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Faculty of Engineering

MEng. ROBOTICS AND CONTROL SYSTEMS

(MRE002A) PERCEPTION

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INTRODUCTION

SENSORS I

PERCEPTION IS HARD!

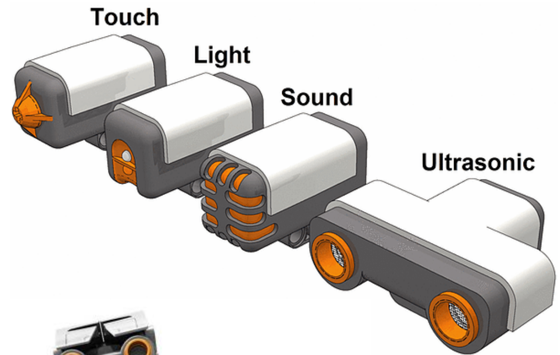
- Understanding = raw data + (probabilistic) models + context

- Intelligent systems interpret **raw data** according to **probabilistic models** and using **contextual information** that gives meaning to the data.

- "In robotics, the *easy* problems are *hard* and the *hard* problems are *easy*" S. Pinker. The Language Instinct. New York: Harper Perennial Modern Classics, 1994

SENSORS FOR MOBILE ROBOTS

- Sensors for Mobile Robots
  - Robot = sensors + actuators
- **Sensors** are the **key components** for **perceiving** the environment
- Perception is the HOT research topic of the last years
- Sensors vary according to:
  - physical principle
  - resolution
  - bandwidth
  - price
  - energy needed



MOBILE ROBOT CONTROL SYSTEM

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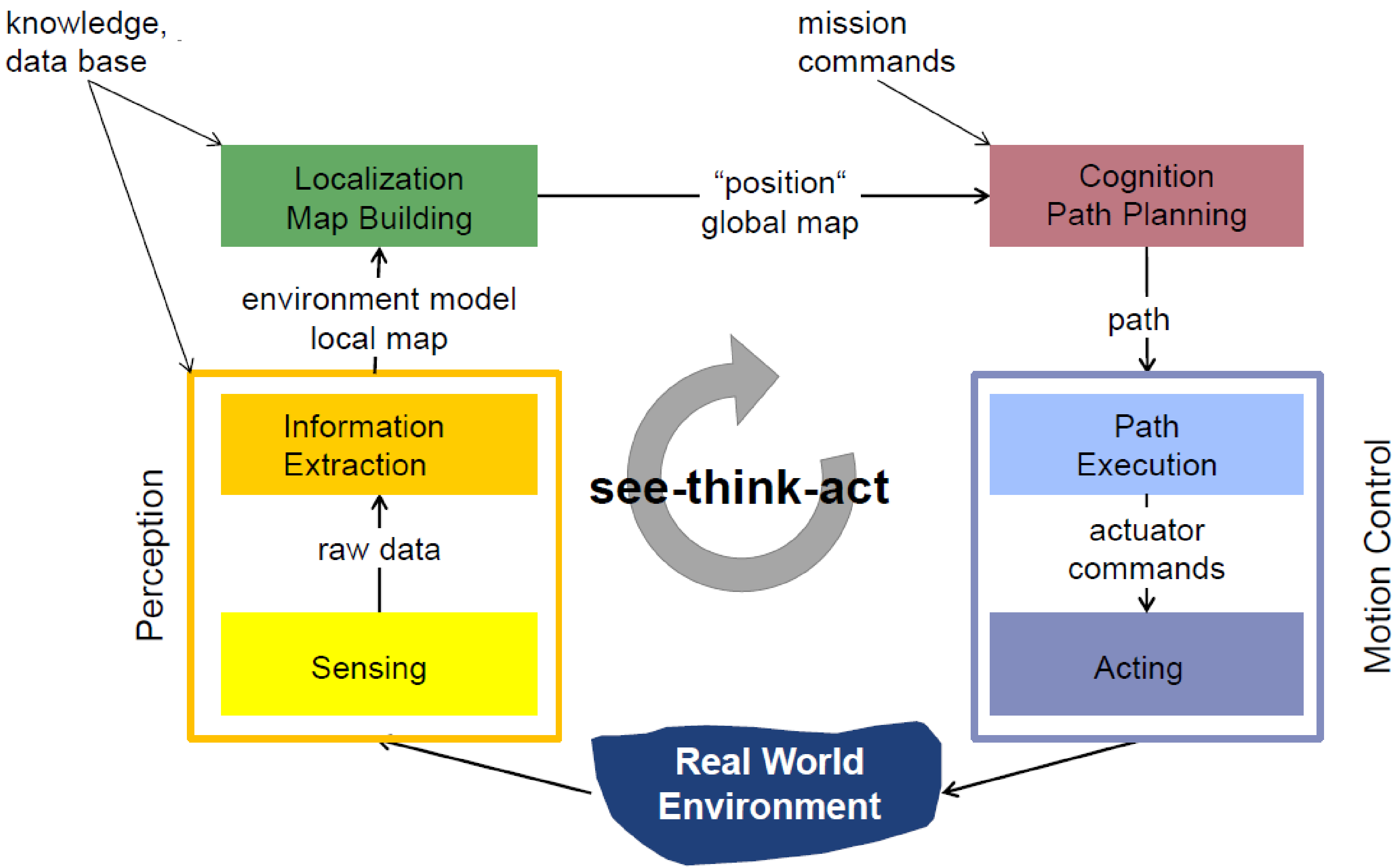
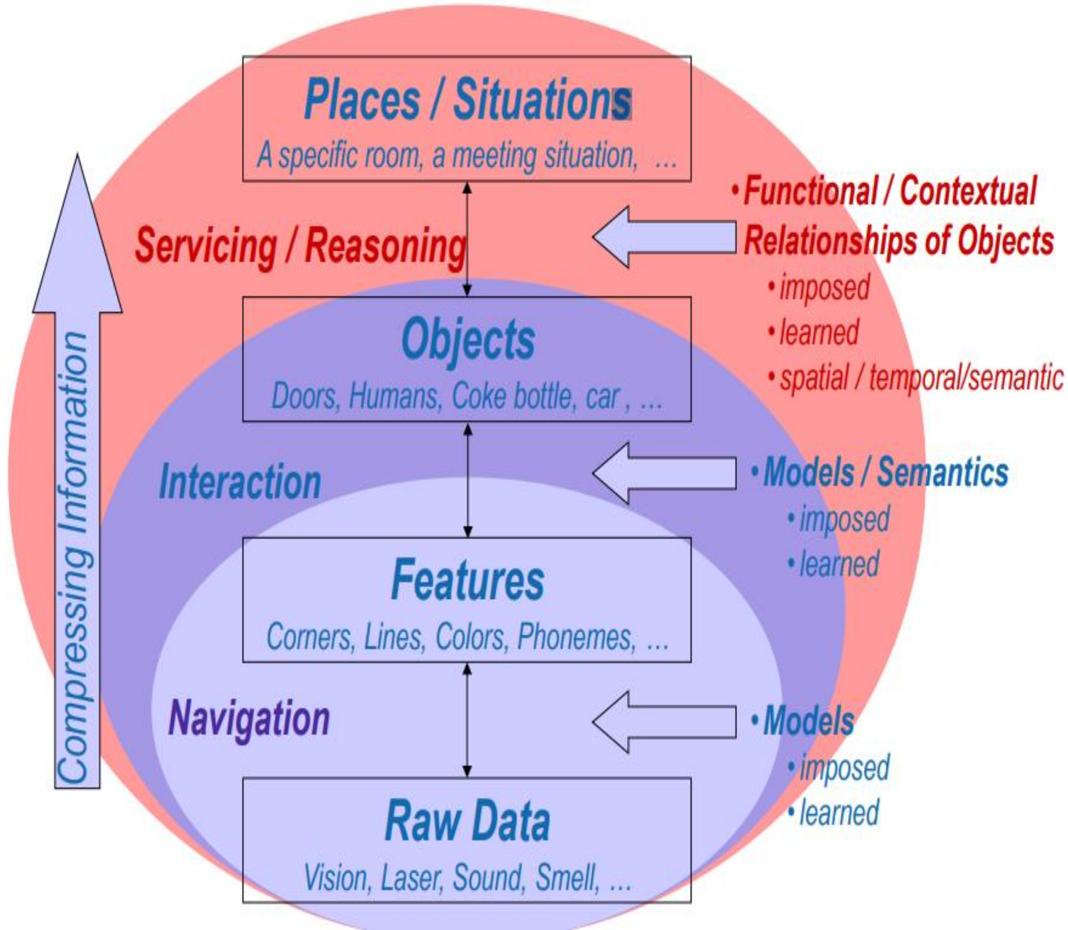


PERCEPTION FOR ROBOTS



PERCEPTION: CHALLENGES

- Dealing with real-world situations
- Reasoning about a situation
- Cognitive systems have to interpret situations based on uncertain and only partially available information
- They need ways to learn functional and contextual information (semantics /understanding)

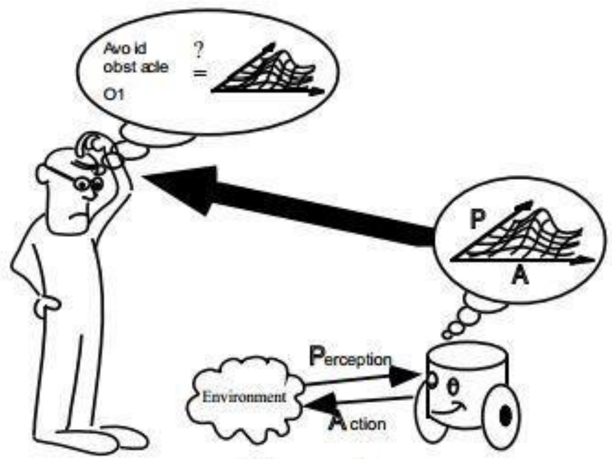
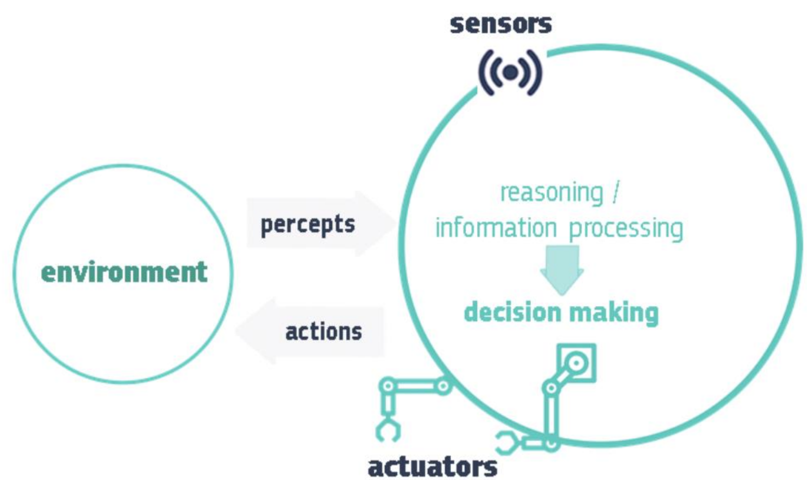


Figure 2



THE CHALLENGE

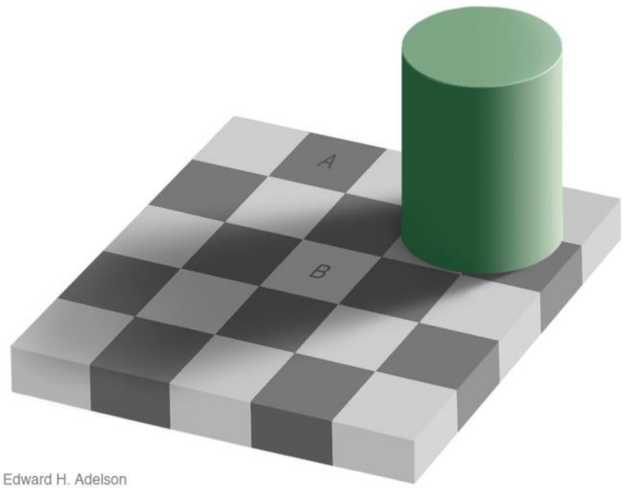
- Perception and models are strongly linked:

- *What is the difference in brightness?*

- **Brightness** is an attribute of visual perception in which a source appears to be radiating or reflecting light.

- Is the perception elicited by the luminance of a visual target.

- It is not necessarily proportional to luminance.



Edward H. Adelson

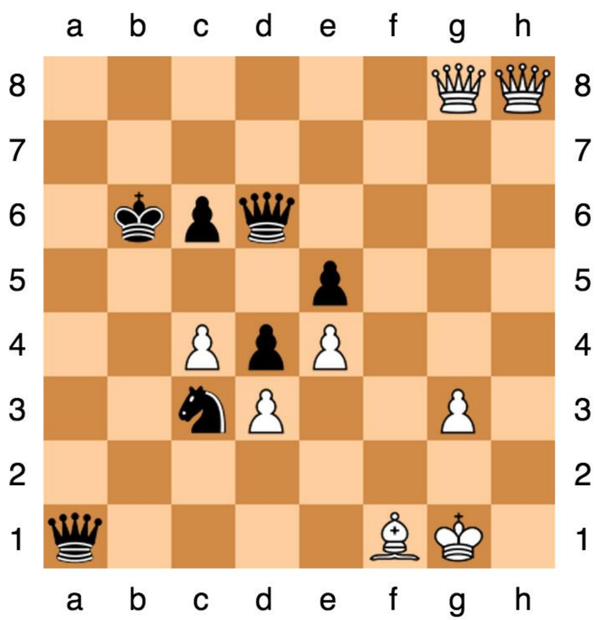
- This is a subjective attribute/property of an object being observed
- Is one of the colour appearance parameters of colour appearance models.

$$\mu = \frac{R + G + B}{3}$$

PERCEPTION IS HARD!

- Beating the world's chess master:

EASY



- Create a machine with some "common sense":

VERY HARD

UNCERTAINTY REPRESENTATION

- Sensing is always related to uncertainties
  - How can uncertainty be represented or quantified?
  - How do they propagate - uncertainty of a function of uncertain values?

- Systematic errors (deterministic)
  - They are caused by factors or processes that can in theory be modelled and, thus, calibrated, (for example, the diameters of the robot wheels, the distance between the wheels, etc.)

- Random errors
  - They cannot be predicted using a sophisticated model but can only be described in probabilistic terms

UNCERTAINTY REPRESENTATION

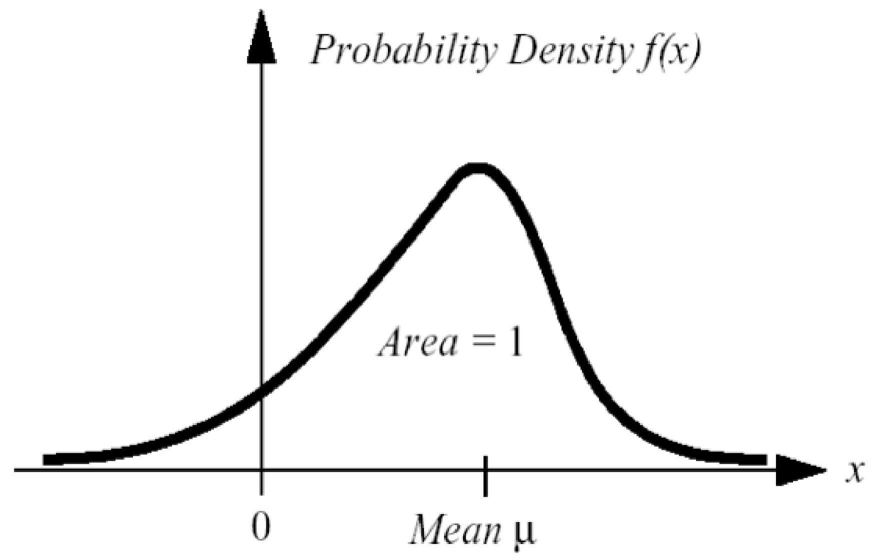
- The density function identifies for each possible x value of X a probability $f(x)$ density along the y-axis

- The area under the curve is 1, indicating the complete chance of X having some value

$$\int_{-\infty}^{\infty} f(x)\,dx = 1$$

$$\mu = E[X] = \int_{-\infty}^{\infty} x f(x)\,dx$$

$$\sigma^2 = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)\,dx$$



UNCERTAINTY REPRESENTATION

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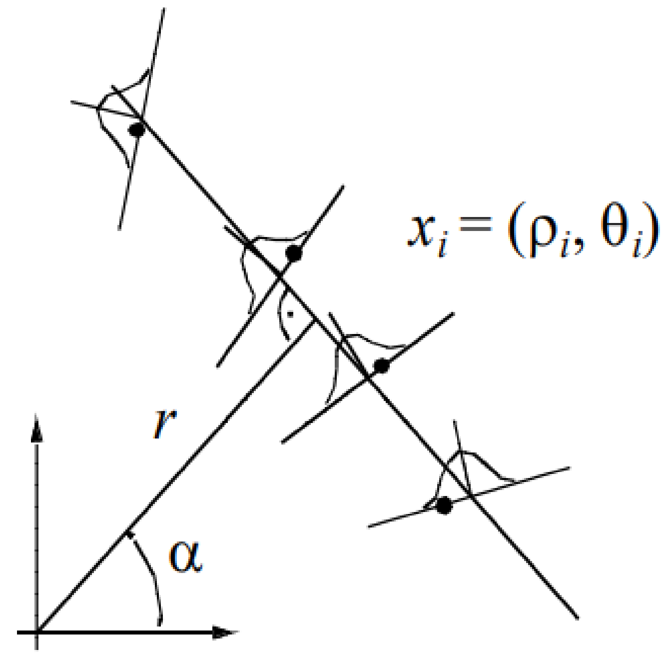
- Error propagation law:

- Imagine extracting a line based on point measurements with uncertainties

- The model parameters ρ_i (length of the perpendicular) and θ_i (its angle to the abscissa) describe a line uniquely

- What is the uncertainty of the extracted line knowing the uncertainties of the measurement points that contribute to it ?



UNCERTAINTY REPRESENTATION

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- Error propagation law:

- Error propagation in a multiple-input multi-output system with n inputs and m outputs

$$Y_j = f_j(X_1 \dots X_n)$$

- It can be shown that the output covariance matrix Cy is given by the error propagation law:

$$C_Y = F_X \, C_X \, F_X^T$$

- C_X : covariance matrix representing the input uncertainties
- C_Y : covariance matrix representing the propagated uncertainties for the outputs.
- F_X : is the Jacobian matrix defined as:

$$F_X = \begin{bmatrix} \frac{\partial f_1}{\partial X_1} & \cdots & \frac{\partial f_1}{\partial X_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial fm}{\partial X_1} & \cdots & \frac{\partial f_m}{\partial X_n} \end{bmatrix}$$

PERCEPTION FOR ROBOTS

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EVOLUTION OF ROBOTIC SENSORS

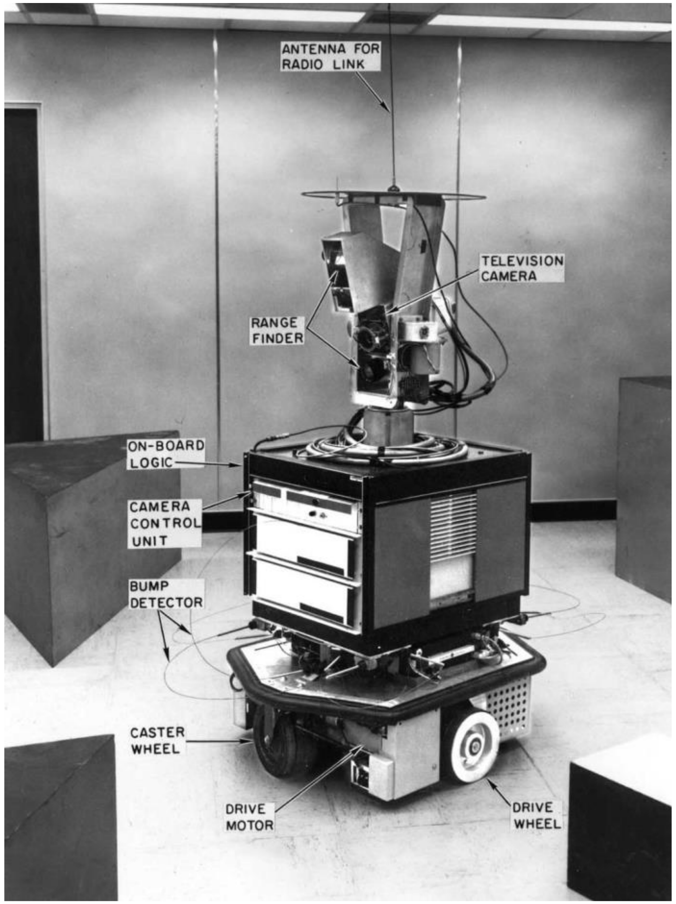
- Historically, robotic sensors have become richer and richer
  - 1960s: Shakey
  - 1990s: Tourguide robots
  - 2010s: Willow Garage PR2
  - 2010s: SmartTer – the autonomous car
  - 2011: Google autonomous car
- Reasons:
  - **Commodization** of consumer electronics
  - **More computation** available to process the data

EVOLUTION OF ROBOTIC SENSORS

- Shakey the Robot (1966-1972), SRI International

- Operating environment
  - Indoors
  - Engineered

- Sensors
  - Wheel encoders
  - Bumbp detector
  - Sonar range finder
  - Camera



EVOLUTION OF ROBOTIC SENSORS

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- Rhino Tourguide Robot (1995-1998), University of Bonn

- Operating environment
  - Indoors (Museum: unstructured and dynamic)

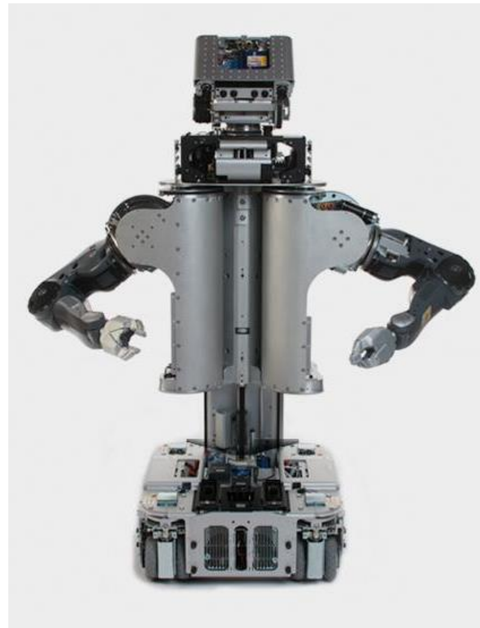
- Sensors
  - Wheel encoders
  - Ring of sonar sensors
  - Pan-tilt camera

EVOLUTION OF ROBOTIC SENSORS

- PR2 (201-), Willow Garage

- Operating environment
  - Indoors and outdoors
  - Onroad only

- 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
  - …



EVOLUTION OF ROBOTIC SENSORS

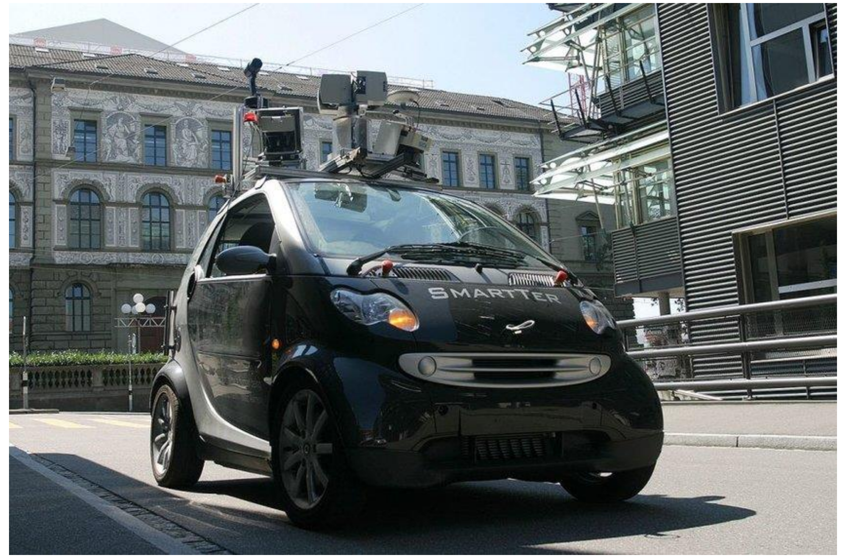
- The SmartTer Platform (2004-2007)

- Three navigation SICK laser scanners
  - Obstacle avoidance and local navigation

- Two rotating laser scanners (3D SICK)
  - 3D mapping of the environment
  - Scene interpretation

- Omnidirectional camera
  - Texture information for the 3D terrain maps
  - Scene interpretation

- Monocular camera
  - Scene interpretation



EVOLUTION OF ROBOTIC SENSORS

- The SmartTer Platform (2004-2007)

- Motion Estimation / Localization
  - Differential GPS system *(Omnistar 8300HP)*
  - Inertial measurement unit *(Crossbow NAV420)*
- Optical Gyro
- Odometry (wheel speed, steering angle)
  - Motion estimation
  - Localization
- Internal car state sensors
  - Vehicle state flags (engine, door, etc.)
  - Engine data, gas pedal value
- Camera for life video streaming
  - Transmission range up to 2 km

MULTIMODAL DETECTION & TRACKING

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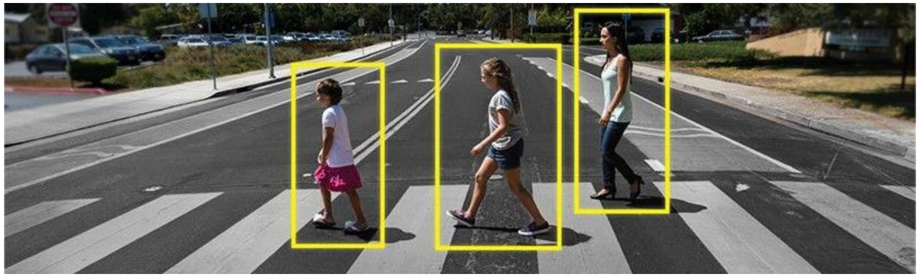
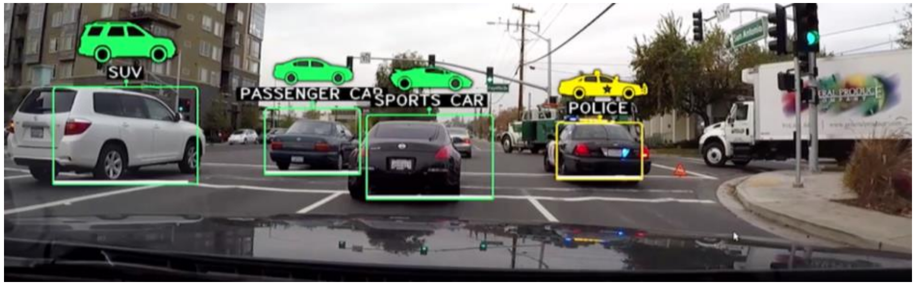


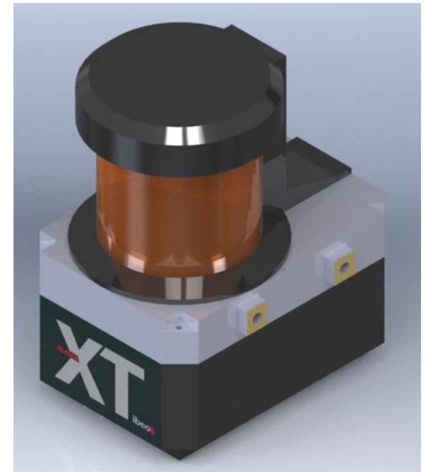
PEDESTRIANS

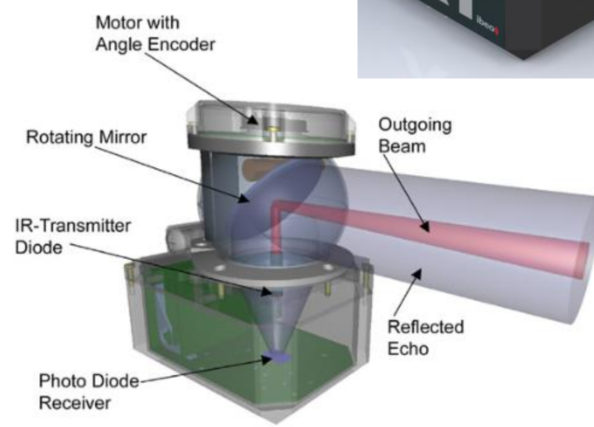
- Rich info
- Inexpensive
- Noise
- No distance

MULTIMODAL DETECTION & TRACKING



CARS





- High accuracy
- Light independent
- Low info

CLASSIFICATION OF SENSORS

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

GENERAL CLASSIFICATION (1)

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.

GENERAL CLASSIFICATION (1)

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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

SENSORS: OUTLINE

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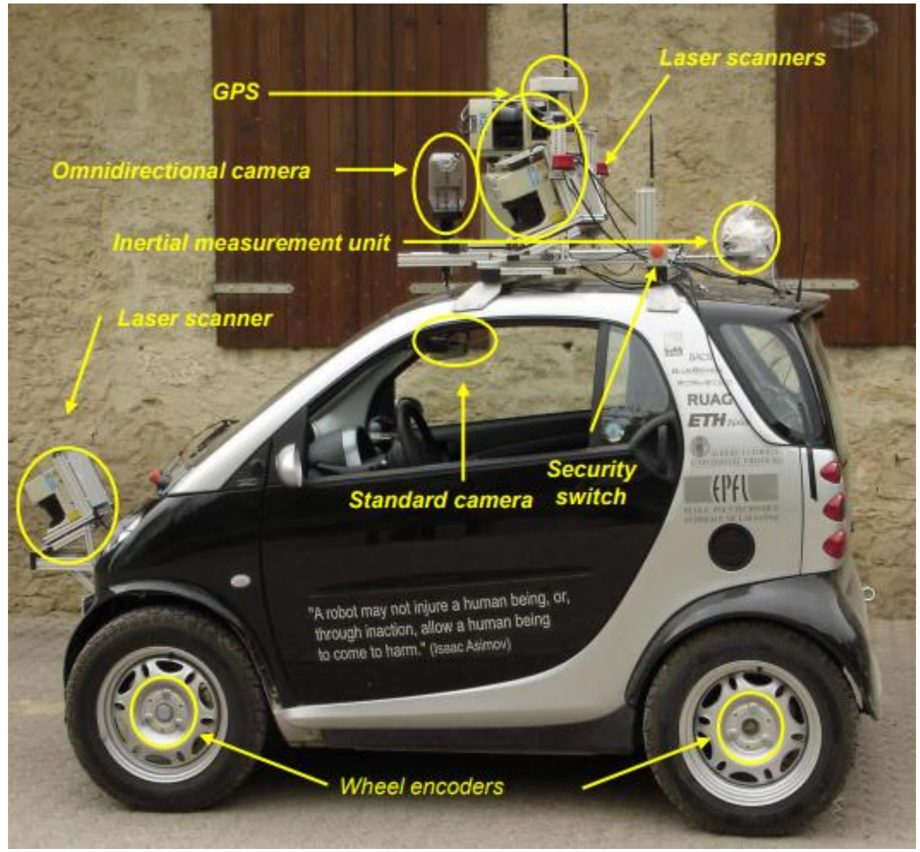
- Tactile sensors or bumpers
  - Detection of physical contact, security switches
- GPS
  - Global localization and navigation
- Inertial Measurement Unit (IMU)
  - Orientation and acceleration of the robot
- Wheel encoders
  - Local motion estimation (odometry)
- Laser scanners
  - Obstacle avoidance, motion estimation, scene interpretation (road detection, pedestrians)
- Cameras
  - Texture information, motion estimation, scene interpretation



SENSORS: OUTLINE

- Optical encoders
- Heading sensors
  - Compass
  - Gyroscopes
- Accelerometer
- IMU
- GPS
- Range sensors (next lectures)
  - Sonar
  - Laser
- Structured light (next lectures)
- Vision based (next lectures)

SENSORS: ENCODERS

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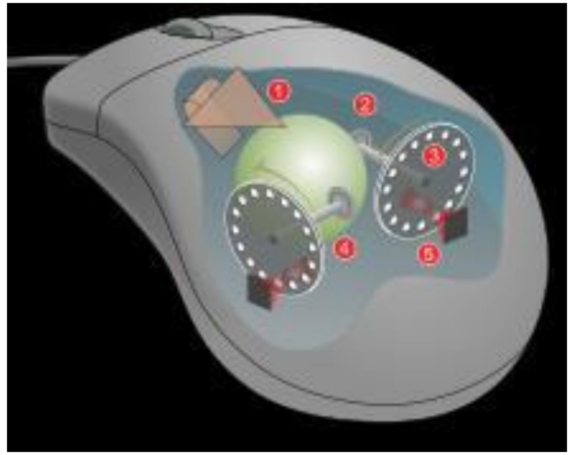
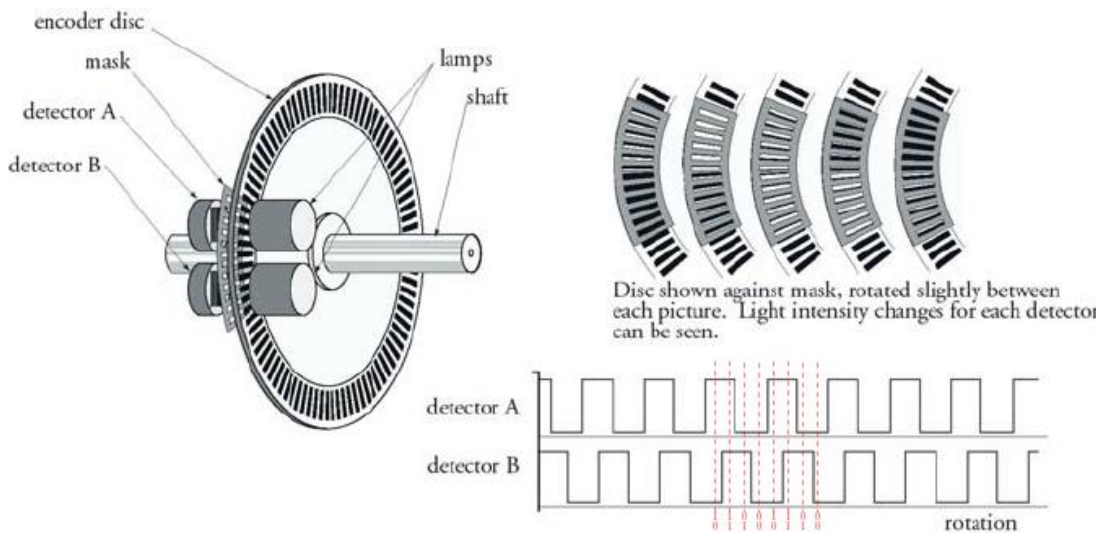
- Definition:

- **Electro-mechanical device** that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/anglular transducer





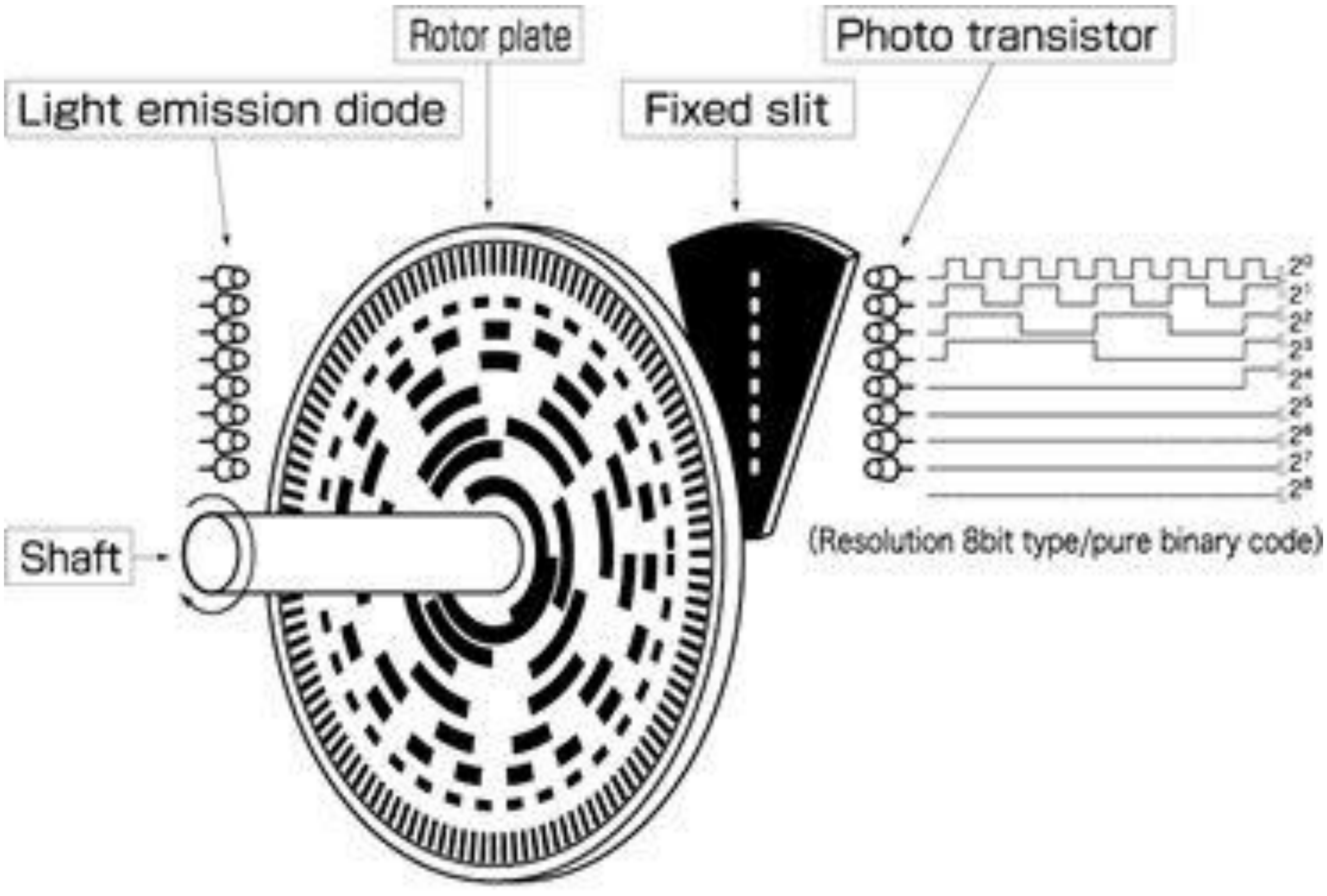
SENSORS: ENCODERS (WHEEL / MOTOR)

- 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
  - typical resolutions: 64 - 2048 increments per revolution.
  - for high resolution: interpolation

- 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

SENSORS: ENCODERS (WHEEL / MOTOR)



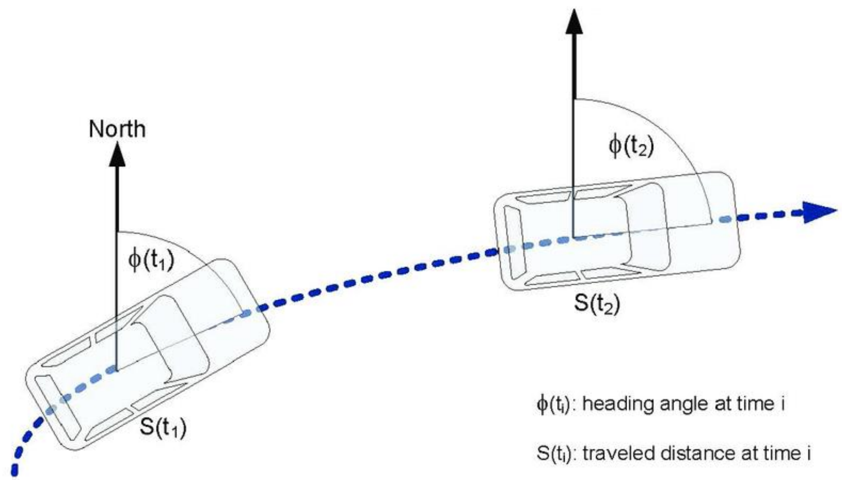
Absolute Encoder Simplified Structure

SENSORS: HEADING SENSORS

- Definition:
  - Heading sensors are sensors that determine the robot's orientation and inclination with respect to a given reference

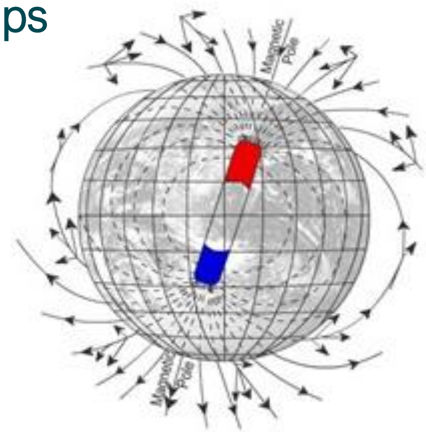
- Heading sensors can be proprioceptive (gyroscope, accelerometer) or exteroceptive (compass, inclinometer).

- Allows, together with an appropriate velocity information, to integrate the movement to a position estimate.
  - This procedure is called **dead reckoning** (ship navigation)



SENSORS: COMPASS

- Used since before 2000 B.C.
  - When 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 (even birds use it for migrations (2001 discovery))
- Large variety of solutions to measure magnetic or true north
  - Mechanical magnetic compass
  - Direct measure of the magnetic field (**Hall-effect**, magneto-resistive sensors)
  - Gyrocompass (**non-magnetic**, finds **true north** by using fast-spinning wheel and friction forces in order to exploit the rotation of the Earth) -> **used on ships**
- Major drawback of magnetic solutions
  - Weakness of the earth field (30 μTesla)
  - Easily disturbed by magnetic objects or other sources
  - Bandwidth limitations (0.5 Hz) and susceptible to vibrations
  - **Not suitable for indoor environments for absolute orientation**
  - Useful indoor (only locally)

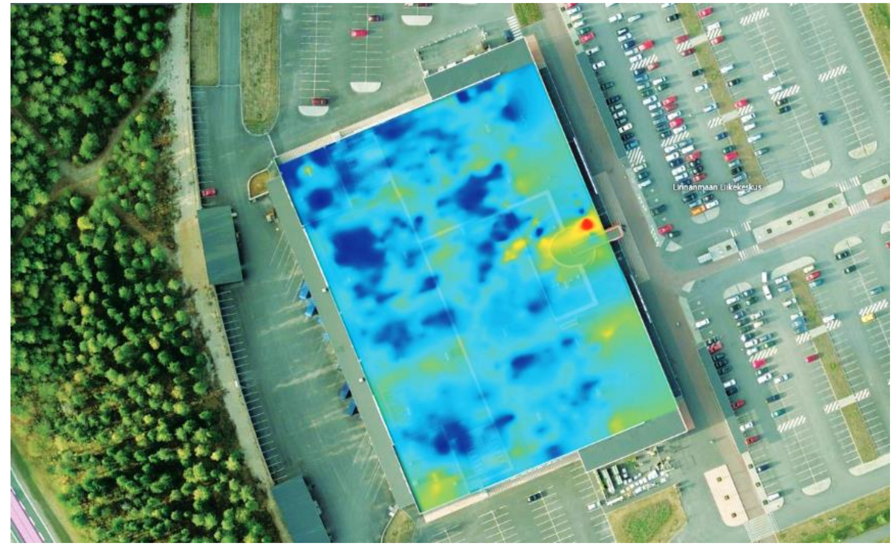


SENSORS: COMPASS EXAMPLE

- Magnetic Field Indoors

- Magnetic positioning was inspired by animal wayfinding in nature. Animals rely upon the Earth's magnetic fields to locate themselves in relation to their destinations (e.g., migratory breeding ground).

- Each building or structure has a unique magnetic "fingerprint," based on the way building materials affect and "distort" the otherwise persistent magnetic field generated by the Earth. Those patterns can be precisely assigned to a building floor plan.



- Smartphone owners (iOS and Android) can then be accurately located inside retail stores, hospitals, malls, airports and other indoor spaces.

SENSORS: GYROSCOPE

- Definition:
  – Heading sensors that preserve their orientation in relation to a fixed reference frame

- They provide an absolute measure for the heading of a mobile system.

- Two categories:
  – Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)
  – Optical Gyroscopes
    - Rate gyro (speed)

- Smartphone owners (iOS and Android) can then be accurately located inside retail stores, hospitals, malls, airports and other indoor spaces.

SENSORS: GYROSCOPE (BODY CONTROL)

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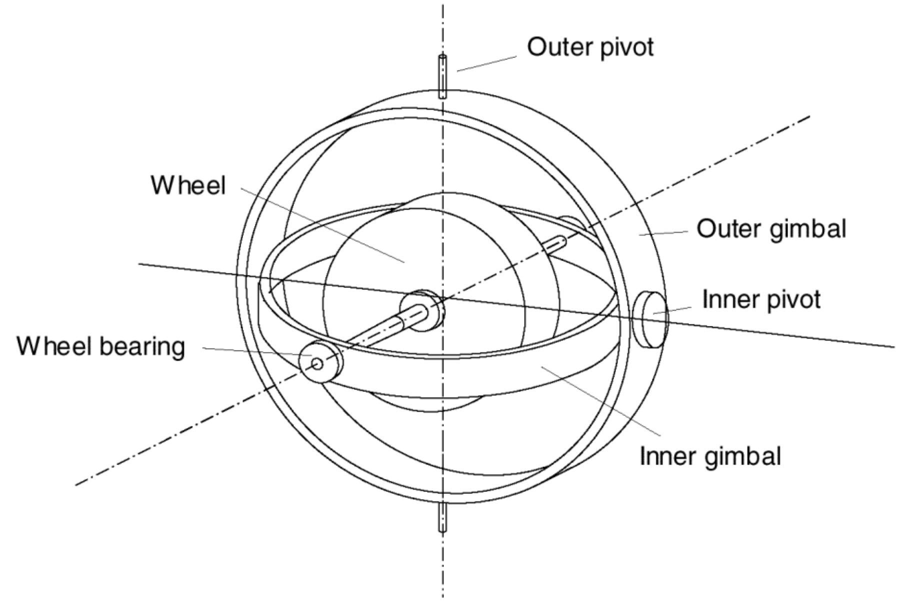
SENSORS: MECHANICAL GYROSCOPES

- Concept:
  - Inertial properties of a fast spinning rotor
  - Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.

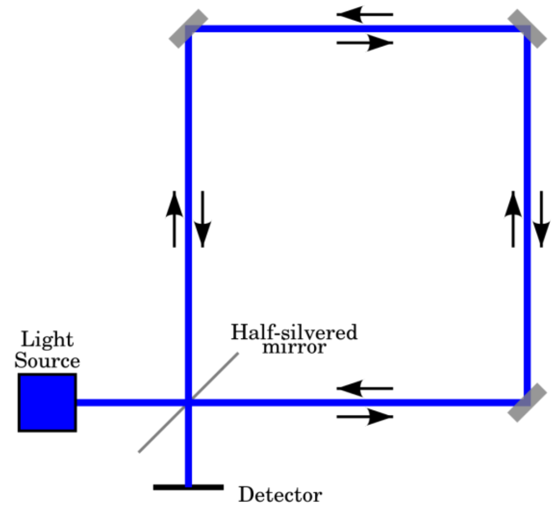


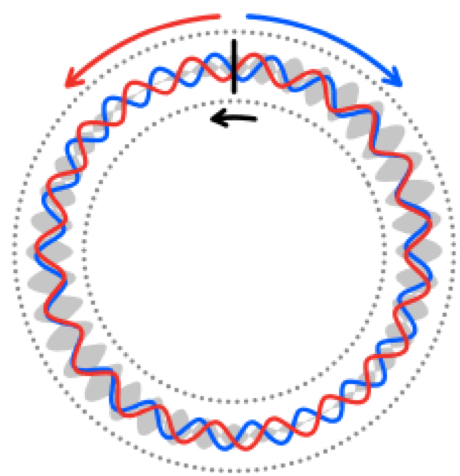
- **No torque can be transmitted from the outer pivot to the wheel axis**
  - spinning axis will therefore be space-stable
  - however friction in the axes bearings will introduce torque and so drift ->precession

- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)

SENSORS: OPTICAL GYROSCOPES

- Optical gyroscopes are based on the Sagnac effect
  - Angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
  - One is traveling in a fiber clockwise, the other counter clockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - Experiences slightly shorter path
  - Phase shift of the two beams is proportional to the angular velocity Ω of the cylinder
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber
- New solid-state optical gyroscopes based on the same principle are built using microfabrication technology.





SENSORS: ACCELEROMETER

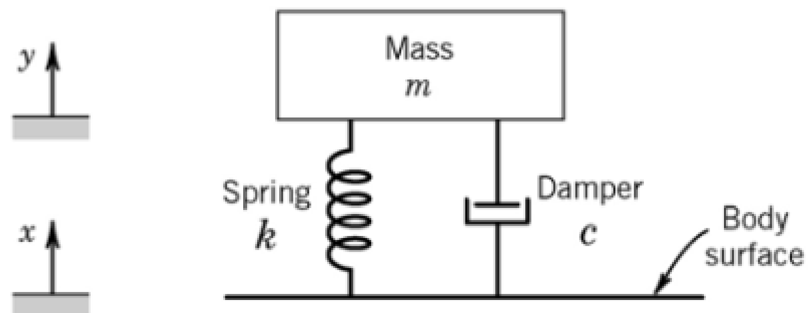
- Mechanical Accelerometer
  - Accelerometers measure all external forces acting upon them, including gravity

- An accelerometer acts like a spring–mass– damper system:

$$F_{applied} = F_{inertial} + F_{damping} + F_{spring} = m\ddot{x} + c\dot{x} + kx$$

- Where m is the proof mass, c the damping coefficient, k the spring constant at steady-state:

$$a_{applied} = \frac{kx}{m}$$



(b) Representation using mass, spring, and damper

SENSORS: ACCELEROMETER

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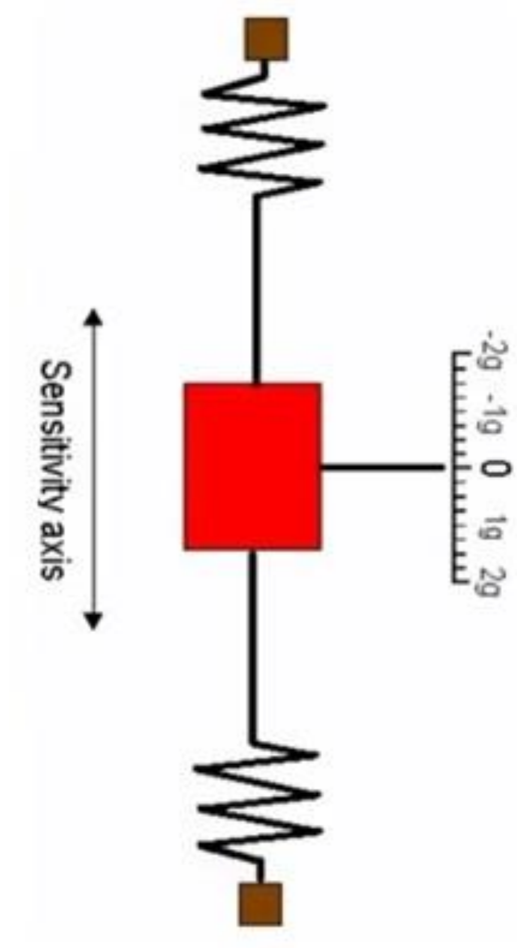
- On the Earth's surface, the accelerometer always indicates 1g along the vertical axis
- To obtain the inertial acceleration (due to motion alone), the gravity must be subtracted. Conversely, the device's output will be zero during free fall
- Bandwidth up to 50 KHz
- An accelerometer measures acceleration only along a single axis. By mounting three accelerometers orthogonally to one another, a three-axis accelerometer can be obtained



SENSORS: ACCELEROMETER

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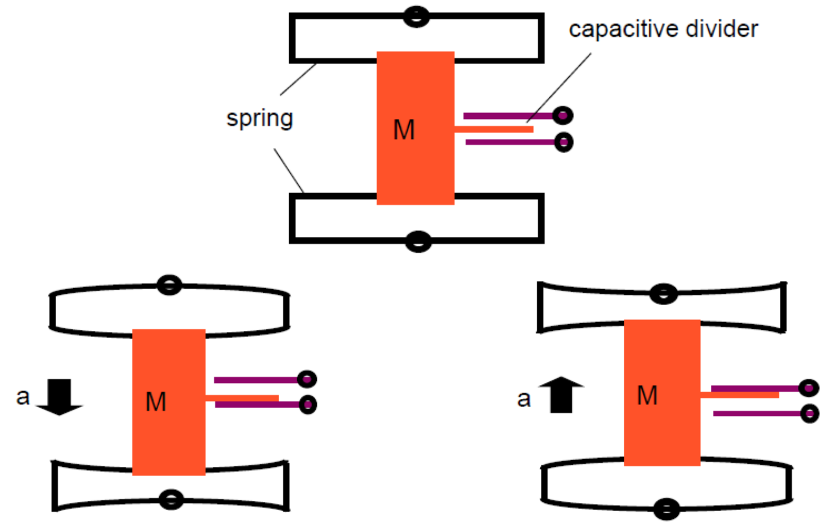
MEMS Accelerometer

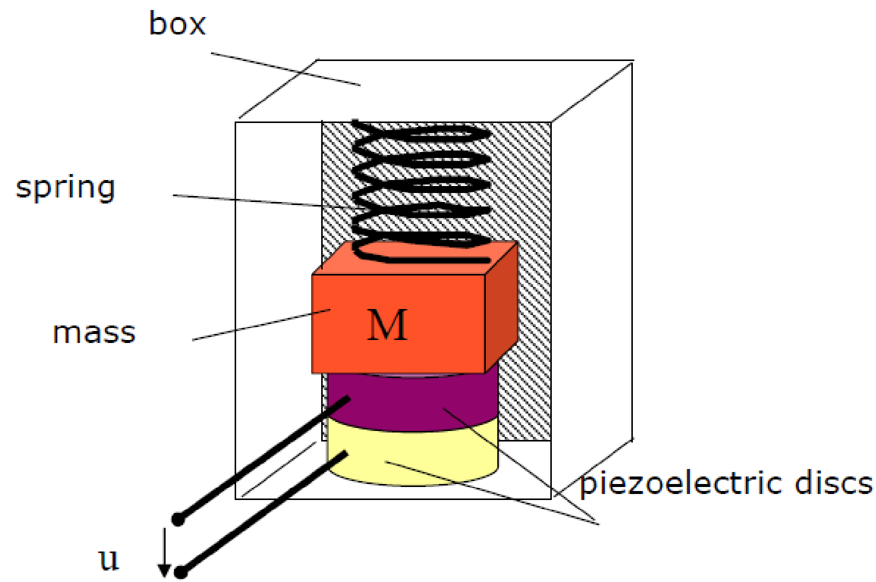


- Operational Principle
  - A spring-like structure connects the device to a seismic mass vibrating in a capacity divider.
  - A capacitive divider converts the displacement of the seismic mass into an electric signal.
  - Damping is created by the gas sealed in the device.
- Main Characteristics
  - Can be multi-directional
  - Can measure accelerations up to 50 g
- Applications
  - Dynamic acceleration
  - Static acceleration (inclinometer)
  - Airbag sensors (+- 35 g)
  - Control of video games (Wii)

SENSORS: ACCELEROMETER

Piezoelectric Accelerometer

- Operational Principle
  - Primary transducer is typically a single-degree-of-freedom spring-mass system that relates acceleration to displacement.
  - Secondary transducer (piezoelectric discs) converts displacement of the seismic mass into an electrical signal (voltage).



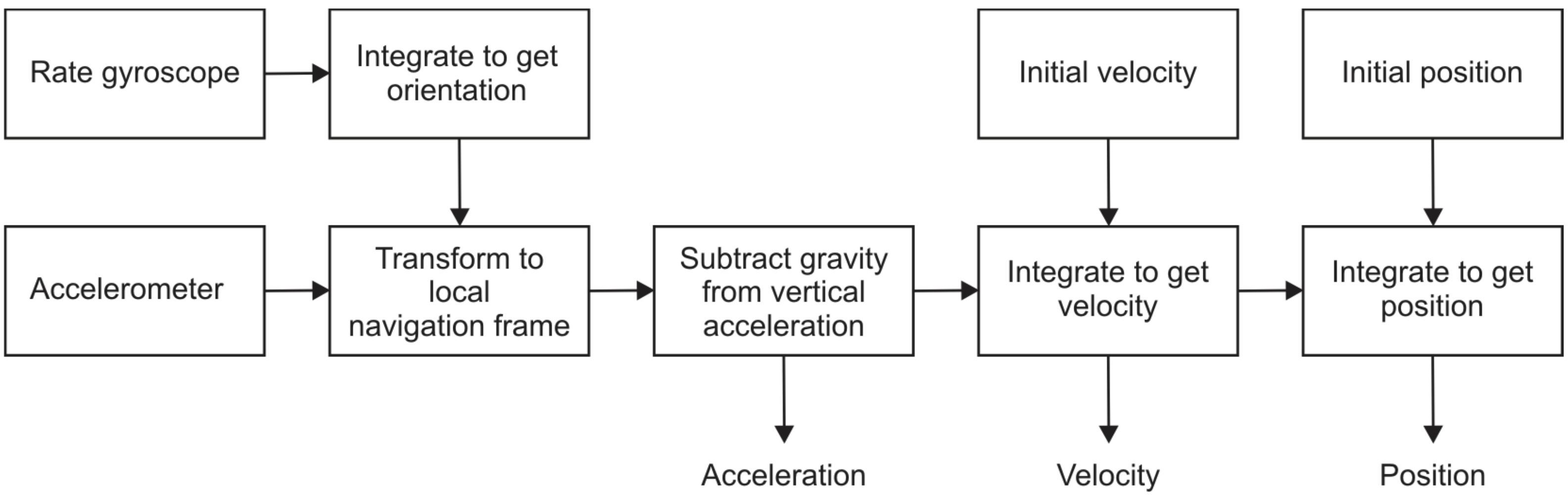
- Main Characteristics
  - Piezoelectric elements cannot produce a signal under constant acceleration (i.e., static) conditions
  - 2-D and 3-D accelerometers can be created by combining 2 or 3 1-D modules

- Applications
  - Vibration analysis
  - Machine diagnostics
  - Active vehicle suspension
  - Autonomously guided vehicles
  - Earthquake sensors
  - Modal analysis

SENSORS: INERTIAL MEASUREMENT UNIT

- Definition
  – **An inertial measurement unit (IMU) is a 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 with respect to an inertial frame

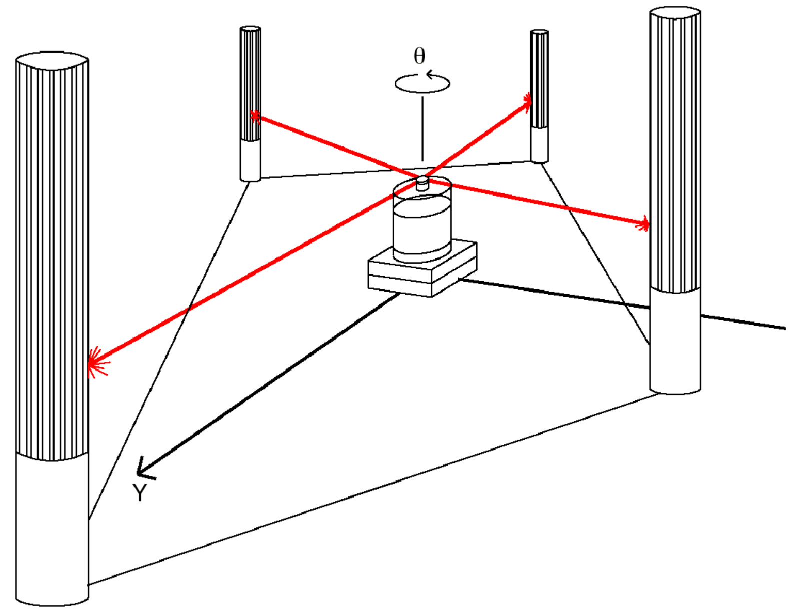
- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.



SENSORS: BEACONS / GPS

- BEACONS:
  - "Elegant" way to solve the localization problem in mobile robotics
- **Beacons are signalling guiding devices with a precisely known position**

- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like **stars, mountains or the sun**
  - Artificial beacons like **lighthouses**



- The recently introduced **Global Positioning System** (GPS) revolutionized modern navigation technology

TO BE CONTINUED…

ACTIVE RANGING AND
VISION BASED SENSORS

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Faculty of Engineering

THANK YOU

MARKOS ALONSO NIETO
Robotics and Automation Group
Electronics and Computer Science Department

Mondragon Unibertsitatea - Faculty of Engineering
Goiru, 2; 20500 Arrasate - Mondragón (Gipuzkoa)
Tel. : +(34) 64640977 / +(34) 943794700 + Ext. 5172
www.mondragon.edu