Intelligent Robots Practice

Perception - Sensors

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Contents

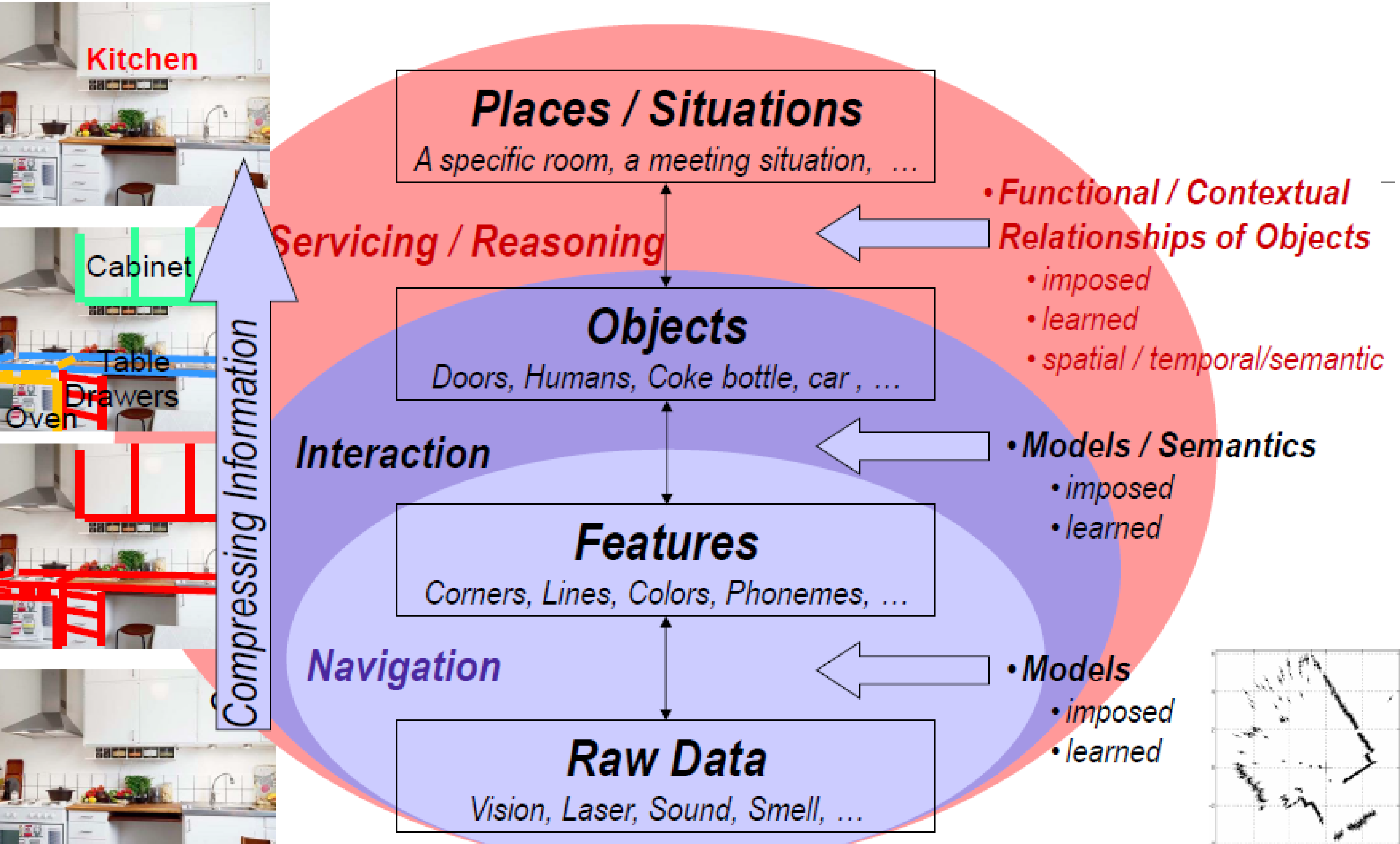
Introduction

Introduction

- Sensors for Mobile Robots
  - Why should a robotics engineer know about sensors?
    - They are **the key components** for perceiving the environment
    - **Understanding the physical principles** 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**

Introduction

- Perception for Mobile Robots

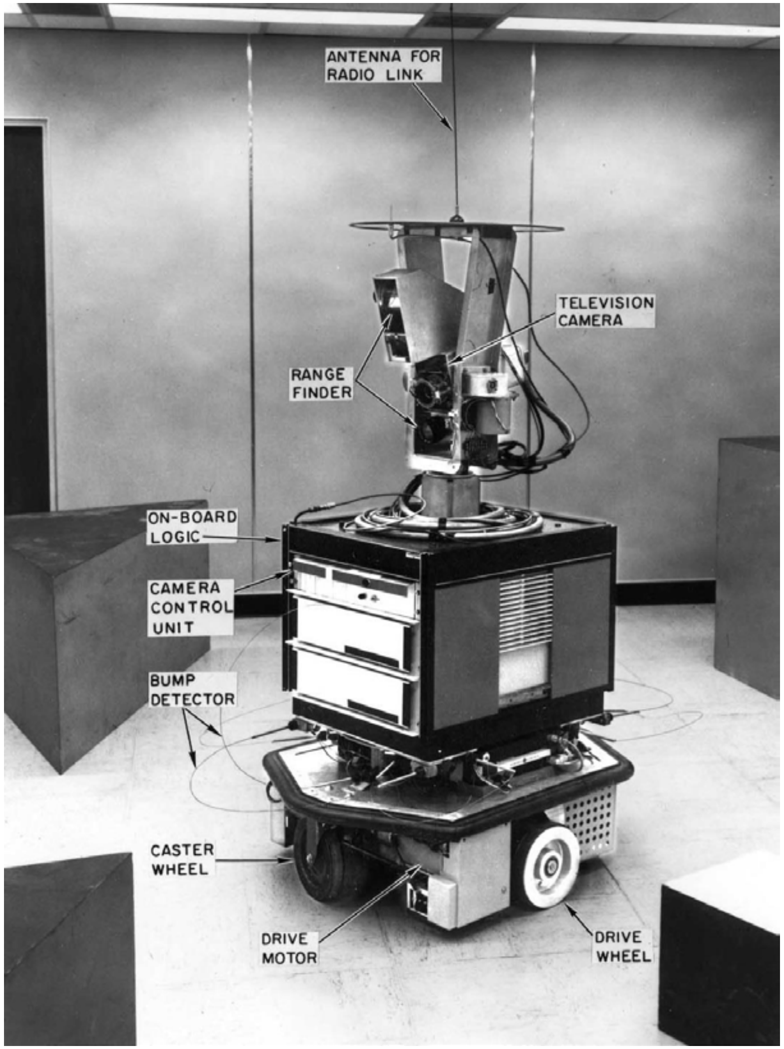


Introduction

- Case Studies
  - Let's look at a couple of case studies before we begin
    - What sensors are commonly employed on robots
    - How has the choice of sensors evolved over time
      - Shakey
      - Tourguide robots late 90ies
      - Willow Garage PR2
      - SmartTer – the autonomous car

Introduction

- Case Studies
  - Shakey the Robot (1966-1972), SRI
    - Operating environment
      - Indoors
    - Sensors
      - Wheel encoders
      - Bumb detector
      - Sonar range finder
      - Camera

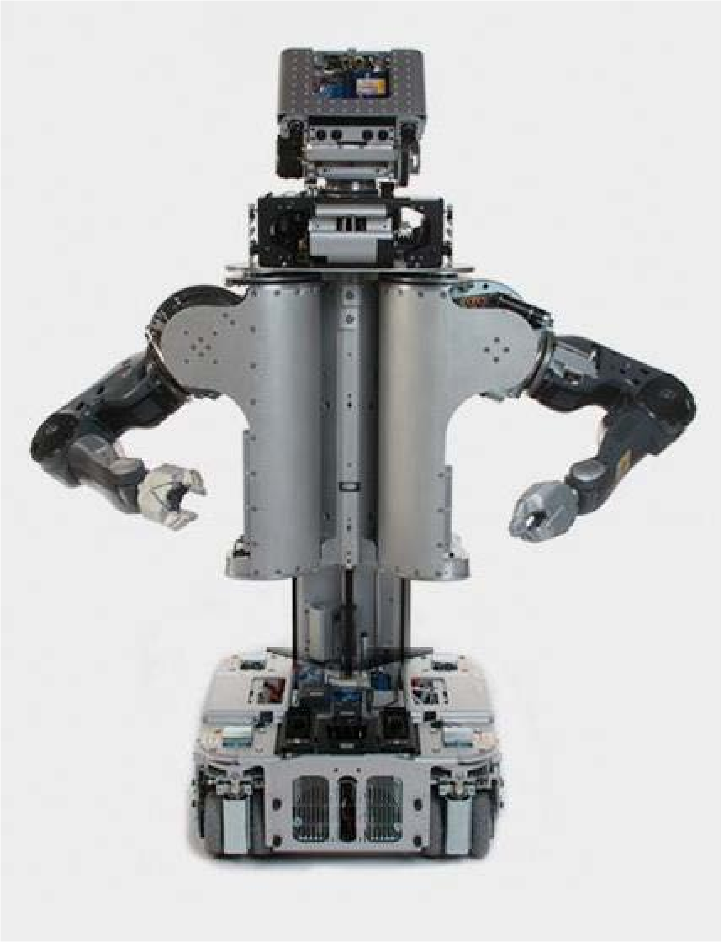


Introduction

- Case Studies
  - Rhino Tourguide Robot (1995-1998), University of Bonn
    - Operating environment
      - Indoors
        (Museum: unstructured and dynamic)
    - Sensors
      - Wheel encoders
      - Ring of sonar sensors
      - Pan-tilt camera

Introduction

- Case Studies
  - PR2 (2010-): Willow Garage
    - Operating environment
      - Indoors and outdoors
    - Sensors
      - Wheel encoders
      - Bumper
      - IR sensors
      - Laser range finder
      - 3D nodding laser range finder
      - Inertial measurement unit
      - Pan-tilt stereo camera with texture projector (active)
      - Pressure sensor and accelerometer inside hands
      - …



Introduction

- Case Studies
  - The SmartTer Platform (2004-2007)
    - Sensors
      - Three navigation SICK laser scanners
      - Two rotating laser scanners (3D SICK)
      - Omnidirectional camera
      - Monocular camera
      - Motion Estimation / Localization
        - Differential GPS system
        - Inertial measurement unit
        - Optical Gyro
        - Odometry (wheel speed, steering angle)
      - etc

Introduction

- Case Studies
  - The SmartTer Platform (2004-2007)
    - Autonomous Navigation and 3D Mapping

Classification of Sensors

Classification of Sensors

- What:
  - Proprioceptive sensors
    - measure values internally to the system (robot),
    - e.g. motor speed, wheel load, heading of the robot, battery status
  - Exteroceptive sensors
    - information from the robots environment
    - distances to objects, intensity of the ambient light, unique features
- How:
  - Passive sensors
    - energy coming for the environment
  - Active sensors
    - emit their proper energy and measure the reaction
    - better performance, but some influence on environment

Classification of Sensors

- 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.

Classification of Sensors

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

Classification of Sensors

- Sensors outline
  - Encoders
  - Heading sensors
    - Compass
    - Gyroscopes
  - Accelerometer
  - IMU
  - GPS
  - Range sensors
    - Sonar
    - Laser
    - Structured light
  - Vision

Characterizing Sensor Performance

Characterizing Sensor Performance

- Basic sensor response ratings
  - Dynamic range
    - ratio between lower and upper limits, usually in decibels (dB)
  - Range
    - upper limit -lower limit
  - Resolution
    - minimum difference between two values
  - Linearity
    - variation of output signal as function of the input signal
  - Bandwidth or Frequency
    - the speed with which a sensor can provide a stream of readings

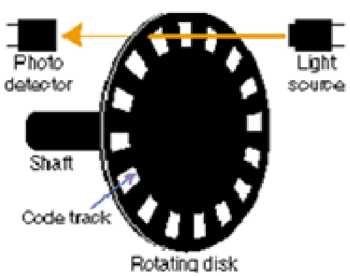
Characterizing Sensor Performance

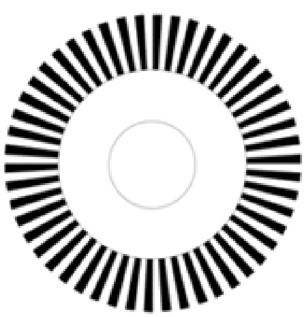
- Basic sensor response ratings
  - Sensitivity
    - ratio of output change to input change
    - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination
  - Error / Accuracy
    - difference between the sensor's output and the true value
  - Systematic error: deterministic errors
    - caused by factors that can (in theory) be modeled (prediction)
    - e.g. calibration of a laser sensor or of the distortion cause by the optics of a camera
  - Random error: non-deterministic
    - no prediction possible
    - however, they can be described probabilistically
  - Precision
    - reproducibility of sensor results: $precision = \frac{range}{\sigma}$

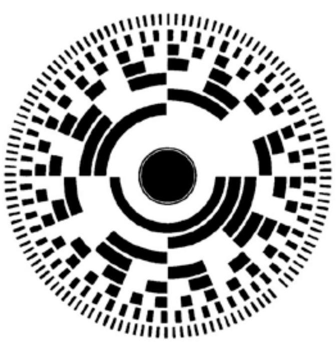
Sensors

Encoders

- Wheel / Motor Encoders
  - Use cases
    - 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
  - Type
    - Absolute Encoder
    - Incremental Encoder

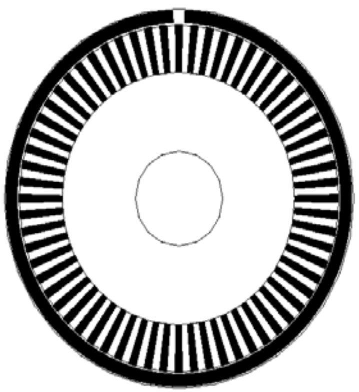


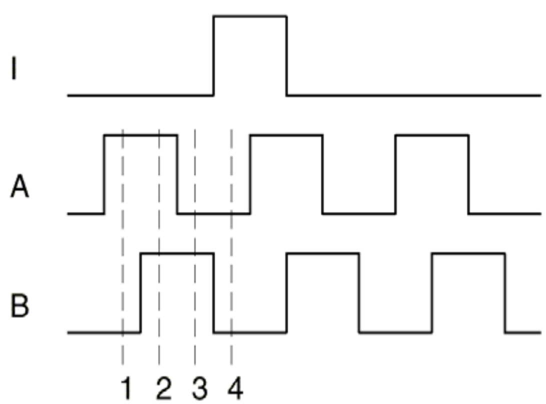




Encoders

- Wheel / Motor Encoders
  - Working principle of optical encoders
    - regular: counts the number of transitions but cannot tell the direction of motion
    - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
    - a single slot in the outer track generates a reference pulse per revolution





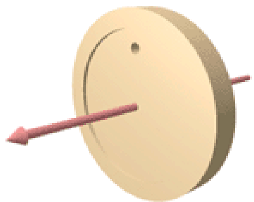
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

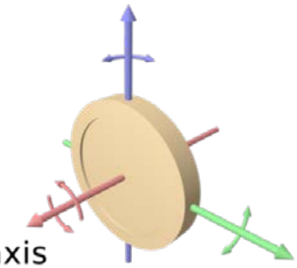
Heading Sensors

- Heading sensors
  - sensors that determine the robot’s orientation and inclination
  - can be proprioceptive(gyroscope, accelerometer) or exteroceptive(compass, inclinometer)
  - Allows, together with an appropriate velocity information, to integrate the movement to a position estimate.
    - This procedure is called dead reckoning(ship navigation)

Heading Sensors

- Gyroscope
  - Definition
    - Heading sensors that preserve their orientation in relation to a fixed reference frame
    - Used for measurement of angular acceleration
    - They provide an absolute measure for the heading of a mobile system
  - Types
    - Mechanical Gyroscopes
      - Standard gyro (angle)
      - Rate gyro (speed)
    - Optical Gyroscopes
      - Rate gyro (speed)

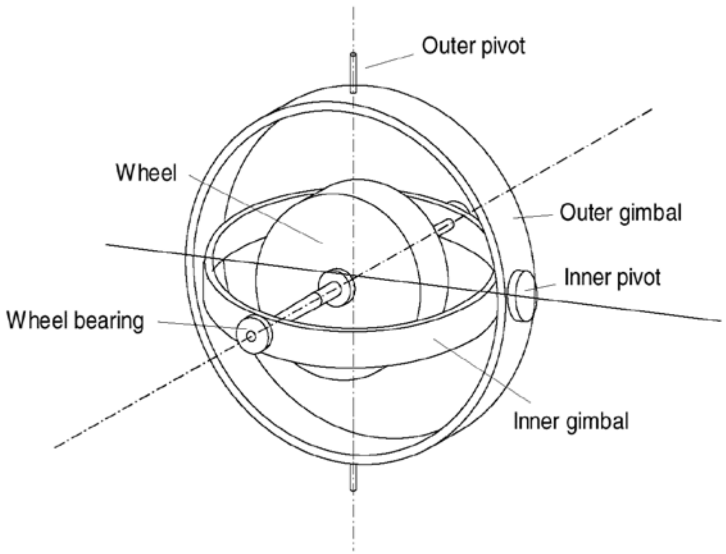




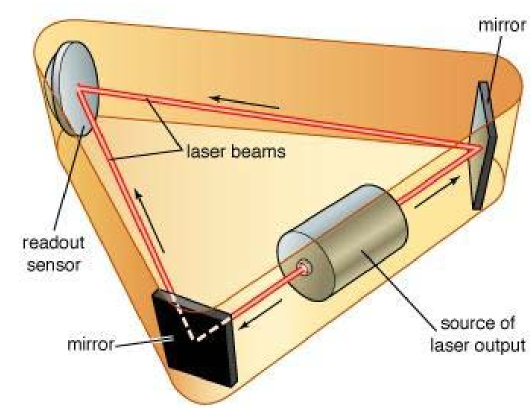
[Ref: Wikipidia]

Heading Sensors

- Gyroscope
  - Rate gyros
    - Measure angular speeds instead of the orientation
    - The rate gyroscope uses the Coriolis effect of a sensor element to sense the speed of rotation (i.e., rate of turn)



  - Optical gyros
    - Exploits difference of traveling distance between two lights
    - Relatively high accurate



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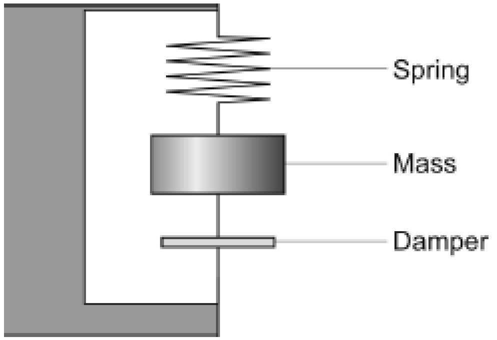
Heading Sensors

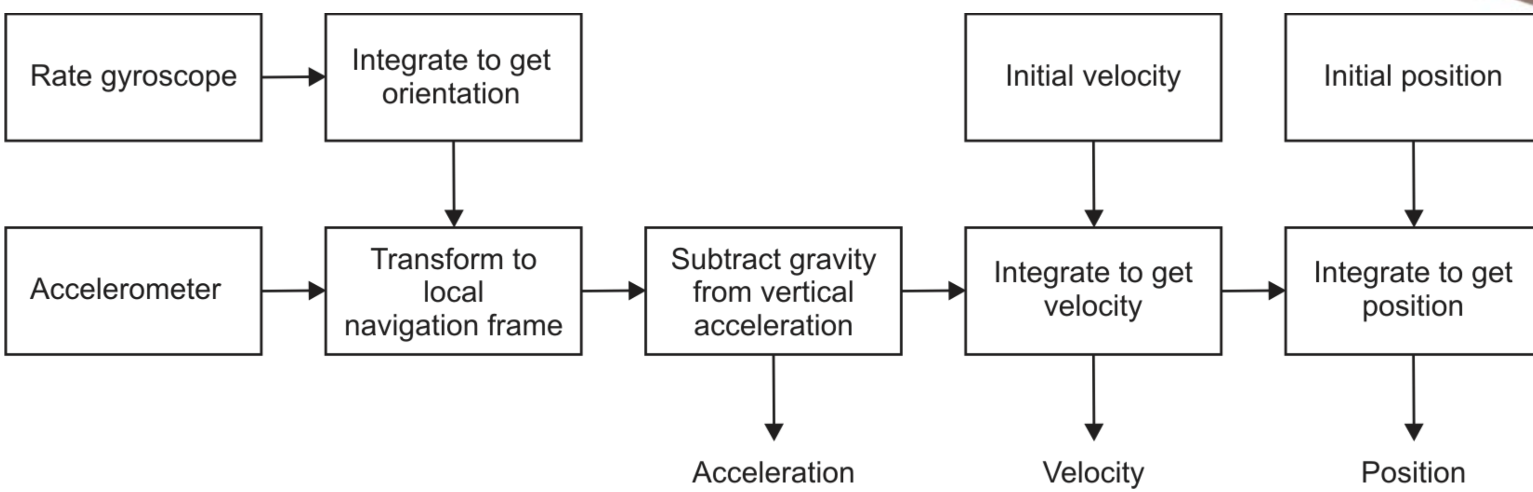
- Accelerometer
  - Rate gyros
    - Used for measurement of linear acceleration
    - Measure all external forces acting upon them, including gravity
    - One way of measuring the acceleration
      - Spring mounted mass:

$$a = \frac{kx^2}{m}$$



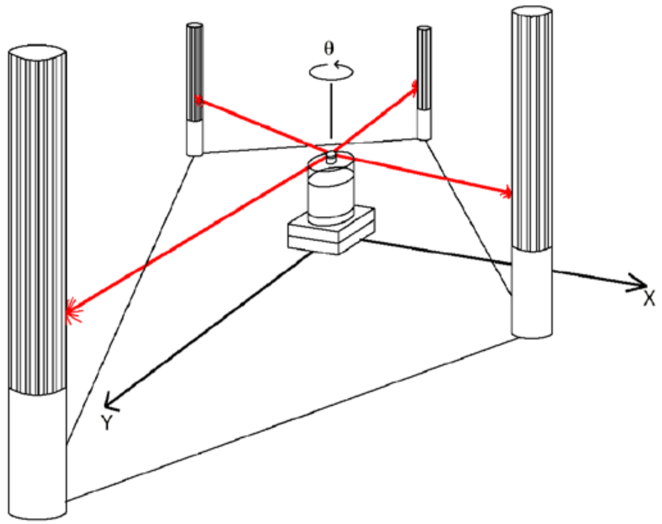
Heading Sensors

- Inertial Measurement Unit (IMU)
  - Definition
    - Device that uses measurement systems such as gyroscopes and accelerometers to estimate the relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration of a moving vehicle.



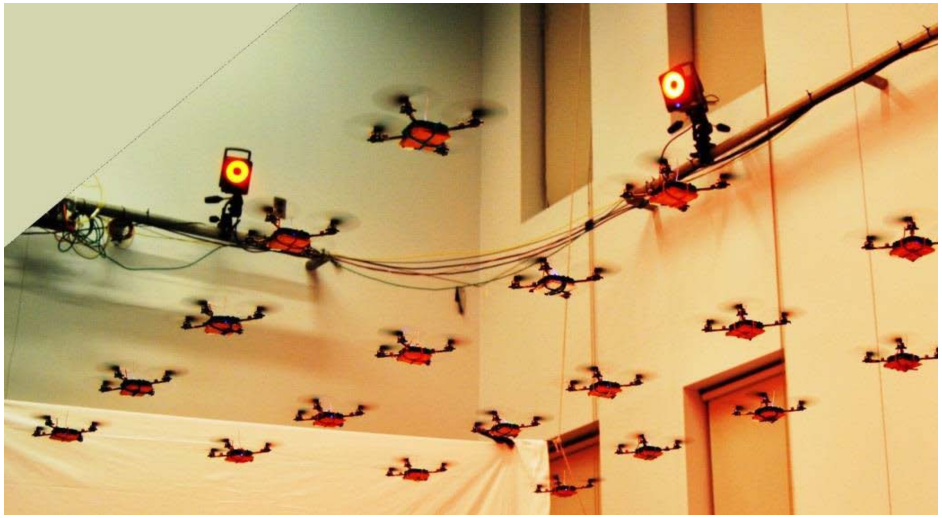
Absolute Position Sensors

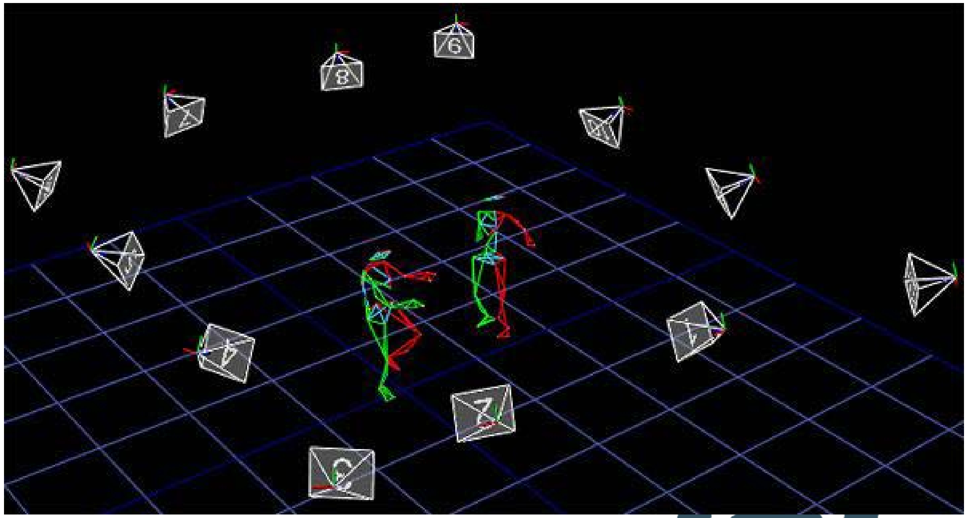
- Ground-Based Active and Passive Beacons
  - Beacons
    - Signaling guiding devices with a precisely known position
    - Natural/Artificial Beacons (or Landmarks)
    - For examples
      - Global Positioning System (GPS)
      - QR code, UWB, RFID, Laser Reflector, etc
    - Major drawback with the use of beacons in indoor:
      - Beacons require changes in the environment → costly
      - Limit flexibility and adaptability to changing environments.



Absolute Position Sensors

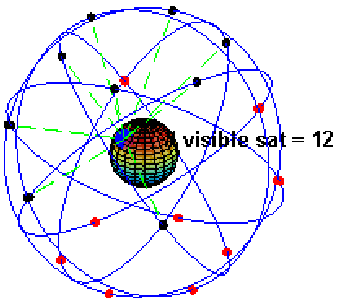
- Motion-Capture Systems
  - Vicon and Optitrack
    - System of several cameras that track the position of reflective markers
    - >300 fps
    - <1 mm precision
    - Indoor or outdoor application
    - Require preinstallation and precalibration of the cameras (done with a special calibration rig moved by the user)





Absolute Position Sensors

- Global Positioning System (GPS)
  - GPS System



    - Became accessible for commercial applications in 1995
    - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km
    - 4 satellites were located in each of 6 orbits with 60 degrees orientation between each other
    - The GPS receiver measures the difference in time-of-flight for signals from a combination of satellites.
      - Latitude, longitude, elevation, and current time can be estimated.
    - At least five satellites are visible at any time from any point on the earth's surface.
    - An estimate of absolute position can be obtained at a rate of up to 2 Hz.

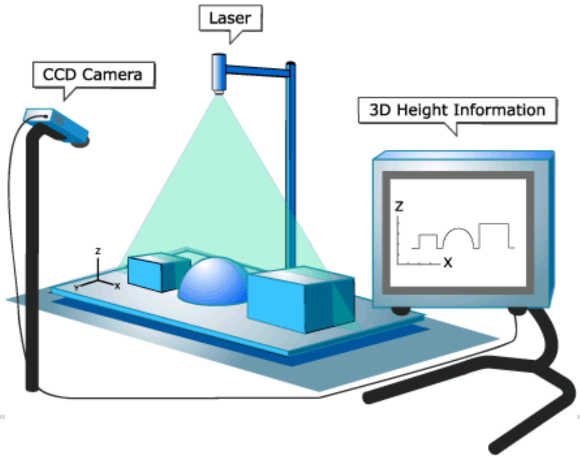
Range Sensors

- Range Sensors
  - Sonar

  - Laser range finder

  - Time of Flight Camera

  - Structured light



KINECT for XBOX 360

Range Sensors

- Range Sensors (time of flight)
  - Range information
    - Key element for localization and environment modeling
  - Sort of Sensors
    - Ultrasonic sensors
      - make use of propagation speed of sound
    - Laser range sensors
      - make use of propagation speed of electromagnetic waves
  - Traveled distance of a sound or electromagnetic wave

$$d = c \cdot t$$

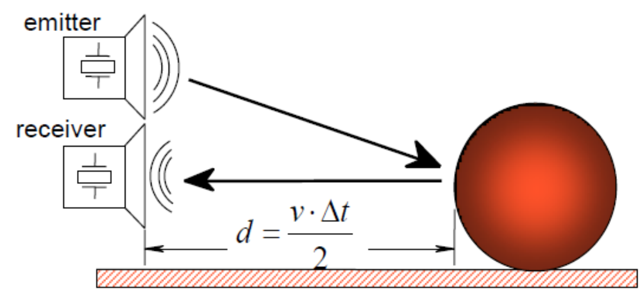
- d = distance traveled (usually round-trip)
- c = speed of wave propagation
- t = time of flight

Range Sensors

- Range Sensors (time of flight)
  - Sources of Wave
    - Propagation speed v of sound: about 0.3 m/ms
      - e.g. 3 meters takes 10 ms for ultrasonic system
    - Propagation speed v of electromagnetic signals: about 0.3 m/ns
      - e.g. 3 meters takes 10 ns for ultrasonic system
  - The quality of ToF range sensors manly 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 (ultrasonic range sensors)
    - Interaction with the target (surface, specular reflections)
    - Variation of propagation speed
    - Speed of mobile robot and target (if not at stand still)

Range Sensors

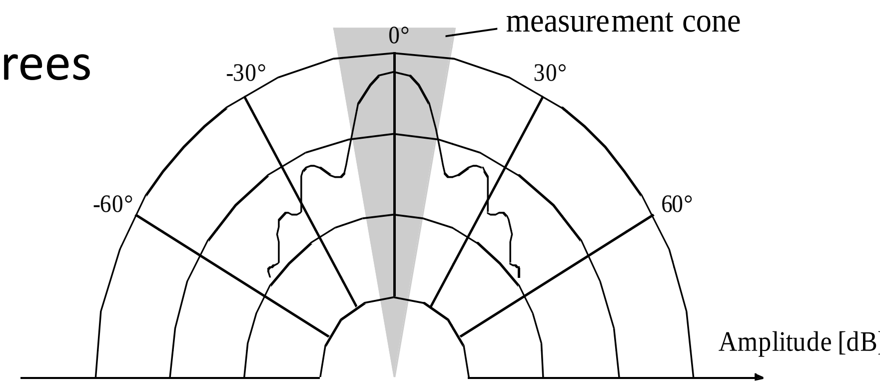
- Ultrasonic Sensor (time of flight, sound)
  - Sonar (SOund NAvigation and Ranging)
    - Acoustic frequency used in commercial sonar units: 40-50 kHz
      - Higher frequencies are attenuated more rapidly, but they provide better spatial resolution.
  - Time-of-flight (TOF)
    - The sonar emits a short sound pulse and measures the time delay until the echo is received.
    - Distance: $$d = \frac{1}{2}ct$$



      - d = distance traveled (round-trip)
      - c = speed of wave propagation (m/s)
      - t = time of flight (time delay between the outgoing sound pulse and the received echo)

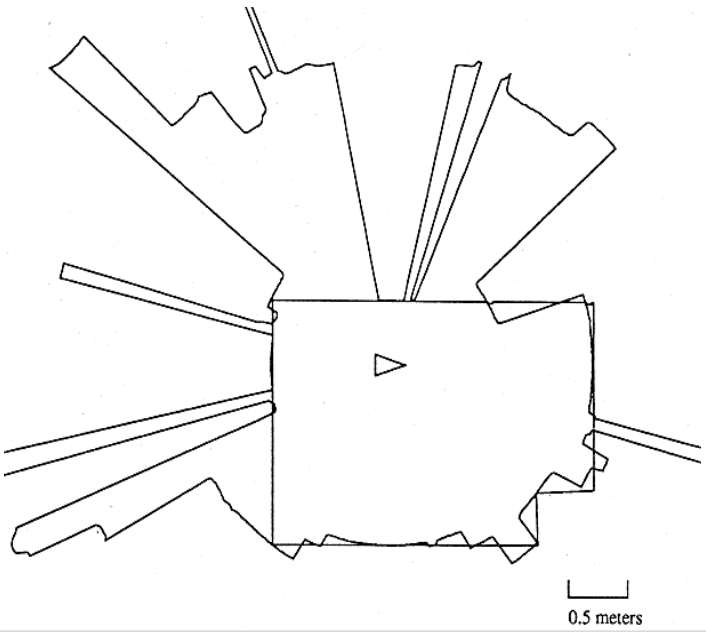
Range Sensors

- Ultrasonic Sensor (time of flight, sound)
  - Generation of sound wave via piezo transducer
    - transmitter and receiver can be separate or integrated in the same unit
  - Range between 12 cm up to 5 m
  - Resolution of ~ 2 cm
  - Relative error 2%
  - Beam width
    - sound beam propagates in a cone (approx.) with nonuniform energy distribution over the cone
    - opening angles around 20 to 40 degrees
    - regions of constant depth
    - segments of an arc (sphere for 3D)



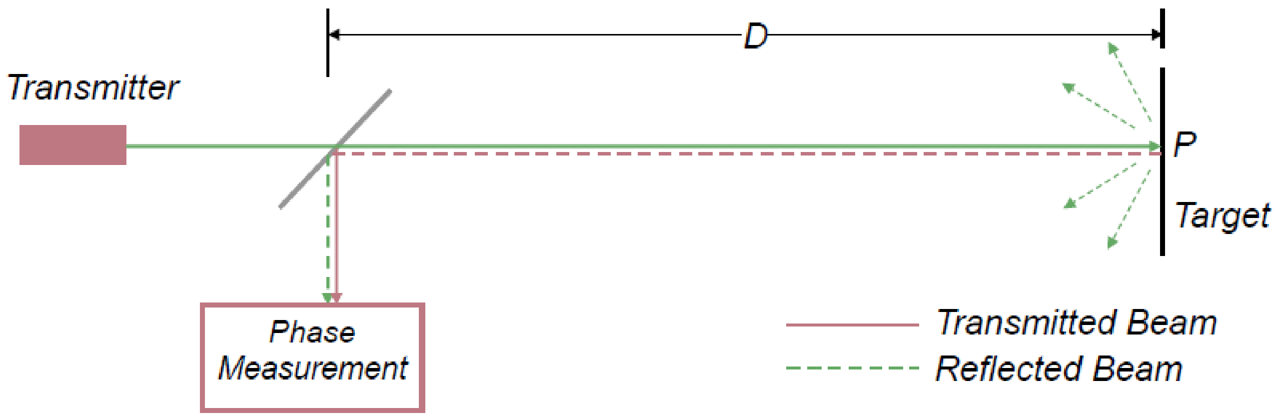
Range Sensors

- Ultrasonic Sensor (time of flight, sound)
  - Problems
    - Wide cone-shaped beam (angular uncertainty)
    - Soft surfaces that <u>**absorb**</u> most of the sound energy
    - Specular reflection
      - surfaces that are fare from being perpendicular to the direction of the sound



Range Sensors

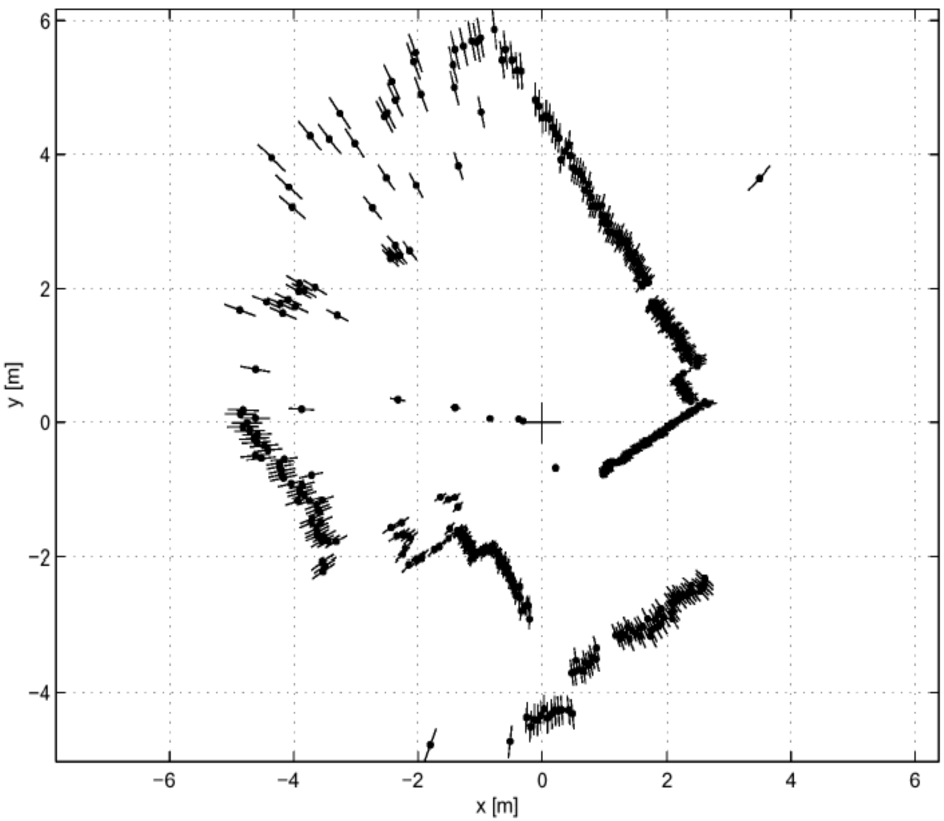
- Laser Range Sensor (time of flight, electromagnetic)
  - Lidar (LIght Detection And Ranging)



  - Principle of operation
    - Time-of-flight: measurement of the time delay between the emitted light beam and the returned reflection.
    - 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

Range Sensors

- Laser Range Sensor (time of flight, electromagnetic)
  - Lidar (LIght Detection And Ranging)
    - Uncertainty of the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
      - Hence dark, distant objects will not produce such good range estimated as closer brighter objects …
    - 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.



Range Sensors

- Laser Range Sensor (time of flight, electromagnetic)
  - 2D Lidar (LIght Detection And Ranging)
    - The SICK LMS 200 Laser Scanner
      - Angular resolution 0.25 deg
      - Depth resolution ranges between ~10 mm
      - Typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m)
        - depending on the reflectivity of the object being ranged.
      - This device performs 75 180-degrees scans per second

Range Sensors

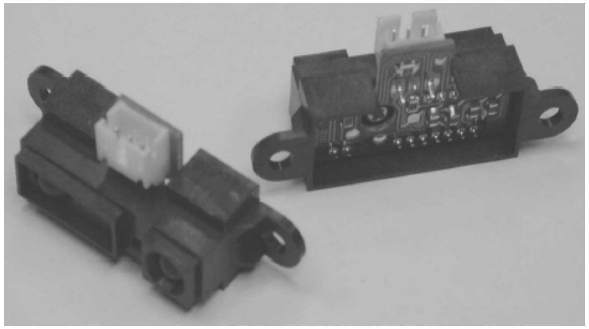
- Laser Range Sensor (time of flight, electromagnetic)
  - 3D Lidar (LIght Detection And Ranging)
    - Velodyne HDL-64E
      - 64 Channels
      - 120m range
      - Up to ~2.2 Million Points per Second
      - 360° Horizontal FOV
      - 26.9° Vertical FOV
      - 0.08° angular resolution (azimuth)
      - ~0.4° Vertical Resolution

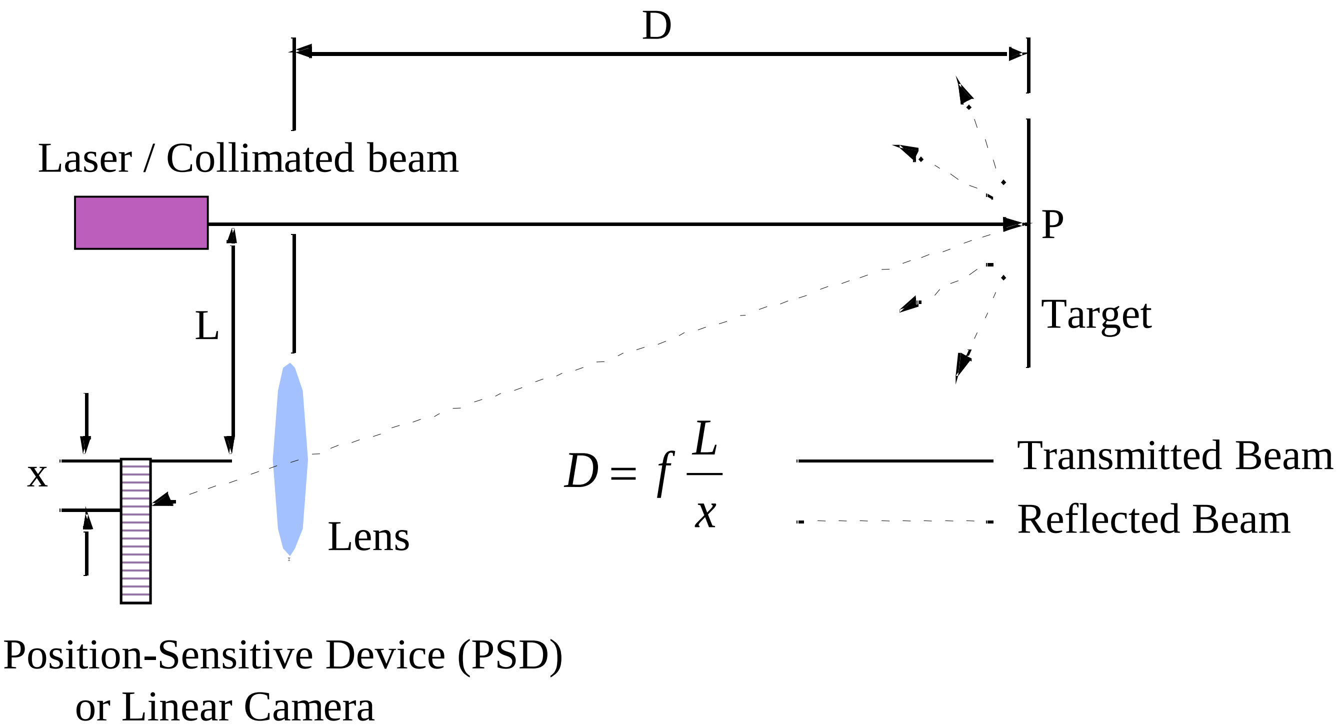
Range Sensors

- Triangulation Ranging
  - Principles
    - Use of geometrical properties of the image to establish a distance measurement
    - If a well-defined light pattern (e.g. point, line) is projected onto the environment
      - reflected light is then captured by a photo-sensitive line or matrix (camera) sensor device
      - simple triangulation allows to establish a distance.
    - If size of a captured object is precisely known
      - triangulation without light projecting

Range Sensors

- Triangulation Ranging
  - Laser Triangulation (1D)
    - PSD Sensor

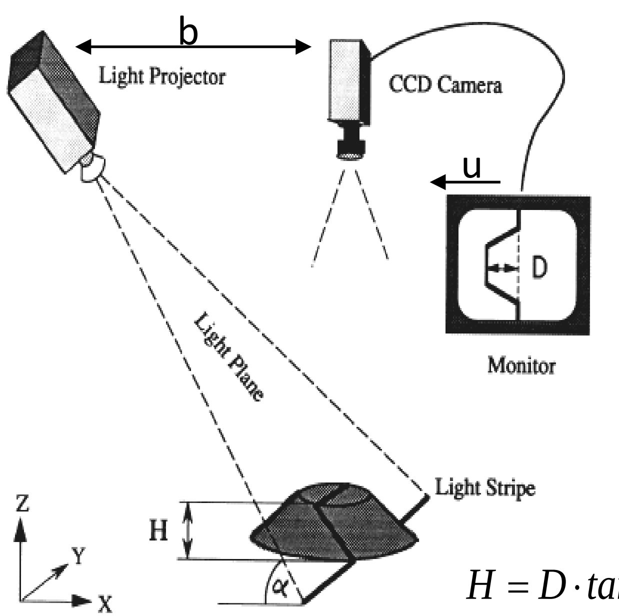




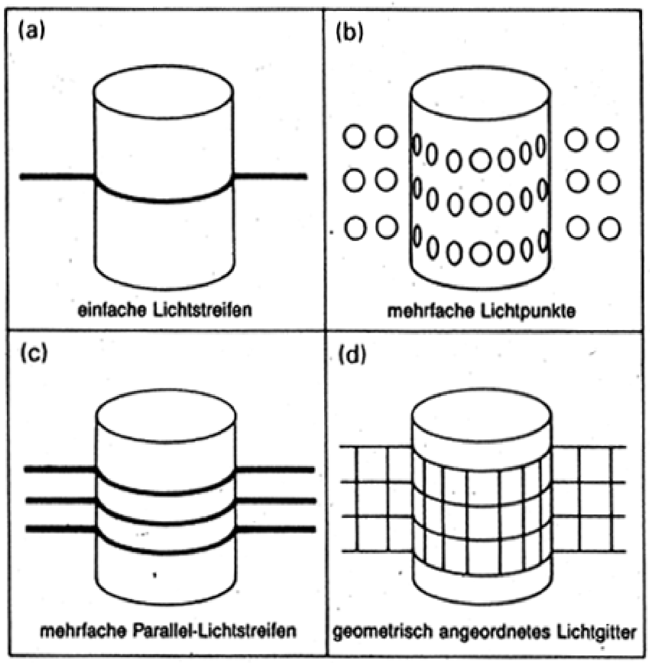
$$D = f\frac{L}{x}$$

Range Sensors

- Triangulation Ranging
  - Structured Light (vision, 2 or 3D)



$$H = D \cdot \tan\alpha$$



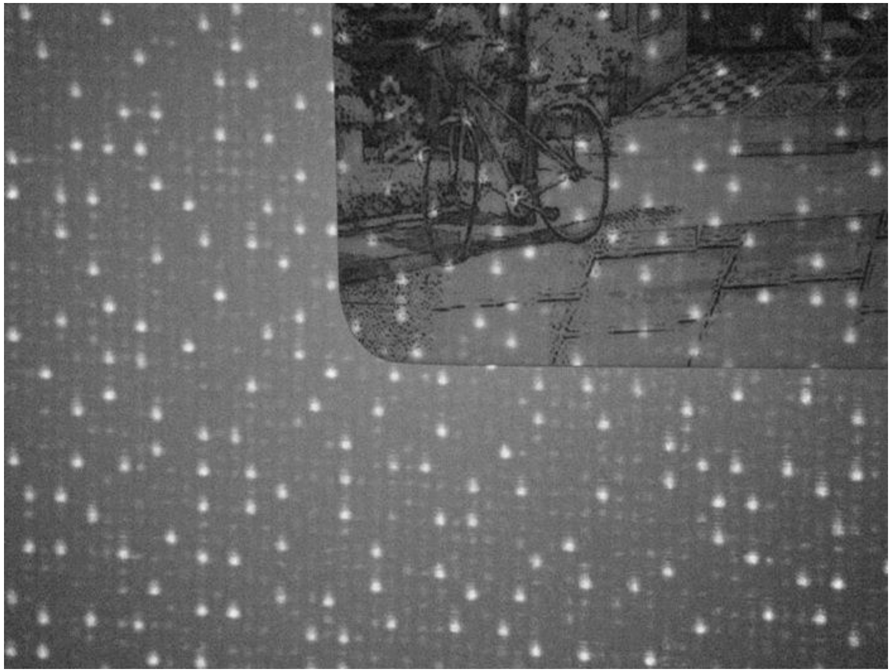
- Eliminate the correspondence problem
  - by projecting structured light on the scene
- Range from simple geometry

Range Sensors

- Triangulation Ranging
  - Structured Light (vision, 2 or 3D)
    - Microsoft Kinect
      - Developed by Israeli company PrimeSense in 2010
      - Major components
        - IR Projector
        - IR Camera
        - VGA Camera
        - Microphone Array
        - Motorized Tilt

Range Sensors

- Triangulation Ranging
  - Structured Light (vision, 2 or 3D)
    - Microsoft Kinect
      - IR Pattern



Range Sensors

- Triangulation Ranging
  - Structured Light (vision, 2 or 3D)
    - Microsoft Kinect
      - Depth Map
        - uses an infrared projector and an infrared sensor
        - not use its RGB camera for depth computation