saturation is controlled with sinusoidal or quadratic wave in the drive-coil

The expanding and collapsing magnetic flux induces to the sense coil an emf. relative to the existing magnetic field



A



B

Inertial sensors

INS = Inertial Navigation System

IMU = Inertial Measurement Unit

Gyros and acceleration sensors

Based on conservation of momentum/inertia or changes of the path length (optical gyros)

à no external support needed, work everywhere under the known physical laws

Gyroscopes

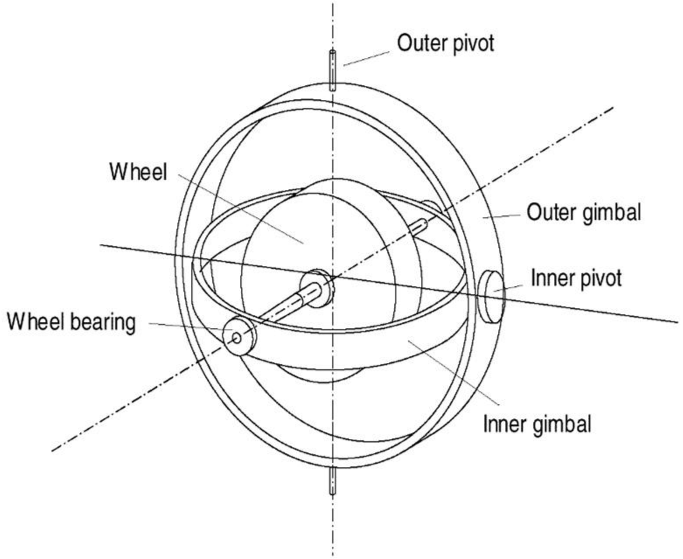
There are two basic classes of rotation sensing gyros:

- Rate gyros
    - the output is relative to the angular speed
- Rate integrating gyros
    - Indicate the actual turn angle or heading
    - The angle is relative => must be initiallly referenced to a known orientation
    - Angle is anyway integrated from angular speed à the primary measuring magnitutude of a gyro is always angular speed!!

Mechanical, optical (fog, laser ring), **MEMS** (tuning fork, vibrating ring)

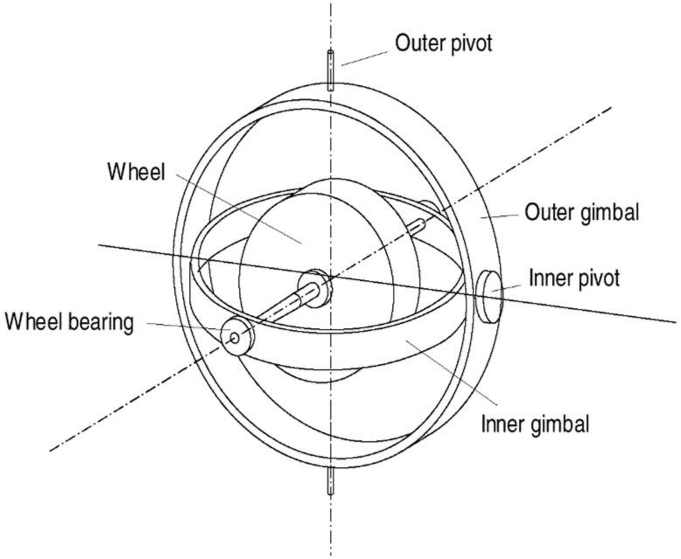
Gyroscopes

- Preserve their orientation relative to a fixed frame.
  - Provide an absolute orientation measurement (with drift).
- Performance classification according to bias drift
  - Rate grade ~10 – 10000 deg/h
  - Tactical grade ~0,01 – 10 deg/h
  - Navigation grade <0,01 deg/h
- Dynamic area: few Hz – 500Hz



Mechanical gyroscopes

- Mechanical gyroscopes (standard and rate gyros)
  - Inertia of a fast spinning rotor keeps the axis stable
  - Navigation grade possible
  - Drift 0.1° in 6 hours (can cost up to 100,000 US$)



Gyro parameters

Check these always!

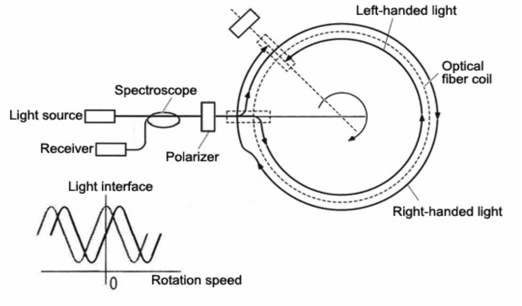
Drift (see previous slide) [deg/h]

Max angular speed [deg/s]

Dynamic resolution [Hz]

Not always easy!

Optical and MEMS gyroscopes

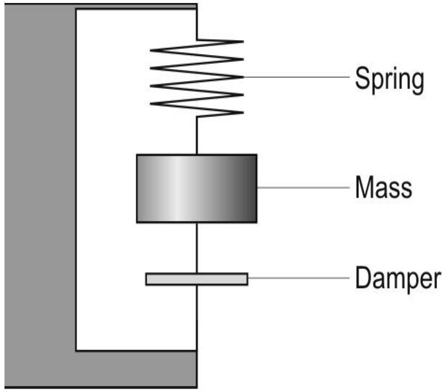


- Optical gyros based on Sagnac effect
  - Phase shift between two beams in different directions due to different distances traveled
  - Expensive
- MEMS gyros
  - Based on Coriolis force of a vibrating structure
  - Models e.g. tuning fork, vibrating wheel
  - Drift usually degs/min
  - Tactical grade available
  - Inexpensive, used widely in mobile robotics

Acceleration sensors

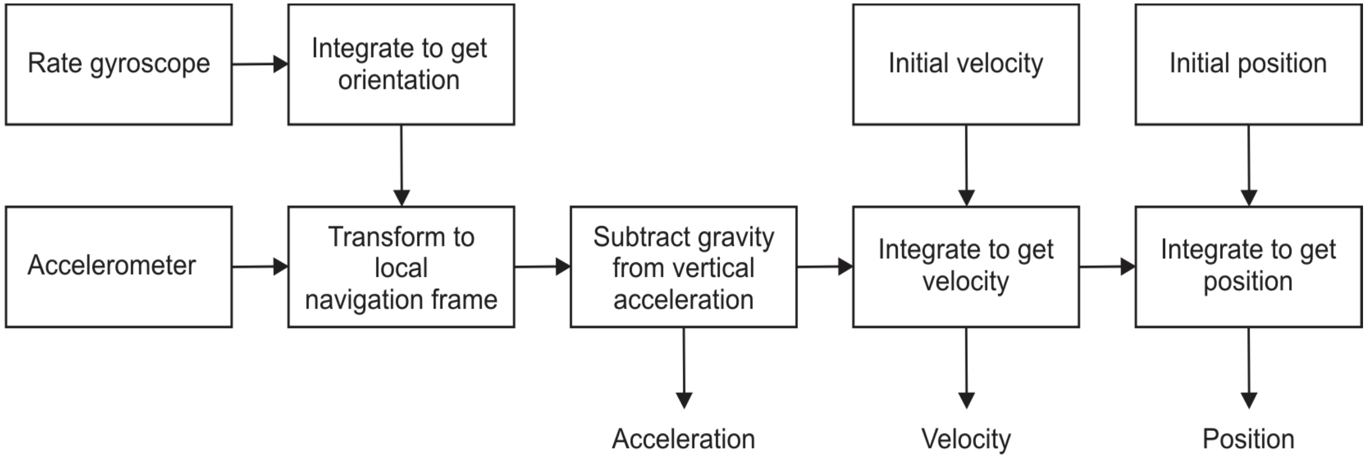
- Measure external forces acting on them (incl. gravity)
- Typically measure a motion of a mass in spring-mass-damper system
- Common operation principles: MEMS, piezoelectric
- Gravity must be subtracted to obtain inertial acceleration
- Inexpensive
- Bandwidth up to 50 kHz
- Often three mounted together to obtain

a 3-axis accelerometer



Inertial measurement units (IMUs)

- Device using sensors such as gyroscopes and accelerometers to estimate the relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration.



IMUs

- Sensitive to measurement errors in gyroscopes and accelerometers because drift causes incorrect cancellation of gravity.
  - Double integrator systems
- All IMUs drift over time.
  - External sensor (e.g. GPS) needs to be used to cancel drift.

http://www.youtube.com/watch?v=s19W-MG-whE

MicroStrain Inertia-Link, a bit old

Inertial Measurement Unit and Vertical Gyro utilizing miniature MEMS sensor technology

triaxial accelerometer

triaxial gyro

temperature sensors

on-board processor running a sophisticated sensor fusion algorithm

http://www.microstrain.com/inertial/Inertia-Link

MicroStrain 3DM-GX1, a bit old

Three angular rate gyros

three orthogonal DC accelerometers

three orthogonal magnetometers

multiplexer, 16 bit A/D converter, and embedded microcontroller

output its orientation in dynamic a static environments.

update rates of 350 Hz

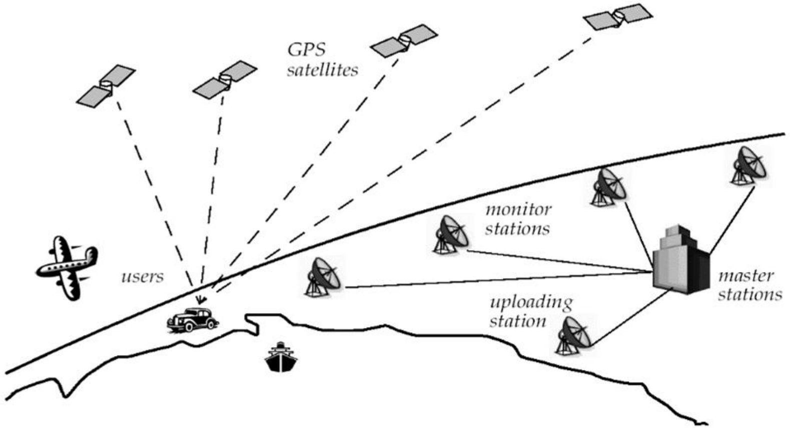
http://www.microstrain.com/inertial/3DM-GX1

Beacons

- Active or passive devices with known positions.
    - Sufficient to measure position relative to beacons.
- Types of beacons
    - Markers, e.g. in motion capture systems (Vicon, Optitrack)
    - GPS satellites
- Motion capture systems
    - Several cameras track markers
    - >300 fps, <1 mm precision
    - System needs to be calibrated
    - Needs environment change

Global navigation satellite systems (GNSS)

- E.g. GPS, GLONASS
- Time of flight to satellites in known locations
- Accuracy of commercial devices down to a few m
- Differential GPS (dGPS)
  - An extra GPS receiver (base station) set up in a known location allows corrections e.g. for trop
  - Accuracy down to cm range
- Limitations
  - Not applicable indoors



Accuracy of GNSS in Forest

GPS and its extensions (*only in open terrain*)

- With phase measurement and DGPS, accuracy 0.5m
- With RTK-correction, less than 10cm, even 2cm

GLONASS (Russia)

- Better in northern areas due to satellites
- DGPS and RTK extensions possible

Galileo (in operation 2020)

- Basic accuracy better than with GPS, about 1m.

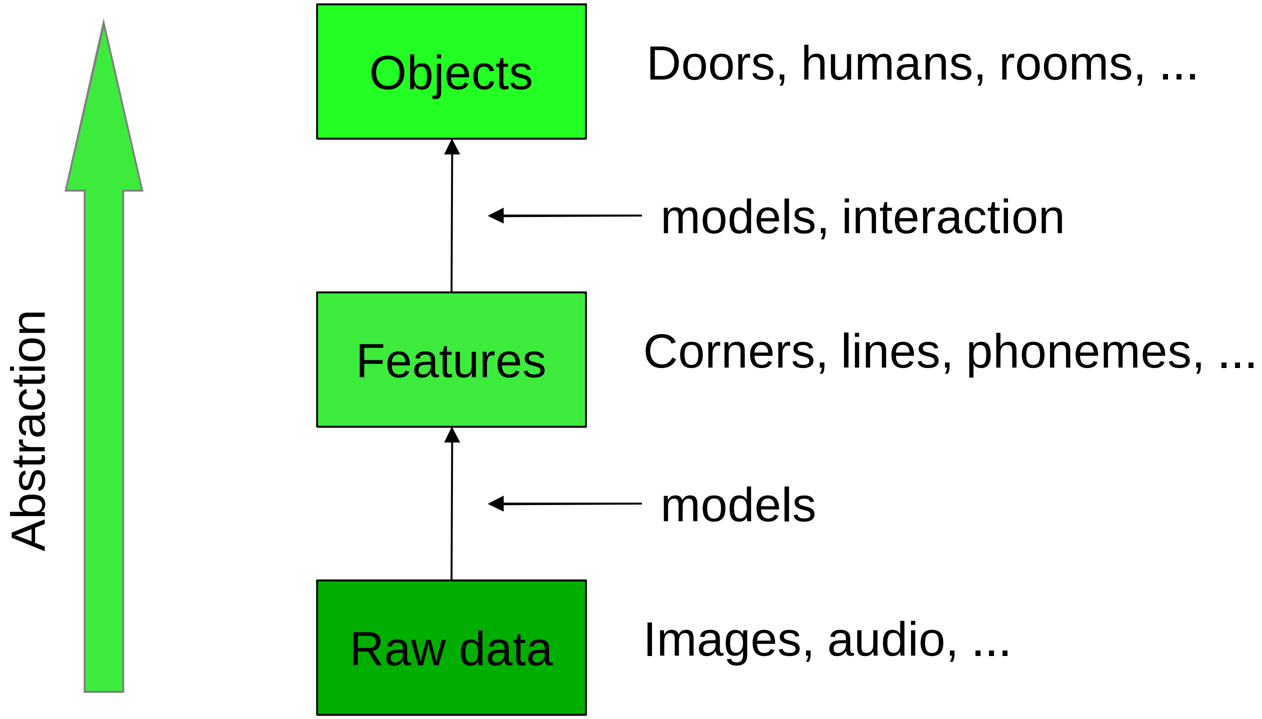
COMPASS (BeiDou-2) (China, internationally in operation 2020)

- 10m accuracy in civil applications, 10cm accuracy for army and government application of China.

Finland is in North, extra errors due shadows in forest

From sensors to perception

- Hierarchical abstraction



Why it is important for a roboticist to understand sensors?

- Sensors are needed to perceive incompletely known environment.

- Understanding physical principles enables
    - Selecting sensors for a particular application.
    - Understanding the limitations of sensing, e.g., resolution, bandwidth, uncertainties.

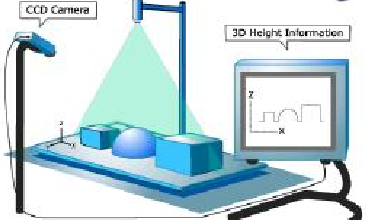
Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera

- Structured light



Time of flight (TOF) range sensors

- Measure distance to environment
- TOF sensor principle
  - Ultrasonic and laser sensors measure time of flight
  - Known propagation speed of sound or electromagnetic waves allows calculation of distance to reflecting target
- Propagation speeds

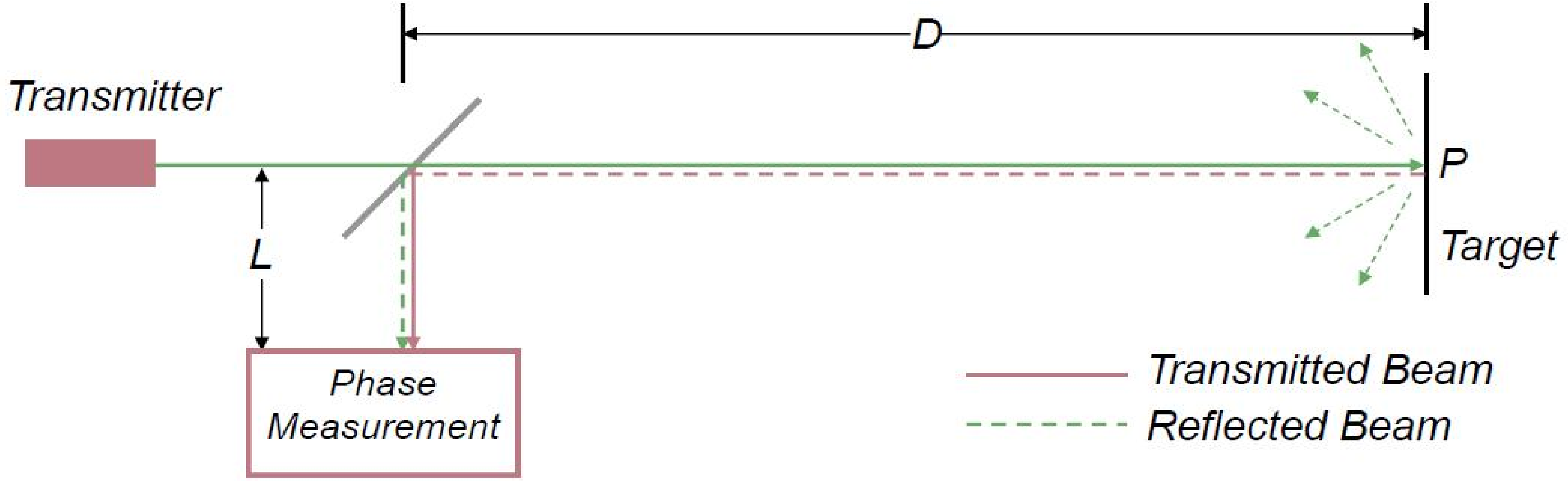
$$d = c \cdot t$$

  - Sound in air ~0.3 m/ms, 3 meters ~ 10 ms
  - Electromagnetic wave (light) ~0.3 m/ns, 3 meters ~ 10 ns
    - Measurement of short time intervals not easy

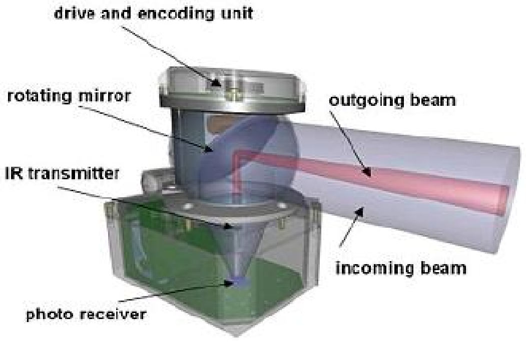
Ultrasonic ranging

- 40 kHz – 180 kHz sound generated by piezo transducer
- Useful range from ~10 cm to ~5-10m, resolution ~2cm
- Inexpensive
- Sound propagates in cone, opening angles 20-40 deg
- Limitations
  - Soft surfaces absorb sound
  - Hard surfaces can cause specular reflections

Laser range finder, phase type, Lidar



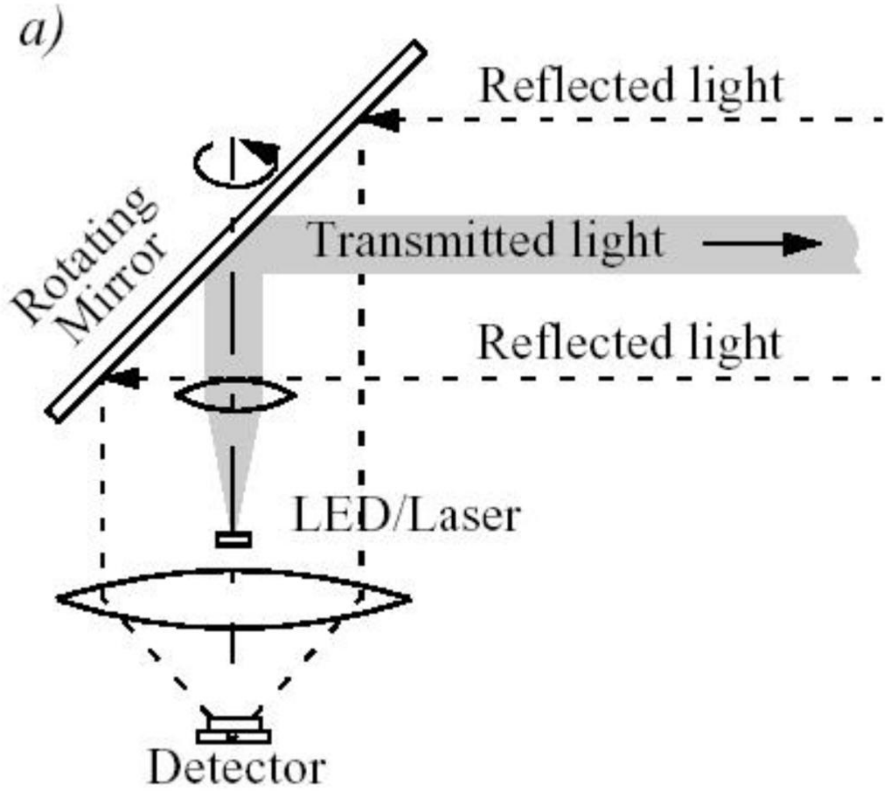
- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated laser beam
- Receiver detects the time needed for round-trip
- A mechanical mechanism with a mirror sweeps
    - 2D or 3D measurement



Laser range finder, time of flight, Lidar

Operating Principles:

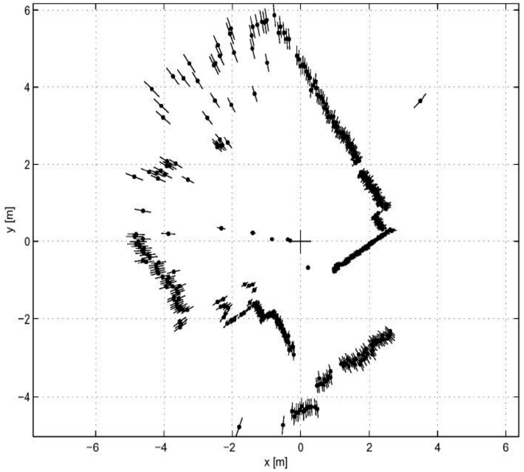
- Pulsed laser (today the standard)
- measurement of elapsed time directly
- resolving picoseconds
- Phase shift measurement to produce range estimation
- technically easier than the above method



Laser ranging

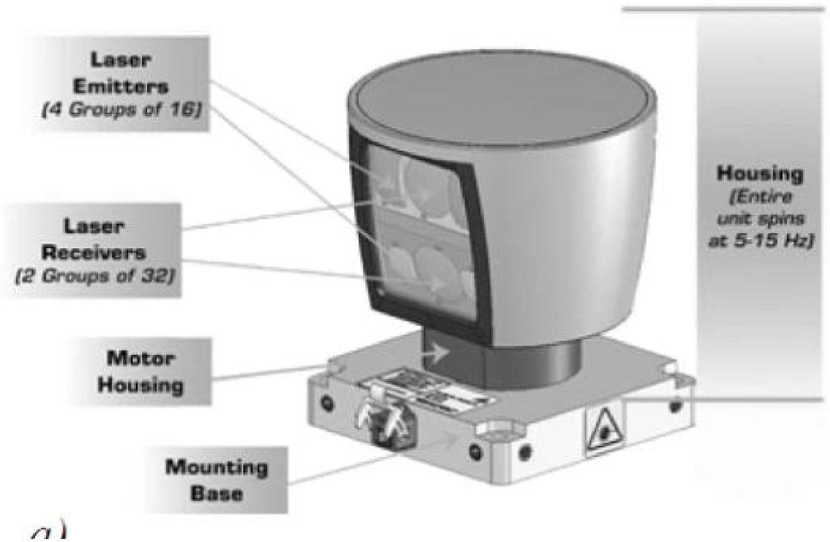
- Limitations
  - Specular reflections (mirror-like surfaces), low reflectance (dark) targets
- Angular resolution ~0.1-0.25 deg
- Resolution ~10mm, accuracy ~20-30mm
- Range ~5cm-50m
- Most important sensor for mobility

in most current robotic platforms



3-D laser ranging, newer Velodynes later

- The Velodyne HDL-64E uses 64 laser emitters.
  - Turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - **Delivers over 1.3 million data points per second**
  - The distance accuracy is better than 2 cm and can measure depth up to 50 m
  - This sensor was the primary means of terrain map construction and obstacle detection for all the top DARPA 2007 Urban Challenge teams. However, the Velodyne iscurrently still much more expensive than Sick laser range finders (SICK ~ 5000 Euros, Velodyne ~50,000 Euros!)



C Carnegie Mellon University

https://www.youtube.com/watch?v=5OieptDxSh8

Up to date LIDARS

Lidars developed for autonomous vehicles are becoming commercial.

Low-cost due to large volume production.

Robust

For real-time processing

Velodyne

http://velodynelidar.com/index.html

Kaarta, integrated with Velodyne-lidars for measuring uniform 3Dpointclouds, creating map in real time; IMU integrated, utilizes laserodometry.

http://www.kaarta.com/stencil/

Quanergy’s

Solid state LiDAR , not anymore rotating mirrow mechanism.

http://quanergy.com/

Up to date LIDARS

Autonomoustuff

Customized R&D-platforms for vehichle applications

http://www.autonomoustuff.com/

Sick-LIDARS

These have been used at Aalto for research

https://www.sick.com/de/en/product-portfolio/c/PRODUCT_ROOT#g91899

Ocularrobotics

The configuration of scanning area and resolution of 3Dpointcloud can be changed during scaning

http://www.ocularrobotics.com/

IBEO automotive

LIDARs for automotives

https://www.ibeo-as.com/

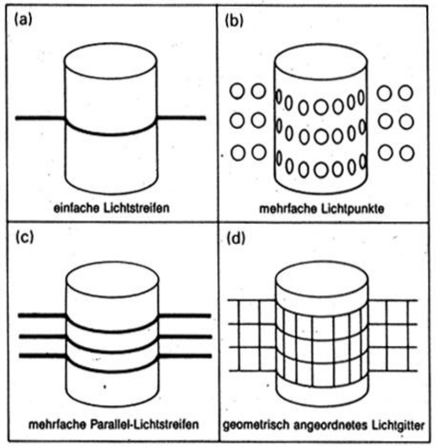
TOF cameras

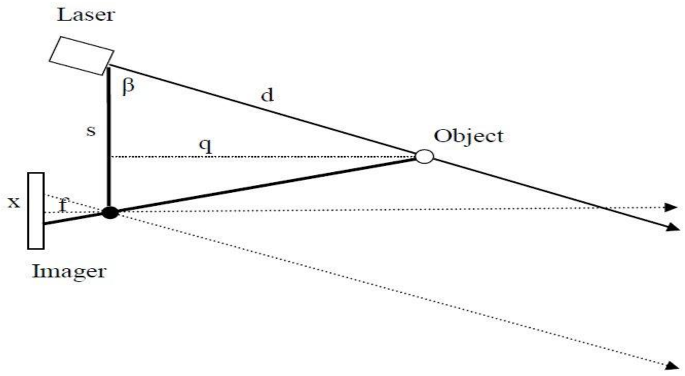
- Similar to Lidar but whole scene captured simultaneously without moving parts
- Often infrared projected
- Accuracy ~2cm, range ~0.8-5m
- High data rate >100Hz
- Limitations
  - Low resolution ~200x150 pixels
  - High noise, outliers

Mesa Swiss Ranger

Projected light and triangulation

- Known pattern is projected and imaged.
- Position of pattern in camera sensor determines distance (via triangulation).





Machine vision cameras

A lot of high resolution cameras available

- Low cost due to large production volumes, robust.
- Illumination in ourdoor application can be problematic, sunshine
- **Real time processing can be realized**
  - Processors powerful enough, cheap memory
  - GPU-processing for strict real time applications

’Depth’ cameras are available Pitempään markkinoilla olleet:

- Stereo and motion vision, Structured light cameras, TOF-cameras

Basler

http://www.baslerweb.com/en/products/cameras/3d-cameras/time-of-flight-camera

Fotonic

http://www.fotonic.com/

RGB-D / Kinect

- Combines IR projector with random pattern with IR (and RGB) camera
- Resolution ~1cm, range 0.8-3.5m
- http://www.youtube.com/watch?v=dTKlNGSH9Po&feature=related
- https://www.youtube.com/watch?v=uq9SEJxZiUg

Beyond

- More about IMUs in a lecture about estimation of orientation, later
- More about vision in a lecture, later .
  - Machine Perception course will concentrate on this.
- More about Laser Range finders in SLAM parts
- Integration of measurements from several sensors essential in practice (sensor fusion).
- Many other sensors also in use, e.g.,
  - Mobility: radars.
  - HRI: microphones, contact sensors.
  - Manipulation: force/torque, pressure/tactile/contact.

Summary

- Proprioceptive and exteroceptive sensors needed to act in an incompletely known environment.
- Range sensors important in mobile robotics for obstacle avoidance.
  - Despite their price, lidars are likely the most important sensors for mobile robots.

Material

- Different sources
- Siegwart & Nourbash, chapter 4