EE6221 Robotics and Intelligent Sensors (Part 3)

Lecture 1: Sensors

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Outline

- Sensor classification
- Sensor characterization
- Motor encoders (position)
- Heading/orientation sensors
- Ground-based beacons
- Active ranging
- Speed sensors
- Vision (sensors, depth from focus, stereo vision, optic flow, etc.)

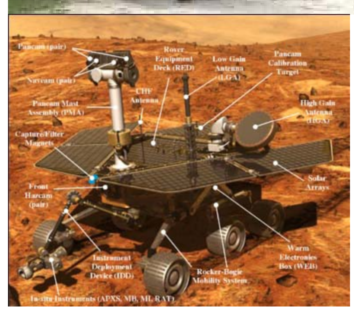
Reference:

- *Introduction to Autonomous Mobile Robots (ch.4),* R. Siegwart, and I. Nourbakhsh, MIT Press, 2004
- *Sensors for Mobile Robots, Theory and Applications,* H.R. Everett, A K Peters Ltd., 1995

Robot Sensors

- Robot Sensors can be divided into two basic classes:
  1) Internal State Sensors
  2) External State Sensors.
- **Internal sensors** are used for control of the internal states of the robot/machine.
- **External sensors** are needed for the robot/machine to react intelligently with its surroundings.

Sonar, IR, haptic feedback, tactile sensors, range of motion sensors, vision sensors (CCD cameras), etc.



Internal State Sensors

- **Internal state sensors** consists of devices used to measure position, velocity, or acceleration of robot joints and/or the end effectors. The following devices are some of the sensors that belong to this class:

- Potentiometers
- Synchros
- Linear inductive scales

- Differential transformers (LVDTs and RVDTs)
- Optical interrupters
- Optical encoders
- Tachometers
- Accelerometers

Internal State Sensors

The successful **control of most robots** depends on being able to obtain accurate information about the joint and/or end effectors.

Necessary to have devices (transducers) that provide such information and can be readily utilized in a robot for this purpose.

In particular, position, velocity, and/or acceleration (or at least analog or digital representations of these quantities) must be measured to ensure that the robotic machine moves in a desired manner.

Internal State Sensors

The **internal state sensors** must not only permit the required degree of ***accuracy*** to be achieved, they must also be ***cost-effective*** since each of the robot's axes will normally utilize such devices.

The sensor selection and the decision to place it either on the load side or on the output of the joint actuator itself is influenced by such factors as:

1) overall sensor cost,
2) power needs for a particular joint,
3) maximum permissible size of the actuator,
4) sensor resolution, and
5) the need to monitor directly the actions of the joint.

External State Sensors

The second class, called **external state sensors**, is used to monitor the robot's geometric and/or dynamic relation to its task, environment, or the objects that it is handling.

Although it is possible to utilize a robot without any **external sensing**, but in order to achieve ***greater flexibilities*** and ***intelligent abilities***, the robot will require such devices to be aware of its surroundings.

Robotic sensing mainly gives robots the ability to see, touch, hear and move, and uses algorithms that require environmental feedback.

Robots use different sensors to detect different factors of the environment.

External State Sensors

The **usage** of external state sensors:

- **Vision**: Visual sensors help robots to identify the surrounding environment and take appropriate action.
- **Touch**: Touch patterns enable robots to interpret human emotions in interactive applications. Robots use touch signals to map the profile of a surface in hostile environment such as a water pipe.
- **Hearing**: Robots can perceive our emotion through the way we talk. Acoustic and linguistic features are generally used to characterize emotions.
- **Movement**: Provide a guidance system for an automated robot to determine the ideal path to perform its task.

External State Sensors

Instruments of external state sensors (not a full list):

Vision (camera, infrared, laser, RFID) for landmark recognition, 3D scene recovery, scene understanding, etc.

Tactile sensors: Four measurable features—force, contact time, repetition, and contact area change—can effectively categorize touch patterns.

Range finders (lasers, ultrasonic) for 3D scene recovery, local position.

GPS (differential GPS) for global positioning

Odometry (encoders, gyroscopes, accelerometers) – absolute motion recovery.

The Role of Multi-Sensor Integration and Fusion

The purpose of external sensors is to provide a system with useful information concerning some features of interest in the system's environment. This enables the machine to ***act intelligently*** via some intelligent programme.

The potential advantages in ***integrating*** and/or ***fusing information*** from ***multiple sensors*** are that the information can be decided more accurately, concerning features that are impossible to perceive with individual sensors, as well as in less time, and at a lesser cost.

These advantages correspond, respectively, to the notions of the ***redundancy****,* ***complementarity****,* ***timeliness****, and* ***cost*** of the information provided the system.

The Role of Multi-Sensor Integration and Fusion

Redundant information is provided from a group of sensors (or a single sensor over time) when each sensor is perceiving, possibly with a different fidelity, the same features in the environment.

The integration or fusion of redundant information ***can reduce overall uncertainty*** and thus serve to increase the accuracy with which the features are perceived by the system.

Multiple sensors providing redundant information can also serve to ***increase reliability*** in the case of sensor error or failure.

The Role of Multi-Sensor Integration and Fusion

Complementary information from multiple sensors allows features in the environment to be perceived that are impossible to perceive using just the information from each individual sensor operating separately.

More timely information, as compared to the speed at which it could be provided by a single sensor, may be provided by multiple sensors either because of the actual speed of operation of each sensor, or because of the ***processing parallelism*** that may possibly be achieved as part of tile integration process.

The Role of Multi-Sensor Integration and Fusion

Less costly information, in the context of a system with multiple sensors, is information obtained at a lesser cost as compared to the equivalent quality of information that could be obtained from a single sensor.

Unless the information provided by the single sensor is being used for additional functions in the system, the total cost of the single sensor should be compared to the total cost of the integrated multi-sensor system.

With redundancy, it is possible then to ***use lower cost sensors with lower quality*** that can be combined to achieve the same quality of reading from a high quality sensor (thereby being costly).

Classification of Sensors for Robots

Classification based on functions:

- Proprioceptive sensors
  - Measure the internal state of the system (robot), e.g., Angular position of motor wheel, motor speed, wheel load, battery status, etc.
  - Examples: GPS, INS, Shaft Encoders, Compass, etc.

Classification of Sensors for Robots

- Exteroceptive sensors
  - Determine the measurements of objects relative to a robot's frame of reference (i.e., information about the robot’s environment)
  - Measure: e.g., distance from the robot to another object
  - Keep the robot from colliding with other objects
  - Types: contact sensors, range sensors, vision sensors
- Exproprioceptive sensors (Directional Sensors)

Classification of Sensors for Robots

Classification based on where energy comes from:

- Active sensors
  - emit their own energy and measure the reaction
  - better performance, but some influence on the environment and generally consumes more energy
  - Examples: ultrasonic, laser, and IR sensors.

- Passive sensors
  - receives energy already in the environment
  - consume less energy, but often have signal and noise problems
  - Examples: camera

General Classification

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

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

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

General Classification

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

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

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Sensor Characteristics

- Size, weight, power consumption, voltage, interface
- Field of view (FOV)
- Range (or full scale)
  - lower and upper limits
  - e.g., triangulation range finder may provide unpredictable values outside its working range
- Dynamic range (e.g., camera pixels)
  - ratio between the smallest and largest possible values of a changeable quantity (e.g., sound, light, etc.)
  - often specified in decibels (ratio between powers)
  - e.g., power measurement from 1mW to 20W: $10\log[20/0.001]=43\text{dB}$

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Sensor Characteristics

- Resolution
  – smallest input change that can be detected (due to noise, physical limitations or determined by the A/D conversion)
- Linearity
  – variation of output signal as function of the input signal
  – sometimes expressed as % of full scale
- Hysteresis
  – path-dependency (e.g. thermostats, some tactile sensors)

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

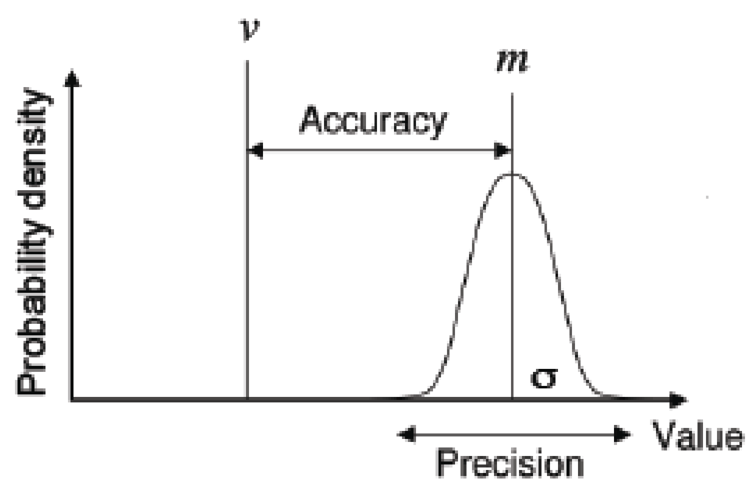
Sensor Characteristics

- Bandwidth or Frequency
  - the speed at which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - one has also to consider delay (phase) of the signal
- Sensitivity
  - ratio of output change to input change
- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters
  - influence of other active sensors

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Sensor Characteristics

- Accuracy (exactitude, opposite of error)
  - degree of conformity between the measurement and true value
  - often expressed as a portion of the true value: *Accuracy=1-|m-v|/v, m = measured value, v = true value*
- Precision (or repeatability)
  - relates to reproducibility of sensor results: precision=range divided by standard deviation



(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

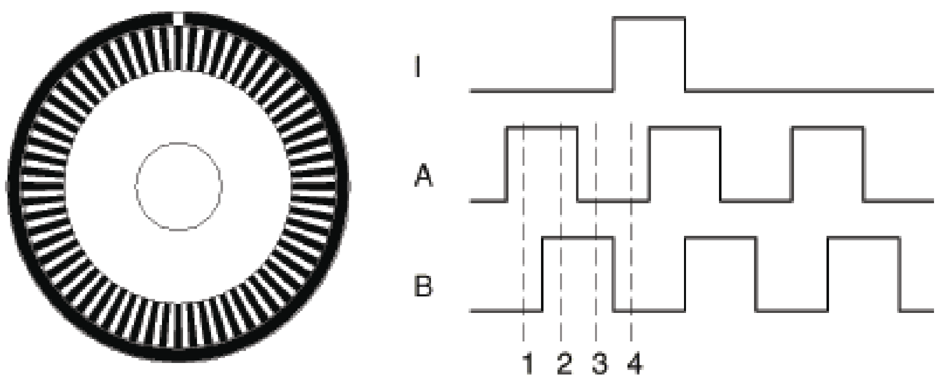
Types of Errors

- Systematic errors: deterministic
  - caused by factors that can (in theory) be modeled and predicted
  - e.g., distortion caused by the optics of a camera
- Random errors: non-deterministic
  - no prediction possible
  - however, they may be described probabilistically
  - e.g., hue instability of camera, black level noise of photoreceptors, non-returning echoes in ultrasonic sensors, etc.
- Others
  - cross-sensitivity of sensors, motion blur
  - rarely possible to model -> appear as “random” errors but are neither systematic nor random
  - systematic errors and random errors might be well defined in controlled environment. *This is often not the case for mobile robots!*

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Wheel/Motor Encoders

- Measure position or speed of the wheels or steering.
- Integrate wheel movements to get an estimate of the position -> odometry
- 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.



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

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Magnetic compasses

- Since over 2000 B.C.
  - when Chinese suspended a piece of naturally magnetite from a silk thread and used it to guide a chariot over land.
- Magnetic field on earth
  - absolute measure of orientation.
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field: Hall-effect, Flux Gate, magnetoresistive sensors
- Major drawback
  - weakness of the Earth magnetic field (0.3-0.6 μT)
  - easily disturbed by magnetic objects or other sourc
  - not working in indoor environments (except locally)
- Often used in attitude sensing…

E.g.: HMC1043 is a miniature three-axis magnetoresistive magnetometer of only 3x3 mm

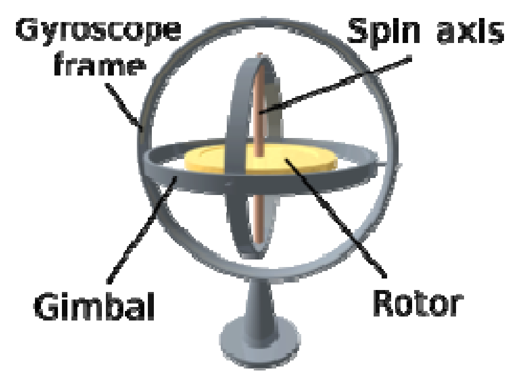
(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Gyroscopes

- The goal of gyroscopic systems is to measure changes in vehicle orientation by taking advantage of physical laws that produce predictable effects under rotation.
- Three functioning principles:
  – Mechanical
  – Optical
  – Micro-electromechanical systems (MEMS)
- Two categories
  – Orientation -> directly measure angles (very rare in robotics!)
  – Rate gyros -> measure rotation velocity, which can be integrated…
- A problem common to all gyroscopes is that of drift => unless the error is corrected through reference to some alternate measurement, the drift will eventually exceed the required accuracy of the system.

Mechanical Gyroscopes

- Rely on angular momentum (gyroscopic inertia): the tendency of a rotating object to keep rotating at the same angular speed about the same axis of rotation in the absence of an external torque.
- Reactive torque is proportional to the spinning speed, the rate of precession and the wheel's inertia.
- No torque can be transmitted from the outer pivot to the wheel axis => spinning axis will therefore be space-stable.
- Nevertheless, remaining friction in the bearings of the gyro axis introduce some errors over time (drift).
- A high-quality mechanical gyro can cost up to $100'000 and drift may be kept as low as 0.02°/h
- Mechanically complex => not much used in mobile robotics.



Optical Gyroscopes

- Based on the behavior of an optical standing wave in a rotating frame (the Sagnac effect).
- Optical gyroscopes use the interference of light to detect mechanical rotation:
  - two light beams travel (e.g. along an optical fiber of up to 5 km in length) in opposite directions
  - the beam traveling against the rotation experiences a slightly shorter path than the other beam
  - the resulting phase shift affects how the beams interfere with each other when they are combined
  - the intensity of the combined beam then depends on the rotation rate of the device
- Resolution can be smaller than 0.0001°/s

MEMS Rate Gyros

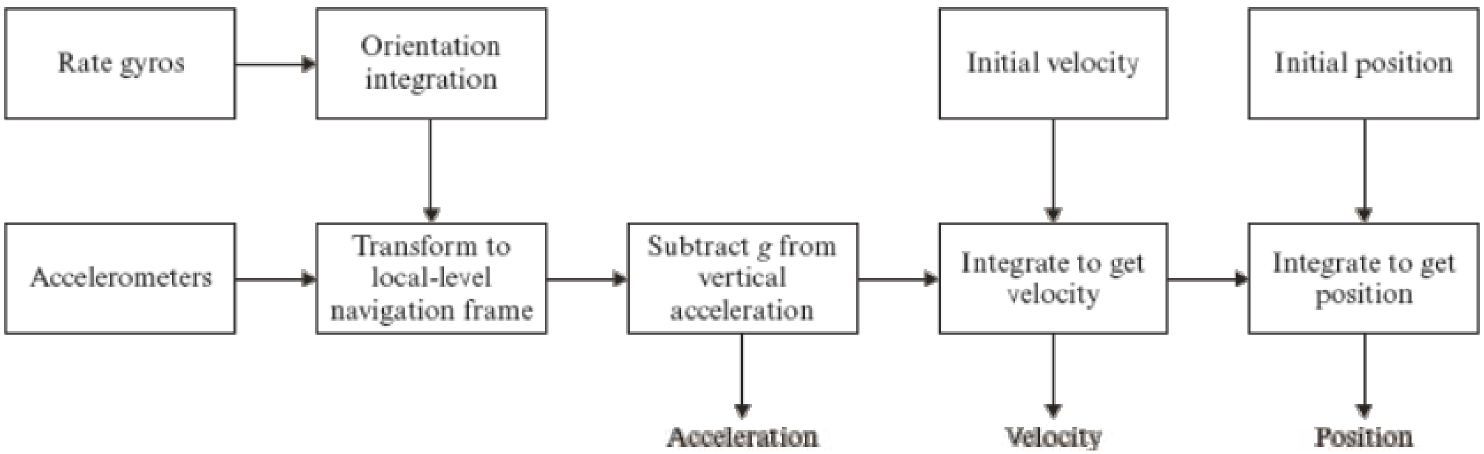
- Based on vibrating mechanical elements to sense Coriolis acceleration.
- Coriolis acceleration is the apparent acceleration that arises in a rotating frame of reference:
- Various possible MEMS structure: tuning-fork, vibrating wheel, wineglass resonator
- MEMS gyros have no rotating parts, have low-power consumption requirements, and are small => they are quickly replacing mechanical and optical gyros in robotic applications.

Accelerometers and Pressure Sensors

- Accelerometers / inclinometers
  - An accelerometer is a device that measures the proper acceleration of the device.
  - Conceptually, an accelerometer behaves as a damped mass on a spring.
  - MEMS are based on a cantilever beam with a proof mass.
  - The way of measuring the beam deflection is often capacitive or piezoresistive.
  - MEMS accelerometers can have three axes => inclinometers.
- Pressure / airspeed / altitude
  - Deforming membrane (piezoresistive, capacitive, optical, electromagnetic, etc.)
  - Either absolute or differential (Pitot tube)
  - Example of the Freescale MPX:
    - resolution of 4 cm in altitude
    - variations due to atmospheric pressure changes over one day: up to 45 m

Inertial Measurement Units (IMU) or Inertial Navigation System (INS)

- A device that utilizes sensors such as gyroscopes and accelerometers to estimate the relative position (velocity, and acceleration) of a vehicle in motion.
- A complete IMU/INS maintains a 6 DOF estimate of the vehicle pose: position (x,y,z) and orientation (yaw, pitch and roll).
- This requires integrating information from the sensors in real time.



- IMU/INS are extremely sensitive to measurement errors => an external source of information such as GPS and/or magnetometer is often required to correct this (cf. ch. 8 for more information on sensor fusion).
- List of IMU/INS products: http://damien.douxchamps.net/research/imu/

(adapted from the Handbook of Robotics, 2008, ch.20.4)

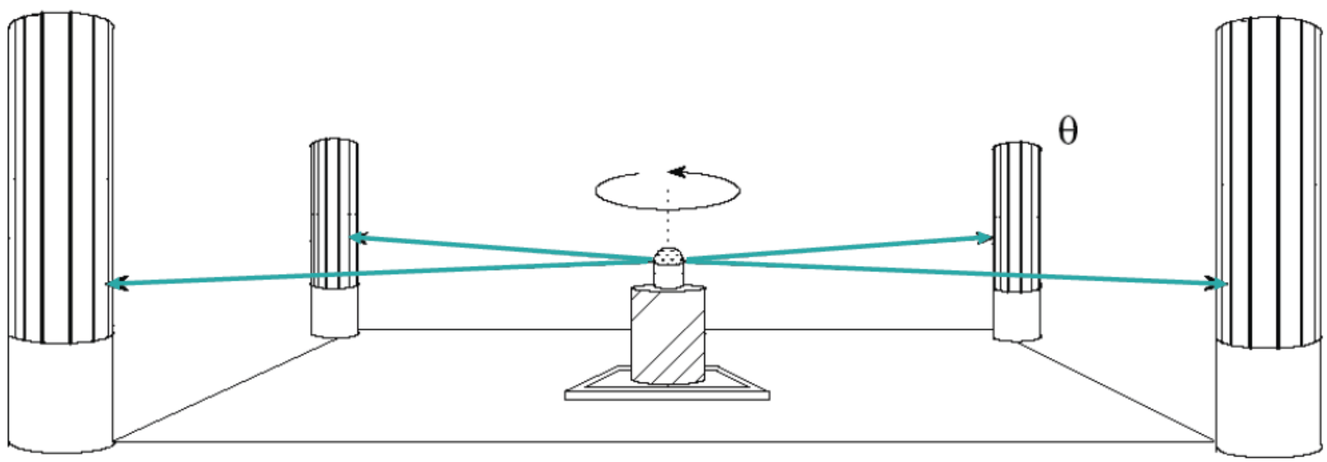
Beacon-based positioning

- Beacons are signaling devices with a precisely known position.
- Beacon-based navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - Already one of the key sensors for outdoor mobile robotics
  - For indoor robots GPS is not applicable
- Major drawback with the use of beacons indoors:
  - Beacons require changes in the environment -> costly
  - Limit flexibility and adaptability to changing environments

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Passive optical beacons

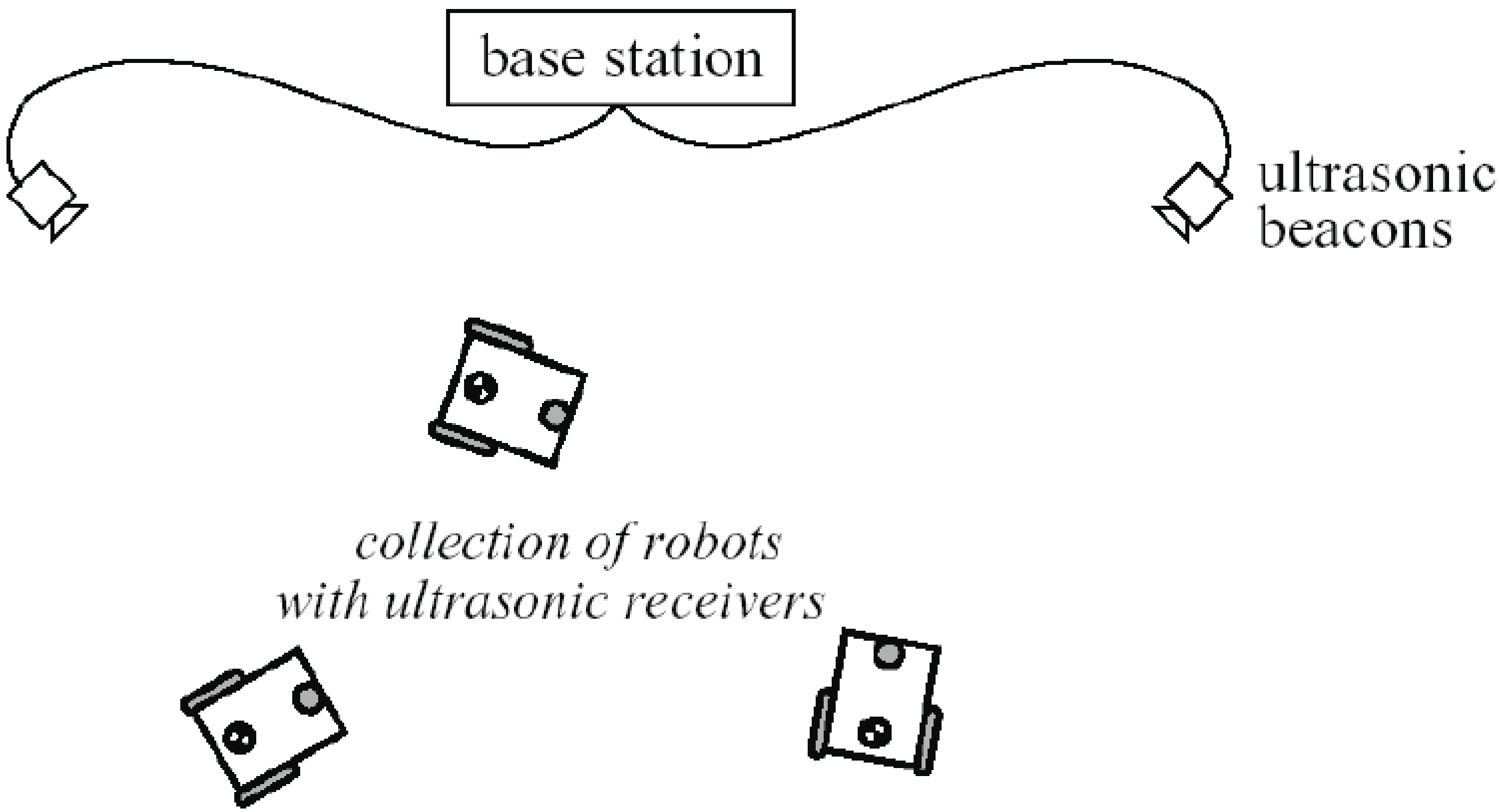
- Passive retroreflective beacons of known position
- Distance and heading of at least two beacons are measured (e.g. using a scanning laser range finder)



(adapted from Siegwart & Nourbakhsh, 2004, ch. 5)

Active ultrasonic beacons

- Robots must know the emitter locations
- Using time of flight (TOF), they can deduce their position
- Time synchronization is required (e.g. RF or IR)

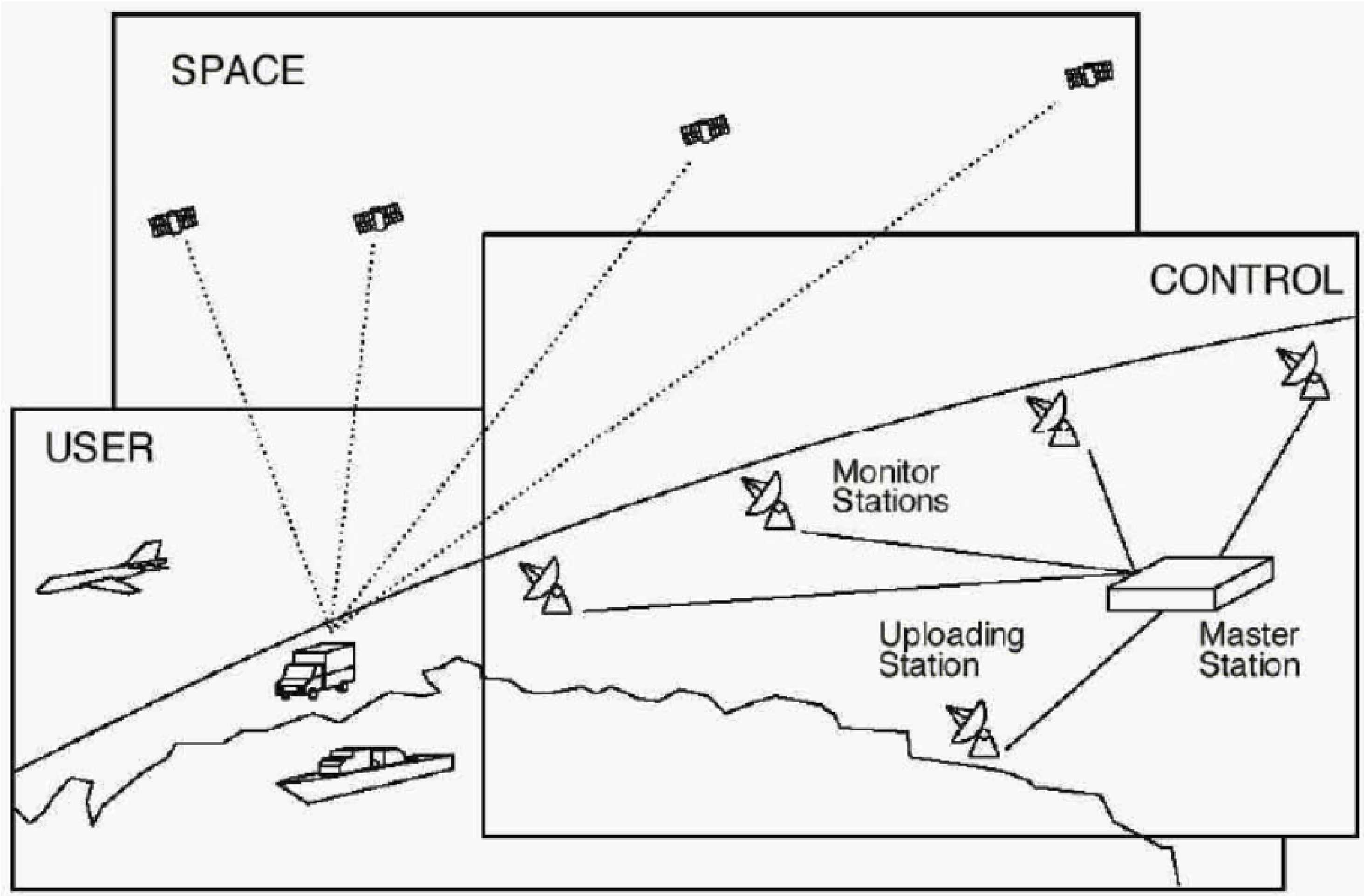


Global positioning system (GPS)

- Facts:
  - Developed for military use by the US (NAVSTAR)
  - Recently became accessible for commercial applications
  - 24 satellites (including three spares) orbiting the Earth every 12 hours at a height of 20’190 km
  - 4 satellites are located in each of six planes inclined by 55° with respect to the plane of the Earth’s equator
  - Location of any GPS receiver is determined through a time of flight measurement
- 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, reflections

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Global positioning system (GPS)



(adapted from Everett, 1995, section 14.2)

Global positioning system (GPS)

- Time synchronization:
  - ultra-precision time synchronization is extremely important
  - roughly 0.3m/ns => position accuracy proportional to precision of time measurement
  - atomic clocks on each satellite
- Real time update of the exact location of the satellites:
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- Exact measurement of the time of flight
  - the receiver correlates a pseudocode with the same code coming from the satellite
  - the delay time for best correlation represents the time of flight
  - quartz clock on the GPS receivers are not very precise
  - the range measurement with four satellites allows to identify the three values (x, y, z) for the position and the clock correction dT
- Recent commercial GPS receivers have a position accuracy within 20 m (typ. 10 m) in the horizontal plane and 45 m in the vertical plane, depending on the number of satellites within line of sight and multipath issues. WAAS allows to get close to 1-2 m accuracy.
- The update rate is typically between 1 and 4 Hz only.

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

TOF Range Sensors

- Range information:
  - key element for obstacle avoidance, localization and environment modeling
- 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 * t
- Where
  - *d = distance traveled (usually round-trip)*
  - *c = speed of wave propagation*
  - *t = time of flight*

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

TOF Range Sensors

- Important to keep in mind:
  - Propagation speed of sound: 0.3m/ms
  - Propagation speed of electromagnetic signals: 0.3m/ns
  - 3 meters correspond to 10ms for an ultrasonic system versus only 10ns for a laser range sensor

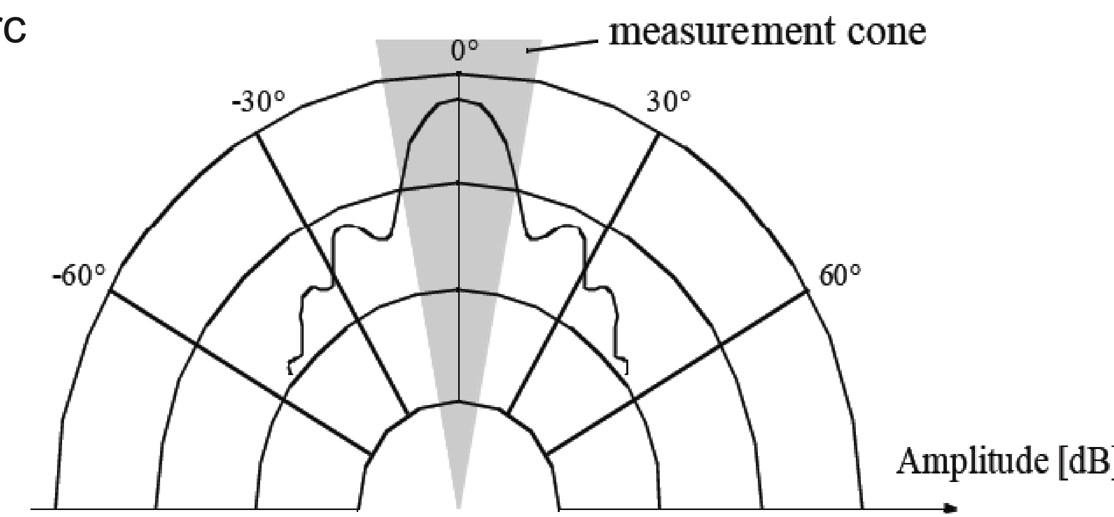
    => time of flight with electromagnetic signals involves very fast electronics

    => laser range sensors are more expensive and delicate to design
- The quality of TOF 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, diffuse/specular reflections)
  - Variation of propagation speed (sound)
  - Speed of mobile robot and target (if not at stand still)

(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

Ultrasonic Sensors

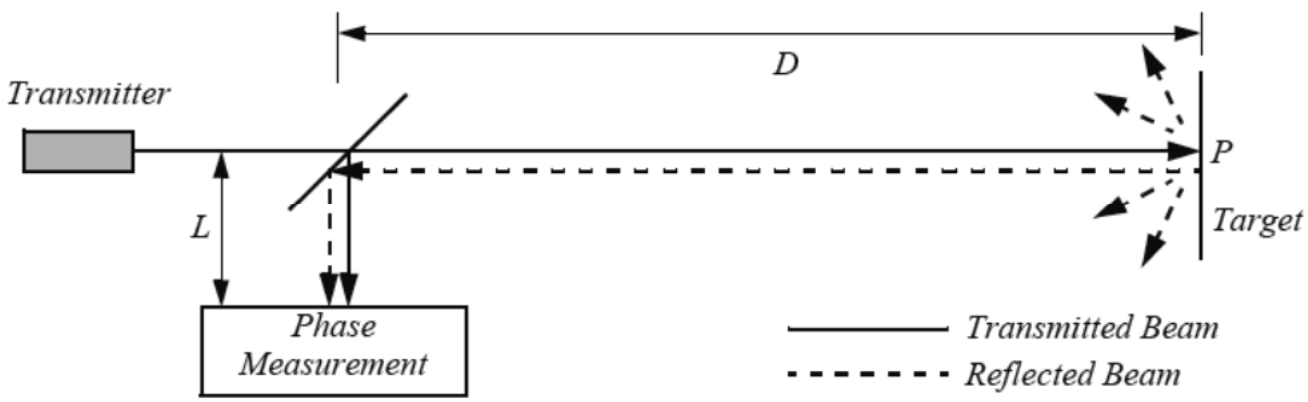
- Transmit a packet of (ultrasonic) pressure waves
- Distance *d of the echoing object can be calculated based on* the propagation speed of sound *c and the time of flight t.* d=c*t/2
- Typical frequency: 40 - 180kHz
- Generation of sound wave: piezo transducer
  - transmitter and receiver can be separated or not
- Sound beam propagates in a cone (*approx.)*
  - opening angles around 20 to 70 degrees
  - regions of constant depth
  - segments of an arc (sphere for 3D)



Typical intensity distribution of a ultrasonic sensor

Laser Rangefinders

- Also known as *laser radar or LIDAR (LIght Detection And Ranging)*
- Transmitted and received beams are coaxial
- Transmitter illuminates a target with a collimated beam (laser)
- Diffuse reflection with most surfaces because wavelength is typ. 824nm
- Receiver detects the time needed for round-trip
- An optional mechanism sweeps the light beam to cover the required scene (in 2D or 3D).



(adapted from Siegwart & Nourbakhsh, 2004, ch. 4)

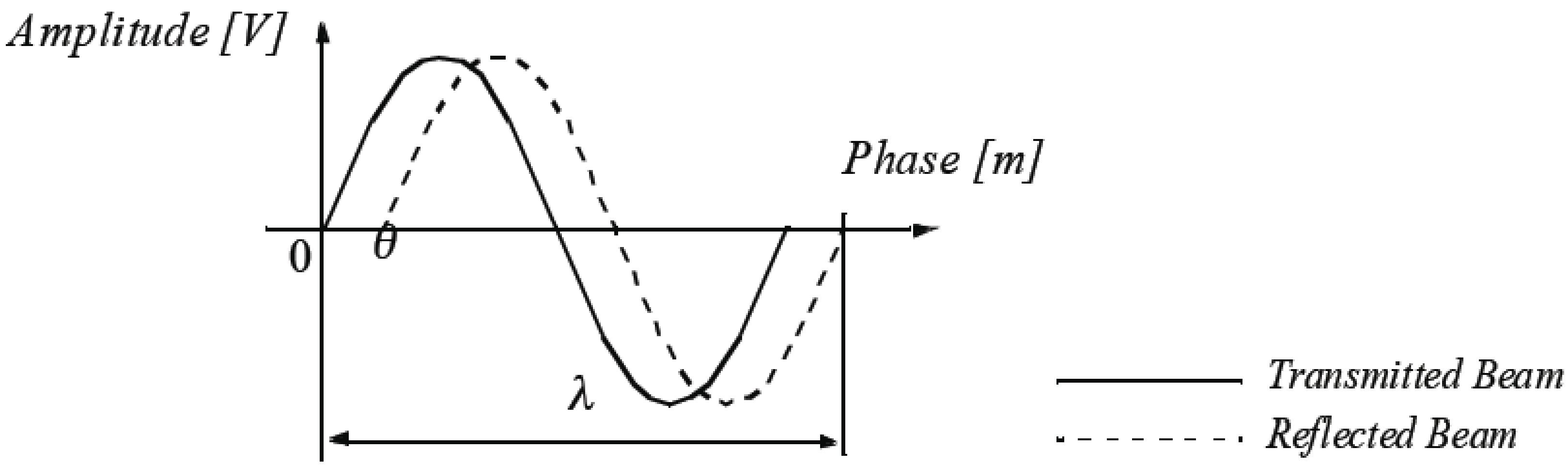
Laser Rangefinders

- Time of flight measurement is generally achieved using one of the following methods:
  - Pulsed laser (e.g. Sick)
    - direct measurement of time of flight
    - requires resolving picoseconds (3m = 10ns)
  - Phase shift measurement (e.g. Hokuyo)
    - sensor transmits 100% amplitude modulated light at a known frequency and measures the phase shift between the transmitted and reflected signals
    - technically easier than the above method

Sick Inc., Germany

Hokuyo, Japan

Phase-shift laser Rangefinders



- Distance *D, between the beam splitter and the target is given by* (Woodbury, et al., 1993): D = lamda*theta/(4*pi)

  where theta is the phase difference between transmitted and reflected beam and with *c the speed of light, f the modulating frequency*
- Confidence in the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
- Hence dark, distant objects will not produce as good range estimates as closer, brighter objects.