Characterizing Sensor Performance (1)

Measurement in real world environment is error prone

- Basic sensor response ratings
  - Dynamic range
    - ratio between lower and upper limits, usually in decibels (dB, power)
    - e.g. power measurement from 1 mW to 20 W

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB$$

$$P = U \cdot I = \frac{1}{R}U^2$$

    - e.g. voltage measurement from 1 mV to 20 V

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86dB$$

    - *20 instead of 10 because square of voltage is equal to power!!*

Characterizing Sensor Performance (2)

- Basic sensor response ratings (cont.)

  - Range
    - upper limit

PERCEPTIVE HORIZON (occlusions + range)

  - Resolution
    - minimum difference between two values
    - usually: lower limit of dynamic range = resolution
    - for digital sensors it is usually the A/D resolution.
      - e.g. 5V / 255 (8 bit)

  - Linearity
    - variation of output signal as function of the input signal
    - linearity is less important when signal is treated with a computer

$$x \to f(x) \qquad y \to f(y)$$

$$\alpha \cdot x + \beta \cdot y \to f(\alpha \cdot x + \beta \cdot y) \stackrel{?}{=} \alpha \cdot f(x) + \beta \cdot f(y)$$

Characterizing Sensor Performance (3)

- Basic sensor response ratings (cont.)
  - Bandwidth or Frequency
    - the speed with which a sensor can provide a stream of readings
    - usually there is an upper limit depending on the sensor and the sampling rate
    - lower limit is also possible, e.g. acceleration sensor
    - one has also to consider phase (delay) of the signal

In Situ Sensor Performance (1)

Characteristics that are especially relevant for real world environments

- 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
- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters
  - influence of other active sensors
- Error / Accuracy
  - difference between the sensor's output and the true value

$$\left(accuracy = 1 - \frac{\underbrace{|m - v|}_{\text{error}}}{v} \right)$$

m = measured value
v = true value

In Situ Sensor Performance (2)

Characteristics that are especially relevant for real world environments

- 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 optic of a camera

- Random error -> non-deterministic
  - no prediction possible
  - however, they can be described probabilistically
  - e.g. Hue instability of camera, black level noise of camera ..

- Precision
  - *reproducibility* of sensor results

$$precision = \frac{range}{\sigma}$$

Properties of measurement systems - 1

- accuracy

  agreement of measured values with a given reference standard (e.g., ideal characteristics)

- repeatability

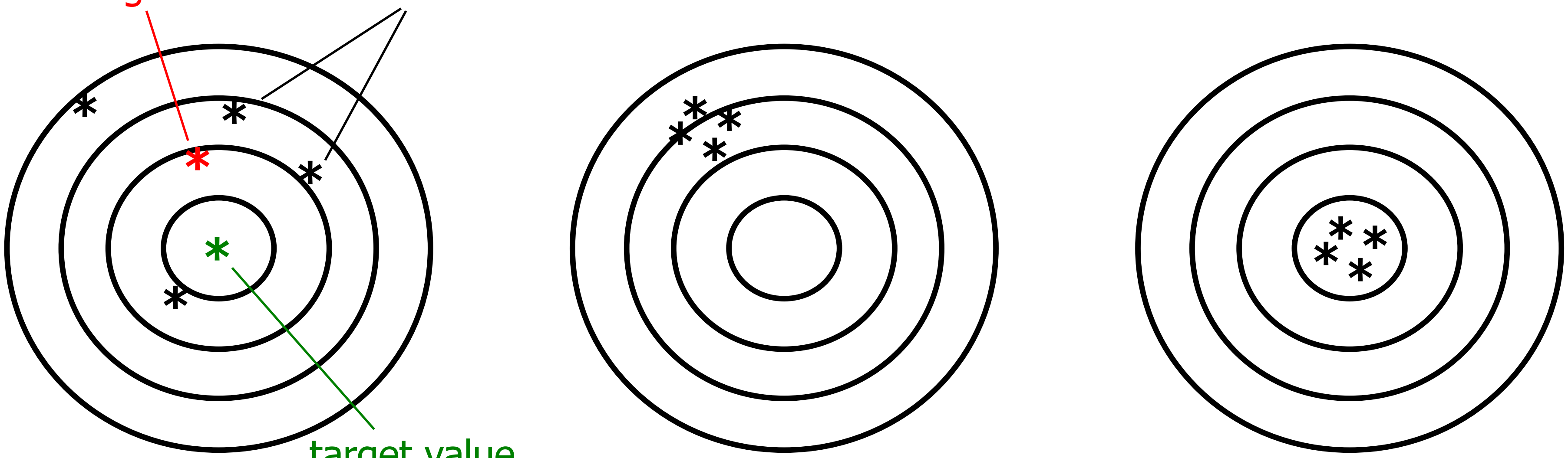
  capability of reproducing as output similar measured values over consecutive measurements of the same constant input quantity

- stability

  capability of keeping the same measuring characteristics over time/temperature (similar to accuracy, but in the long run)

NOT ONLY FOR SENSORS
BUT also for ACTUATORS

Accuracy and Repeatability



low accuracy
low repeatability

low accuracy
high repeatability

high accuracy
high repeatability

better components!

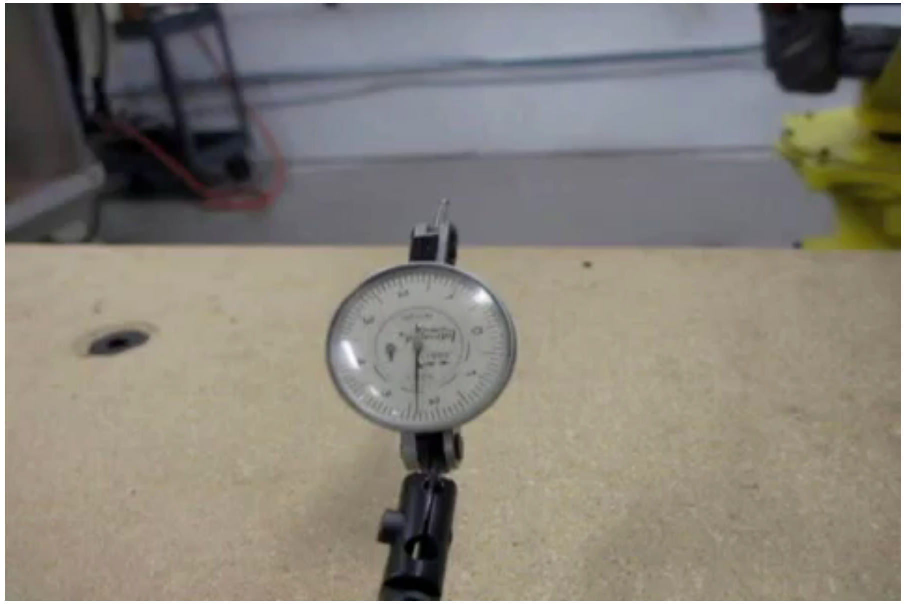
calibration!

Accuracy and Repeatability
in robotics

- accuracy is how close a robot can come to a given point in its workspace
  - depends on machining accuracy in construction/assembly of the robot, flexibility effects of the links, gear backlash, payload changes, round-off errors in control computations, ...
  - can be improved by (kinematic) **calibration**
- repeatability is how close a robot can return to a previously taught point
  - depends only the robot controller/measurement resolution

video

- both may vary in different areas of the robot workspace
  - standard ISO 9283 defines conditions for assessing robot performance
  - limited to static situations (recently, interest also in dynamic motion)
  - robot manufacturers usually provide only data on "repeatability"



simple test on repeatability of a Fanuc ArcMate100i robot (1.3 m reach)

Properties of measurement systems - 2

- linearity error

  maximum deviation of the measured output from the straight line that best fits the real characteristics

  - as % of the output (measurement) range

- offset error

  value of the measured output for zero input

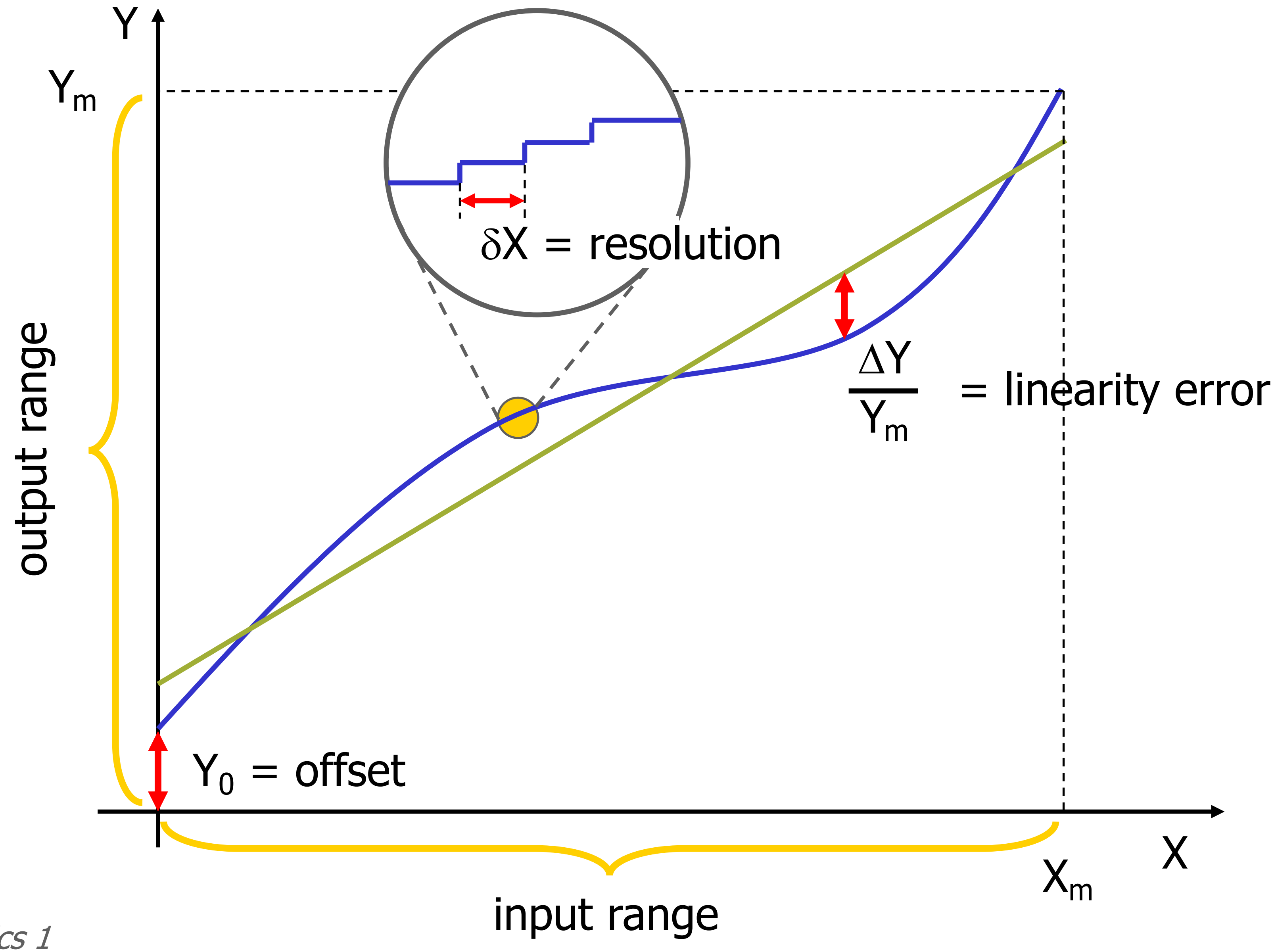
  - sometimes not zero after an operation cycle, due to hysteresis

- resolution error

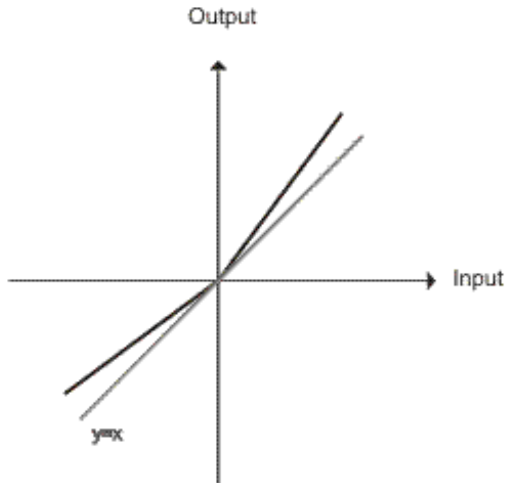
  maximum variation of the input quantity producing no variation of the measured output

  - in absolute value or in % of the input range

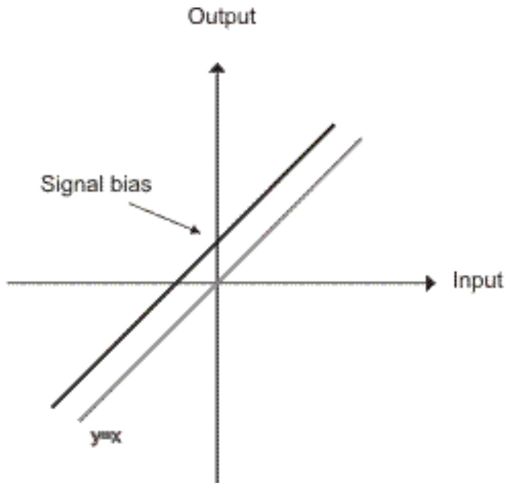
Linearity, Offset, Resolution



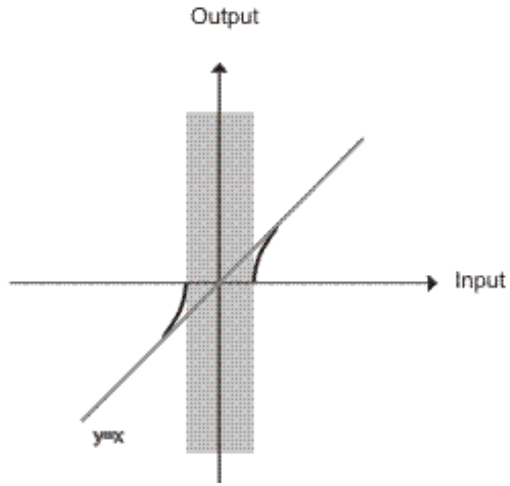
Sensor measurements
some non-idealities



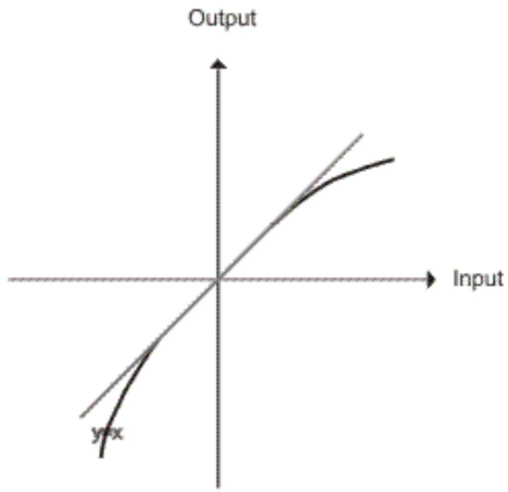
Asymmetry



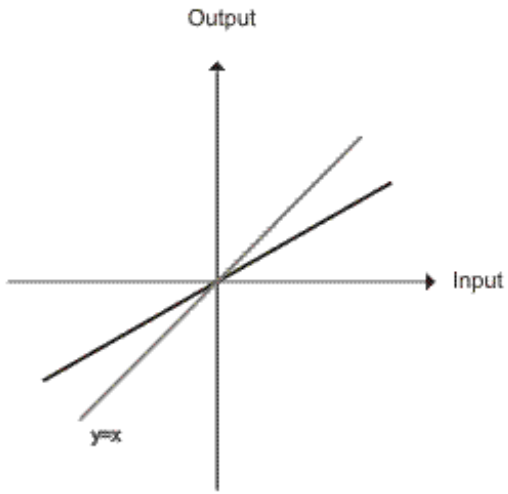
Bias



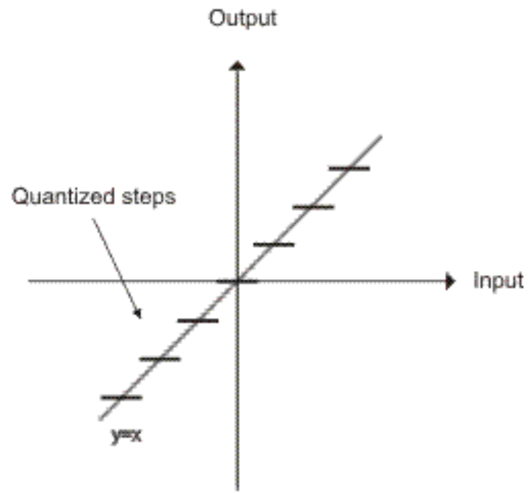
Dead zone



Nonlinearity

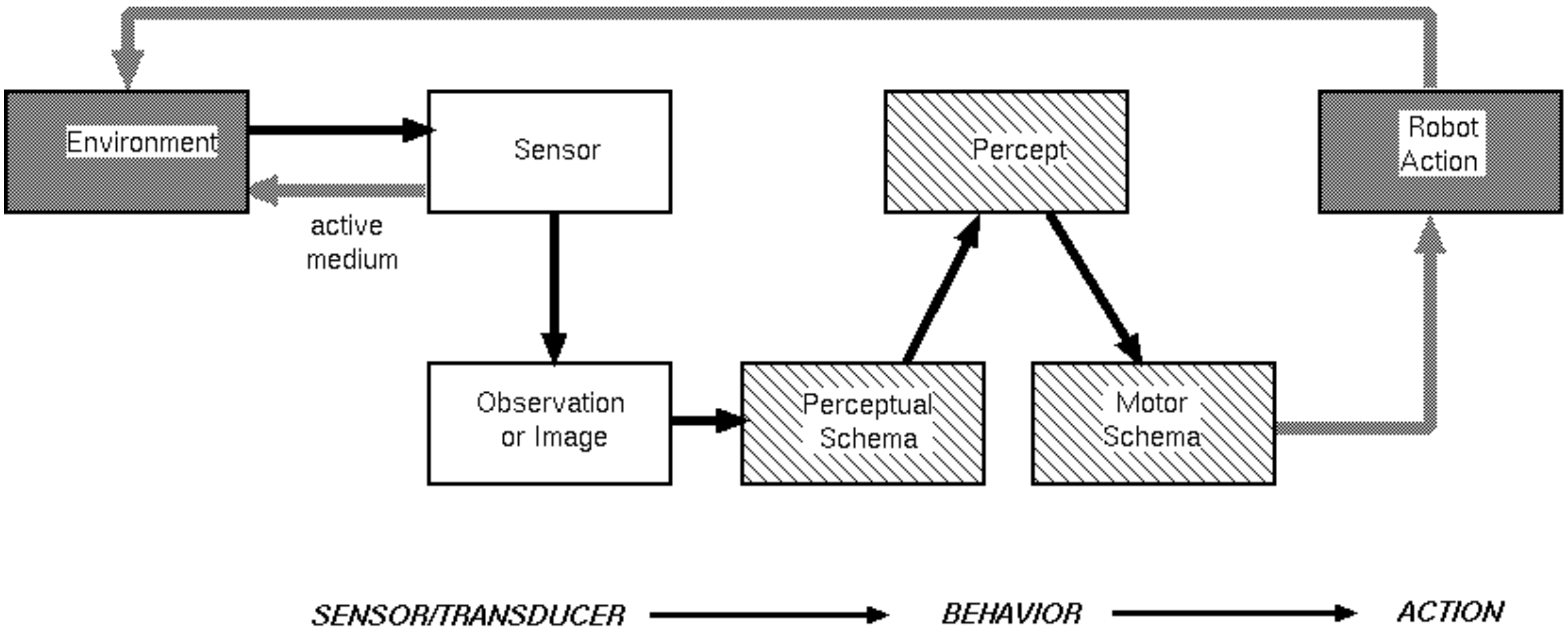


Scaling factor

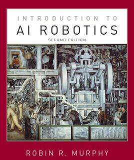


Quantization

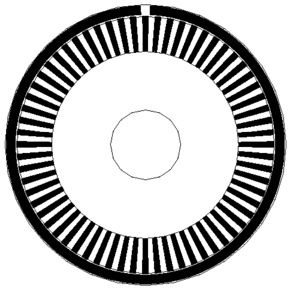
Sensor Model

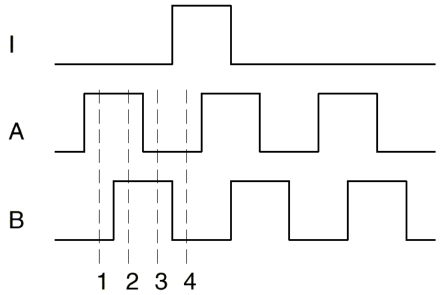


SENSE — ACT



Wheel / Motor Encoders

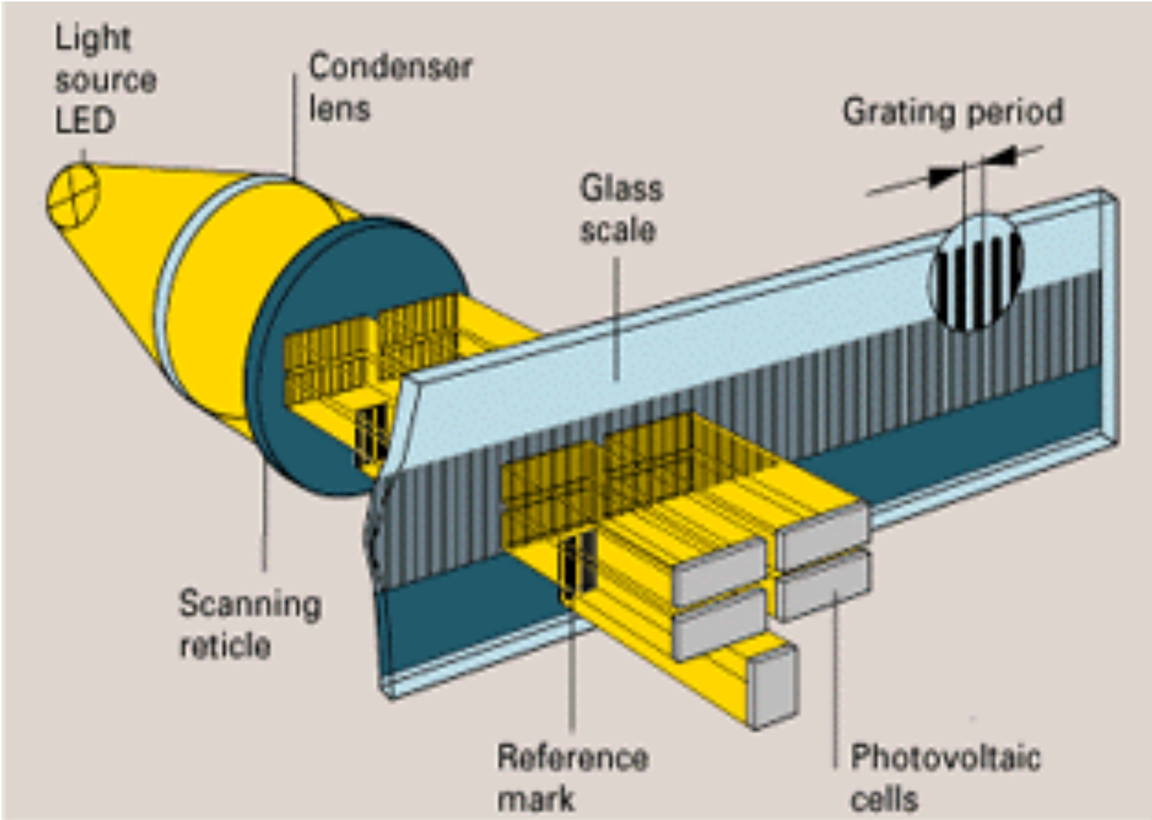




State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

- 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

Wheel / Motor Encoders (2)



Heading Sensors

2.3.2009 – 2nd hour

- Heading sensors can be proprioceptive (gyroscope, acceleration) or exteroceptive (compass, inclinometer).
- Used to determine the robots orientation and inclination.
- Allow, together with an appropriate velocity information, to integrate the movement to an position estimate.
  - This procedure is called **deduced reckoning** (ship navigation)

Compass

- 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 for orientation.
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field (Hall-effect, magnetoresistive sensors)
- Major drawback
  - weakness of the earth field
  - easily disturbed by magnetic objects or other sources
  - not feasible for indoor environments (except locally)

Gyroscope

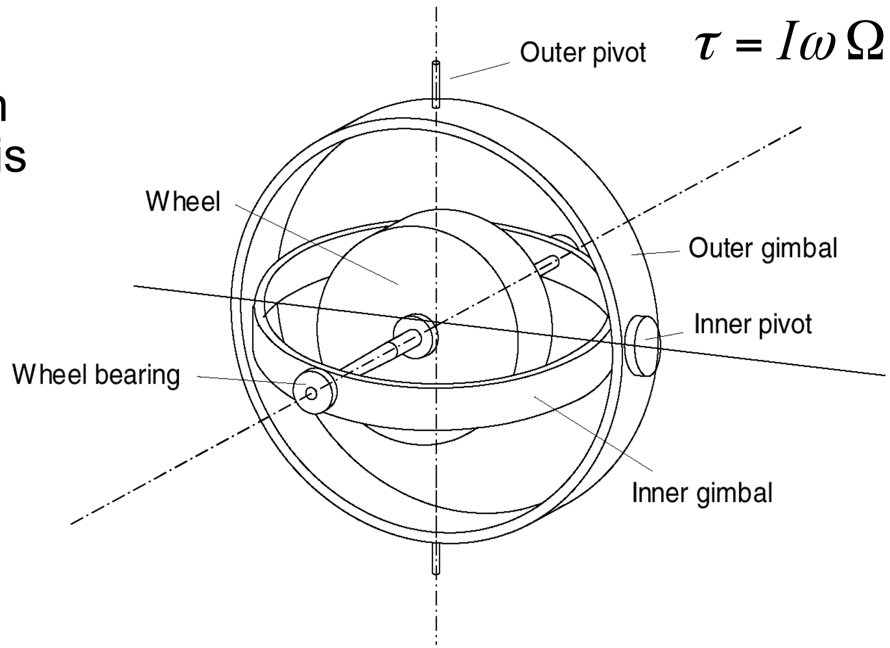
- Heading sensors, that keep the orientation to a fixed frame
  - absolute measure for the heading of a mobile system.
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)
  - Optical Gyroscopes
    - Rate gyro (speed)

Mechanical Gyroscopes

- Concept: inertial properties of a fast spinning rotor
  - gyroscopic precession
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- Reactive torque τ (tracking stability) is proportional to the spinning speed ω, the precession speed Ω and the wheels inertia I.
- No torque can be transmitted from the outer pivot to the wheel axis
  - spinning axis will therefore be space-stable
- Quality: 0.1° in 6 hours

- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
- If it points east-west, the horizontal axis reads the earth rotation

$$\tau = I\omega\Omega$$



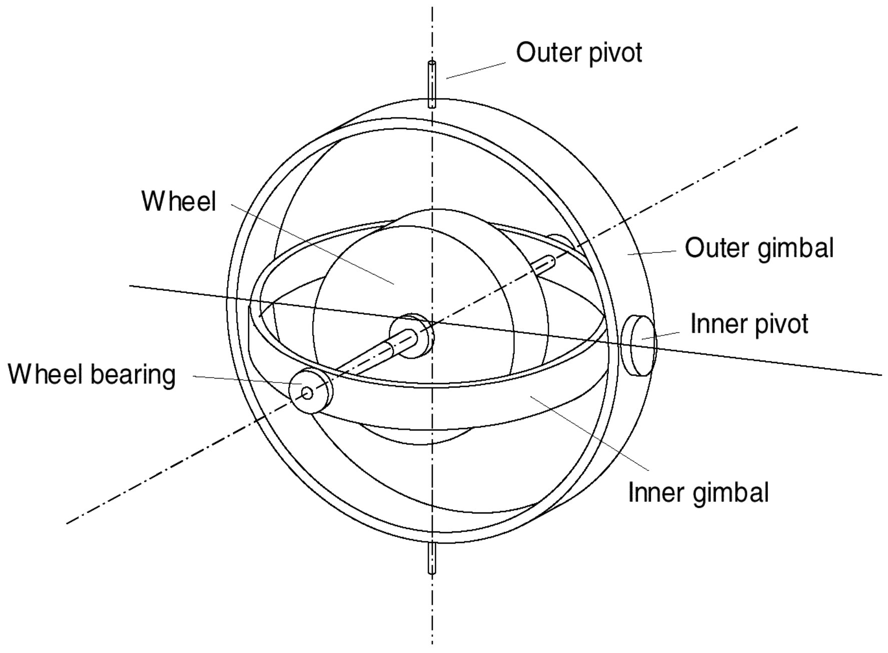
Rate gyros

- Same basic arrangement shown as regular mechanical gyros

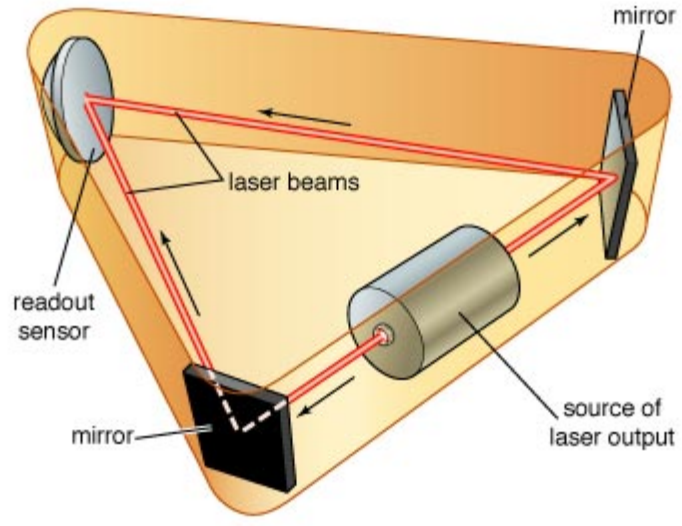
- But: gimble(s) are restrained by a torsional spring
  - enables to measure angular speeds instead of the orientation.

$$\tau = I\omega\Omega$$

- Others, more simple gyroscopes, use Coriolis forces to measure changes in heading.

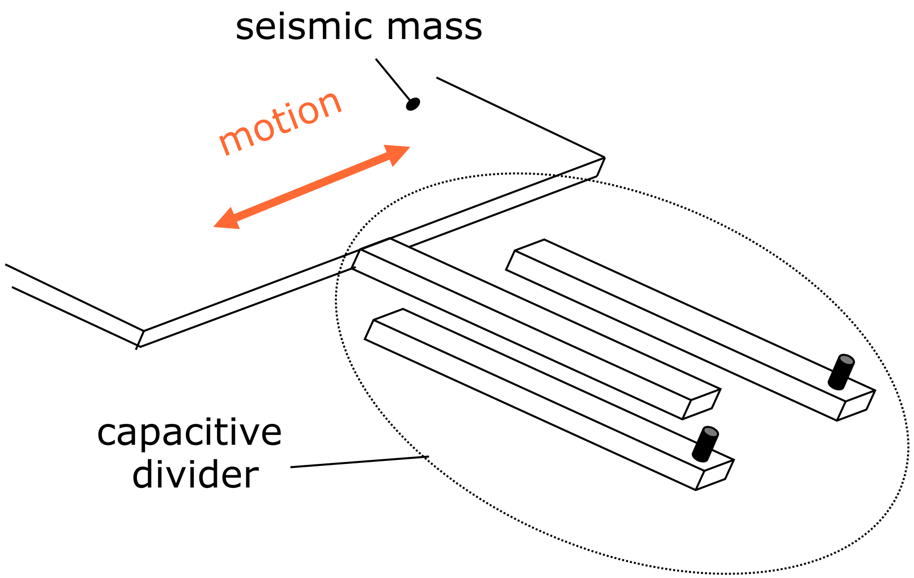


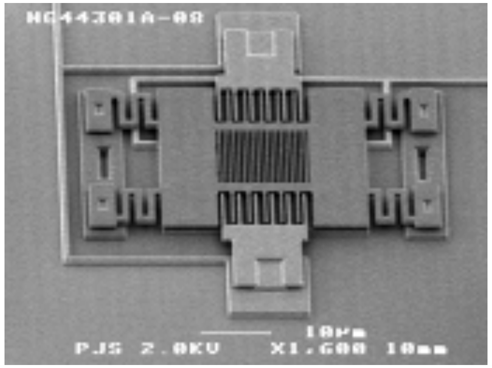
Optical Gyroscopes



- First commercial use started only in the early 1980 when they where first installed in airplanes.
- Optical gyroscopes
  - angular speed (heading) sensors using two monochromic light (or laser) beams f
- On is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - slightly shorter path
  - phase shift Δ f of the two beams is proportional to the angular velocity Ω of the cylinder
- New solid-state optical gyroscopes based on the same principle are build using microfabrication technology.

Factsheet: MEMS Accelerometer (1)





<http://www.mems.sandia.gov/>

1. Operational Principle

The primary transducer is a vibrating mass that relates acceleration to displacement. The secondary transducer (a capacitive divider) converts the displacement of the seismic mass into an electric signal.

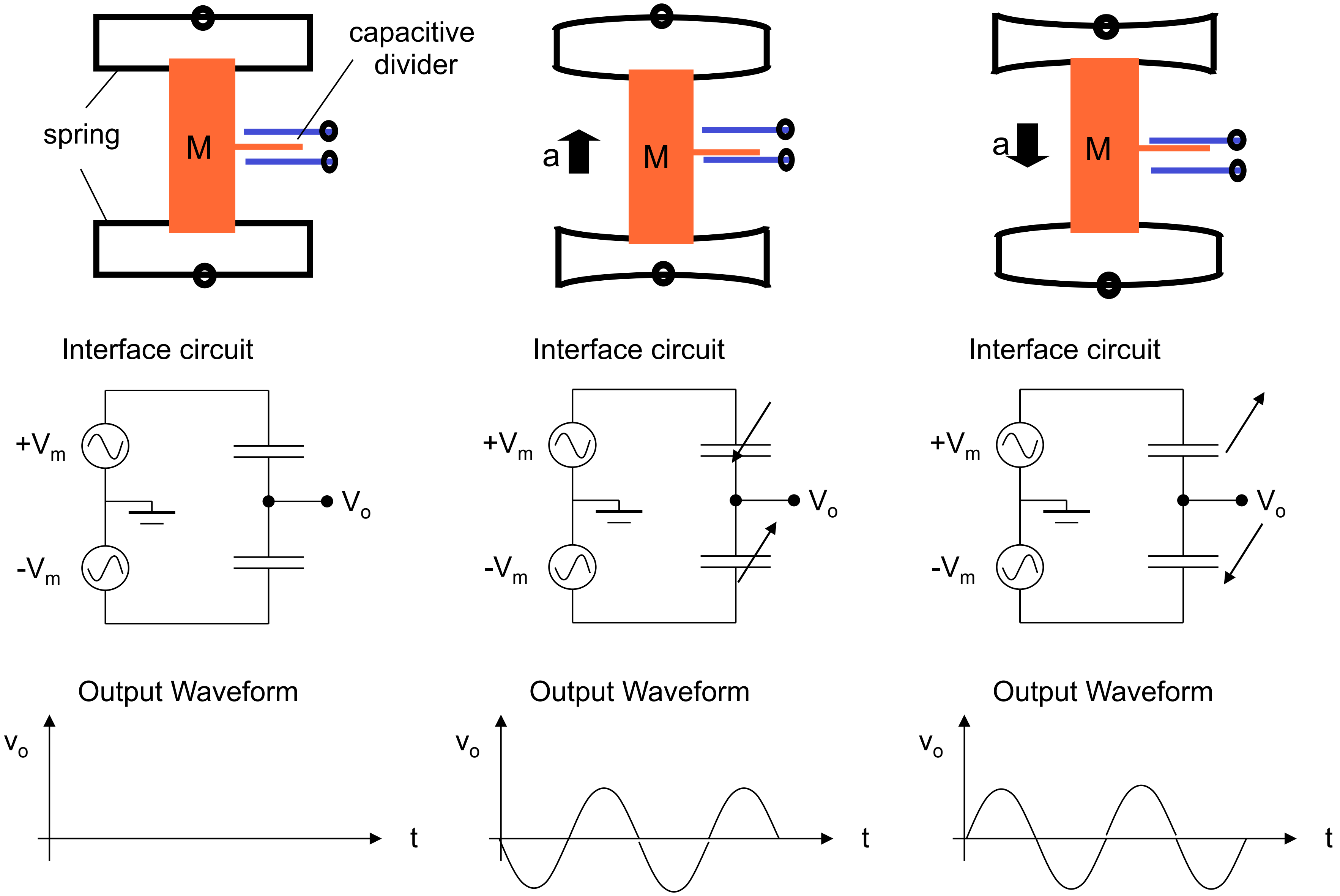
2. Main Characteristics

- Can be multi-directional
- Various sensing ranges from 1 to 50 g

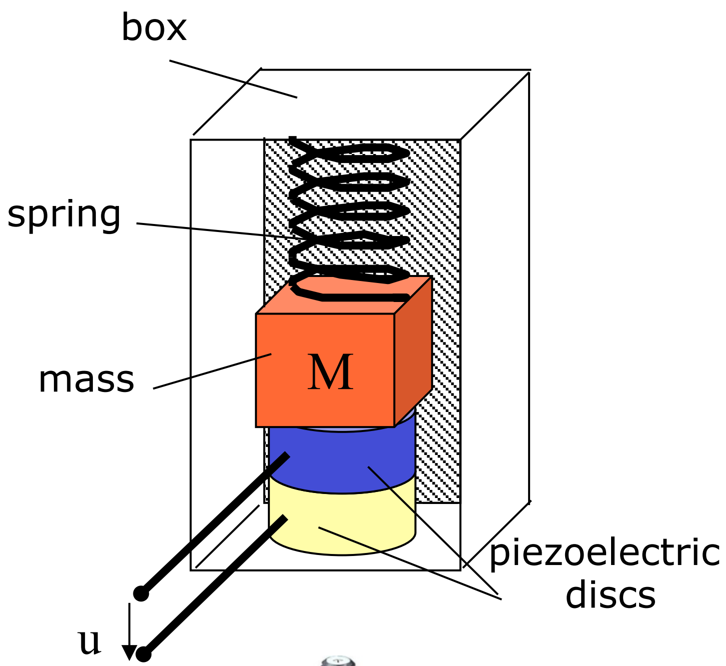
3. Applications

- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors
- Control of video games (Wii)

Factsheet: MEMS Accelerometer (2)



Factsheet: Piezoelectric Accelerometer



<http://www.pcb.com/>

1. 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).

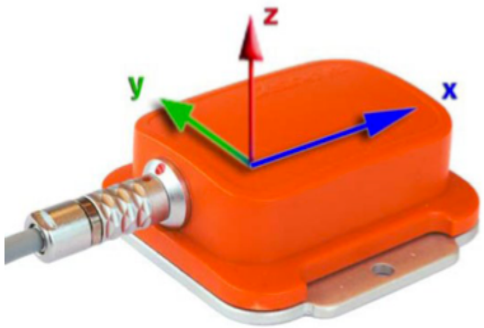
2. Main Characteristics

- 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
- Possible to measure force by applying Newton's Second Law

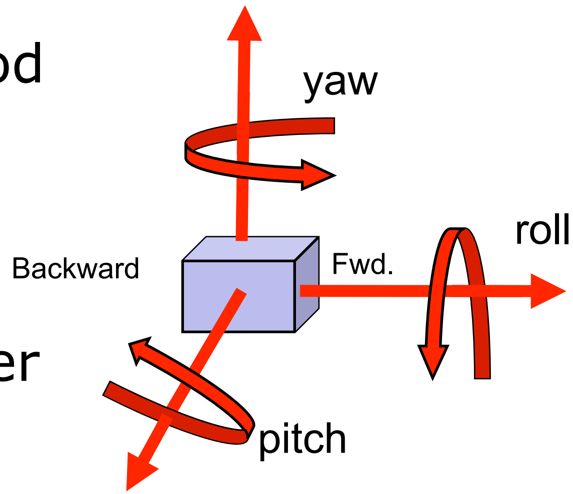
3. Applications

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

Inertial Measurement Unit (IMU)



- A closed system for detecting orientation and motion of a vehicle or human
- Typically consists of 3 accelerometer, 3 gyroscopes, and 3 magnetometers
  - Data rate @100 Hz
- Gyro reliable only within some time period (temperature drift)
- Magnetometer data can locally be wrong (magnetic perturbation)
- Data from all 3 is fused by a Kalman Filter inside the IMU sensor



dead reckoning

the process of calculating one's position, especially at sea, by estimating the direction and distance travelled rather than by using landmarks or astronomical observations.

Also called “deduced recogning”, but

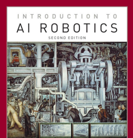
….The term "dead reckoning" was not originally used to abbreviate "deduced reckoning," nor is it a misspelling of the term "ded reckoning." The use of "ded" or "deduced reckoning" is not known to have appeared earlier than 1931, much later in history than "dead reckoning" appearing as early as 1613 in the Oxford English Dictionary.

Contact Sensors

- About them:
  - Passive
- Advantages:
  - Cheap
- Disadvantages:
  - Poor sensitivity
  - Poor coverage
  - Poor localization

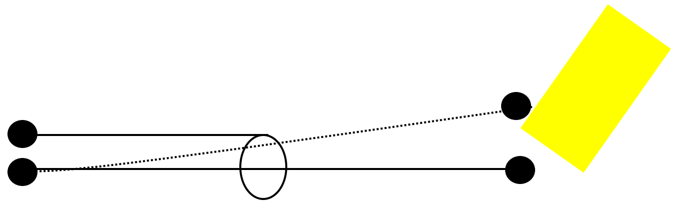
- *In development*
  - *Capacitance based "skins"*
  - *Mouse whiskers for robots*

Bump sensor

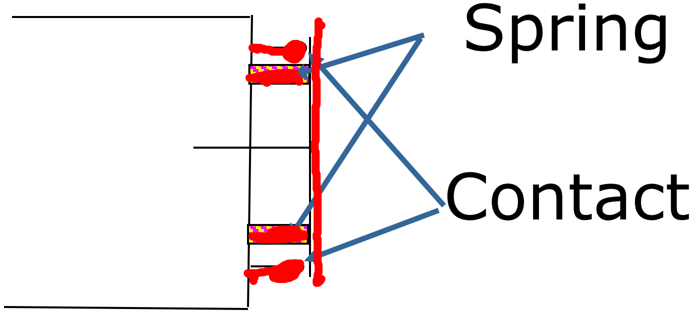


Tactile Sensors

Measure contact with objects



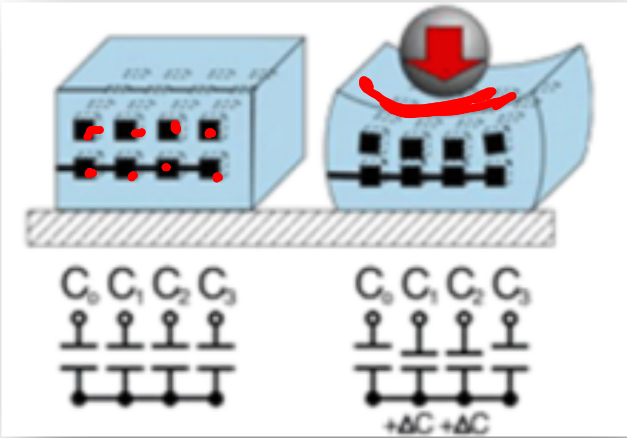
Touch sensor



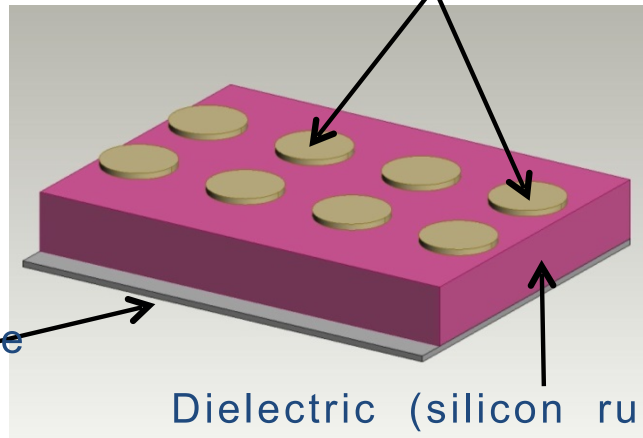
Bumper sensor

The ROBOSKIN concept

Principle



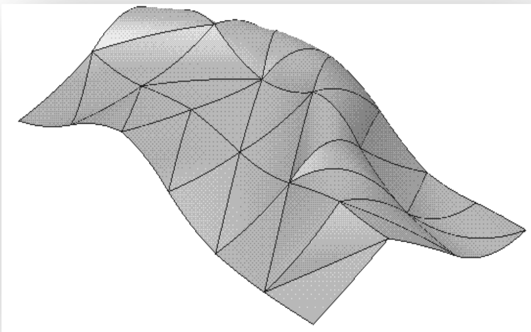
Electrodes (on flex substrate)



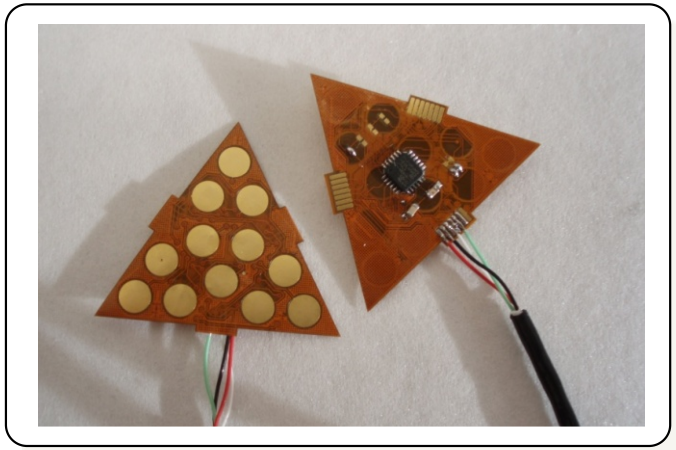
Ground plane

Dielectric (silicon rubber, foam, ...)

Concept



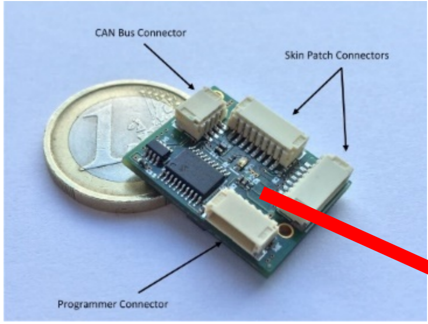
Triangular Module

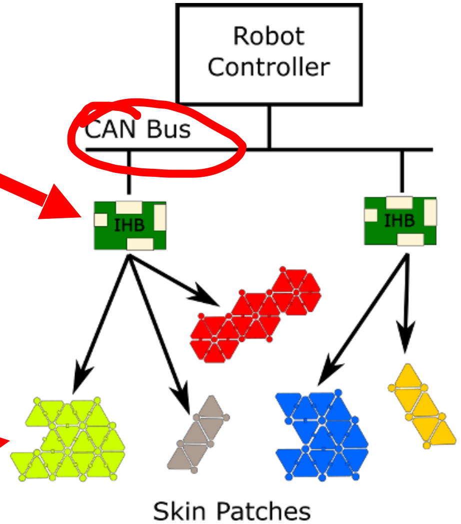


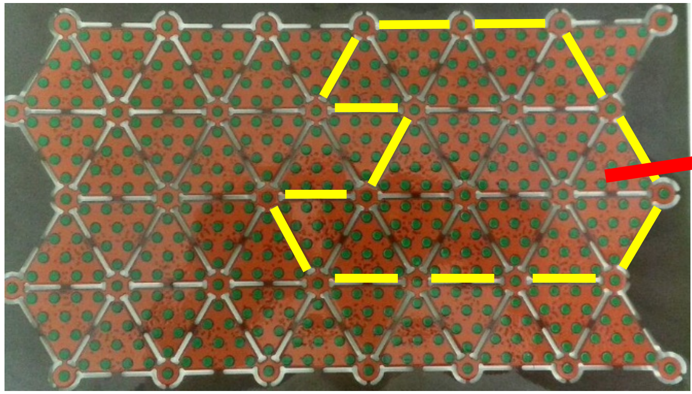
Patented - M. Maggiali, G. Cannata , G. Metta , G. Sandini "Organization and placement of tactile elements for a haptic sensory system"

Large Area Skin System: CySkin

CAN based I/F
- Up to 4 patches of 48 modules (~1920 taxels)
- Sampling rate T = 50 msec
- …



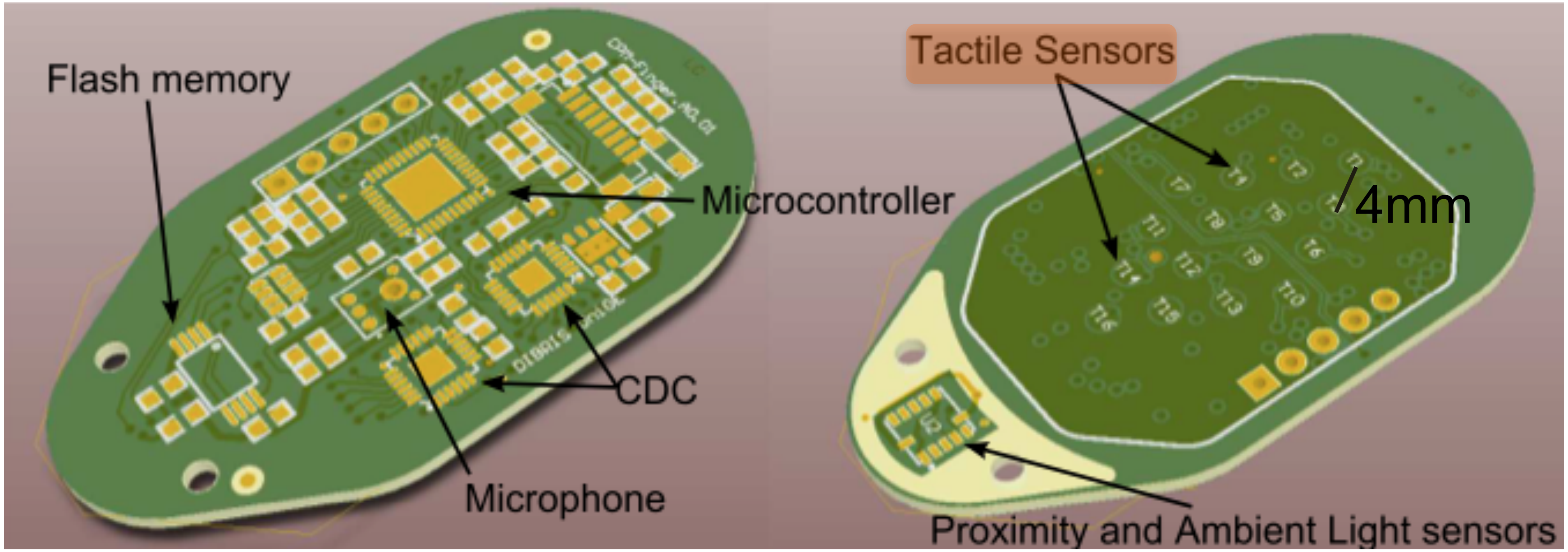




Robot skin (production sheet)
- 48 modules (10/11 taxels)
- Fully connected (no predefined routing)
- Quasi uniform pattern
- …
-

Tactile modules (10/11 taxels)
- Fully programmable
- Taxel dia. ~3.5 mm
- Pitch: ~8 mm
- Temperature compensated
- …
-

Tactile sensor development
PCB Design



FEATURES:

- **Sixteen capacitive tactile sensors**
  - ✓ Two parallel CDCs.
  - ✓ Sampling time around 24ms (down-to 5ms).
  - ✓ 2mm of diameter and 4mm of pitch in order to detect small details of the garment such as buttons of borders.