***Robotics 1***

# Robot components:
## Exteroceptive sensors

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# Summary

- force sensors
  - strain gauges and joint torque sensor
  - 6D force/torque (F/T) sensor at robot wrist
  - RCC = Remote Center of Compliance *(not a sensor, but similar...)*
- proximity/distance sensors
  - infrared (IF)
  - ultrasound (US)
  - laser
  - with structured light
- vision
- examples of robot sensor equipments
- some videos intertwined, with applications

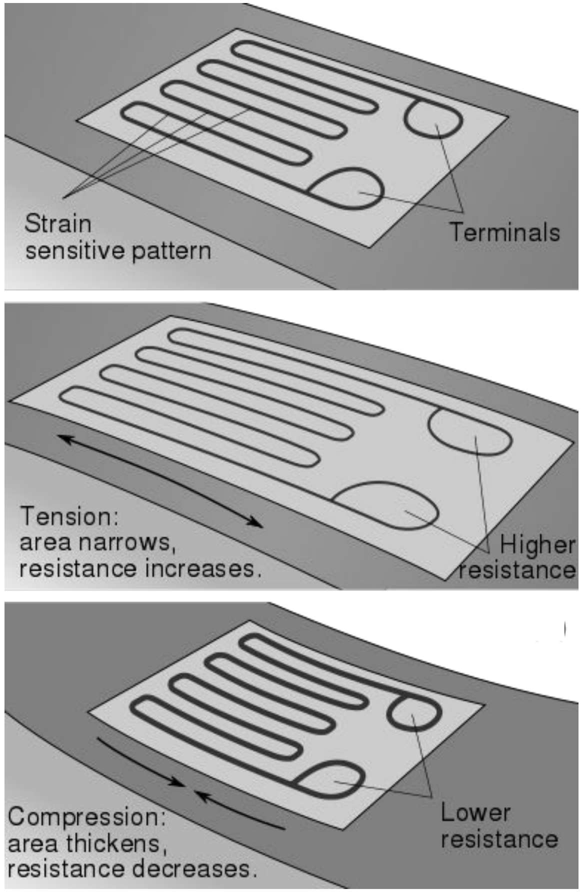
# Force/torque and deformation

- indirect information obtained from the measure of deformation of an elastic element subject to the force or torque to be measured
- basic component is a *strain gauge*: uses the variation of the resistance R of a metal conductor when its length L or cross-section S vary

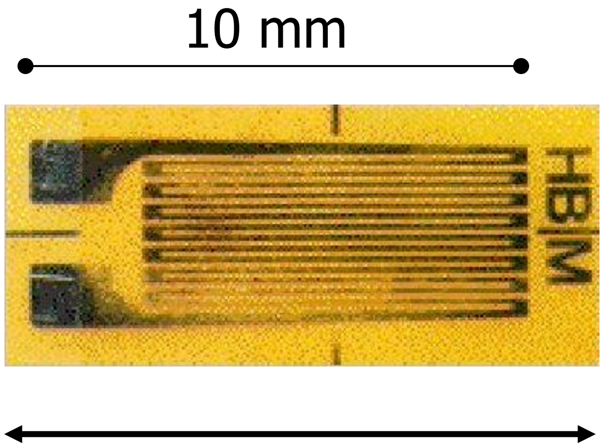
$$\frac{\partial R}{\partial L} > 0 \qquad \frac{\partial R}{\partial S} < 0$$

$$\frac{\partial R}{\partial T} \text{ small}$$

T: temperature



# Strain gauges

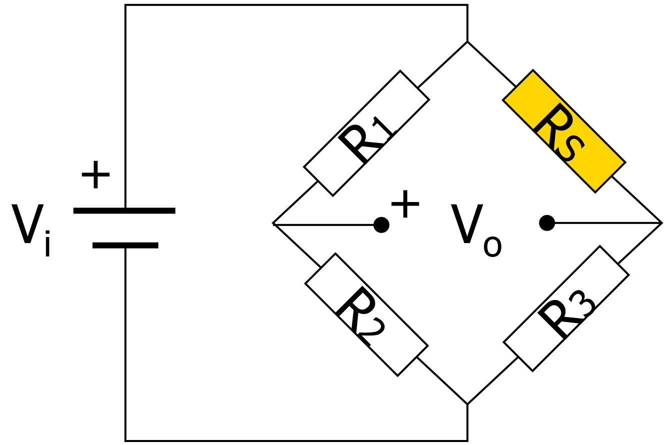



principal measurement axis

Gauge-Factor = GF = $\dfrac{\Delta R/R}{\Delta L/L}$ ← strain $\varepsilon$

(typically $\approx$ 2. i.e., small sensitivity)

Wheatstone single-point bridge connection
(for *accurately* measuring resistance)



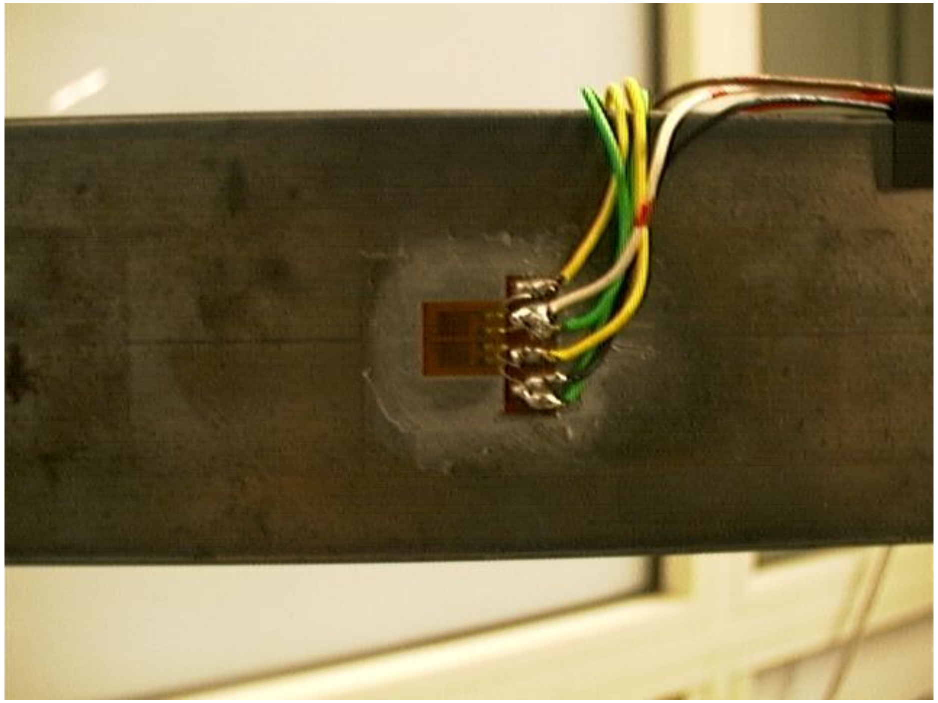

- $R_1$, $R_2$, $R_3$ very well matched ($\approx$R)
- $R_S \approx$ R at rest (no stress)
- two-point bridges have 2 strain gauges connected oppositely (↗ sensitivity)

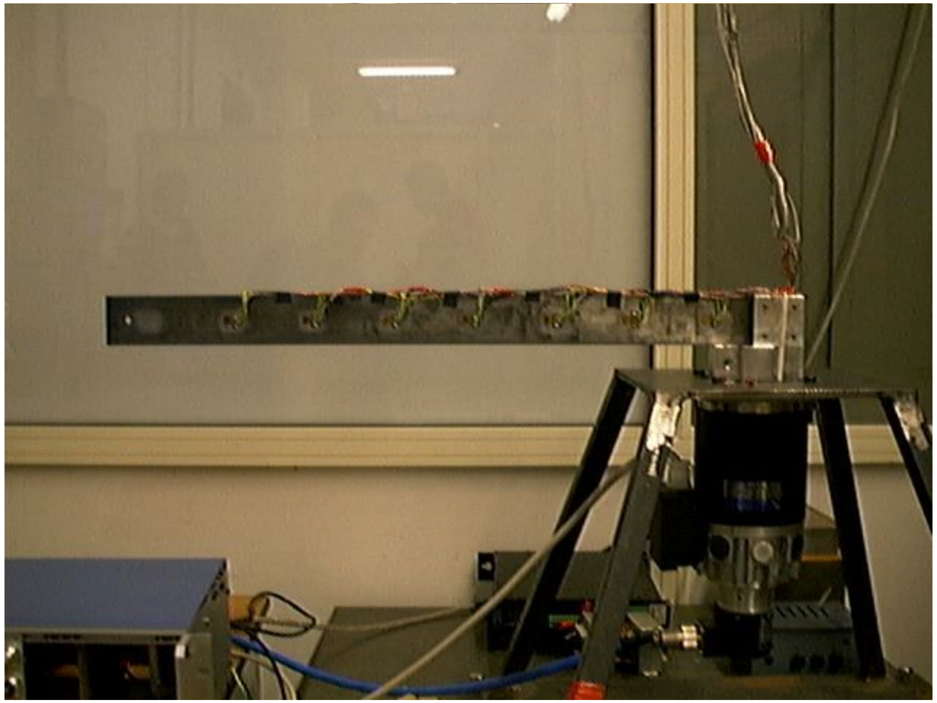
if $R_1$ has the same dependence on T of $R_S$ thermal variations are automatically compensated

$$V_o = \left( \frac{R_2}{R_1+R_2} - \frac{R_3}{R_3+R_S} \right) V_i$$

# Strain gauges in flexible arms

video



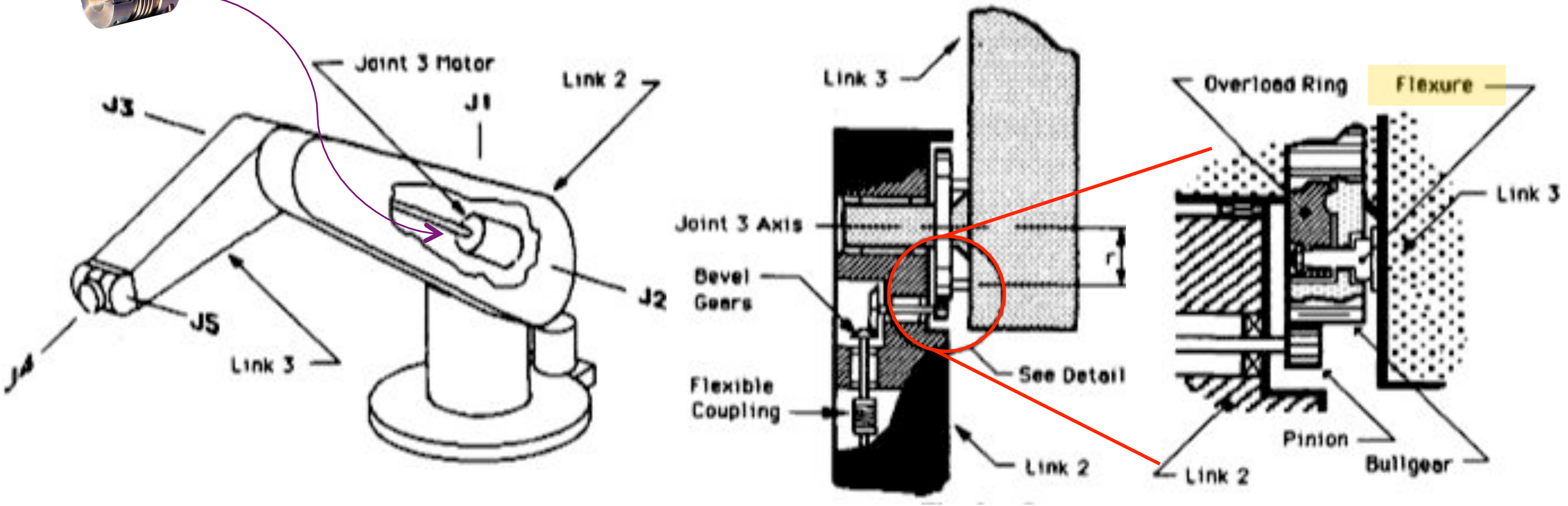


7 strain gauges glued[1] to a flexible aluminum beam (a robot "link") measuring its local "curvature" in dynamic bending during slew motions (a proprioceptive use of these sensors)

[1] by cyanoacrylic glue

# Torque sensor at robot joints

use of flexible *bellow couplings*
for aligning motors and long shafts

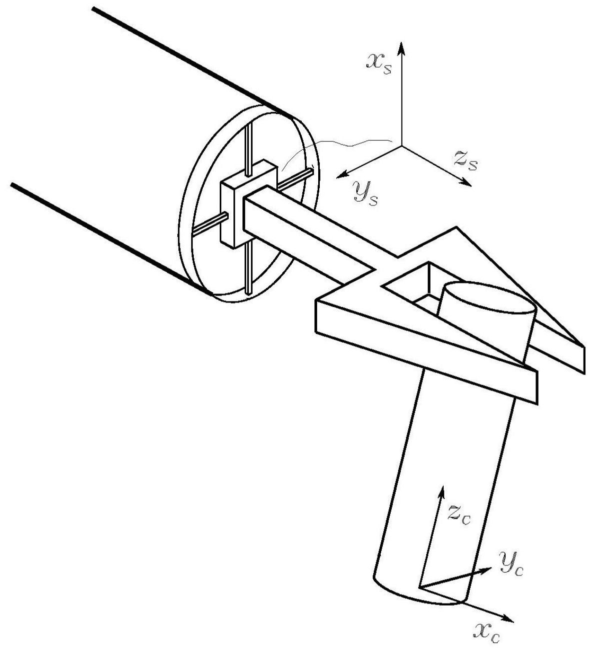


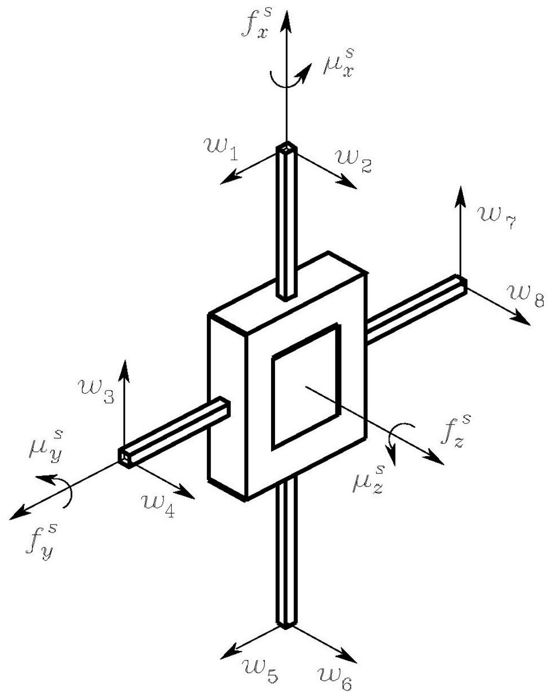

strain gauge mounted to "sense" the axial deformation
of the transmission shaft of joint #3 (elbow) in a PUMA 500 robot
(again, a proprioceptive use of this sensor)

# Force/torque sensor at robot wrist

- a device (with the outer form of a cylinder), typically located between the last robot link and its end-effector
- top and bottom plates are mechanically connected by a number of deformable elements subject to strain under the action of forces and moments
- there should be at least one such element in any direction along/around which a force or torque measure is needed
- since a complete "decoupling" of these measurements is hard to obtain, there are $N > 6$ such deformable elements
- on each element, a pair of strain gauges is glued so as to undergo opposite deformations (e.g., traction/compression) along the main axis of measurement

# Maltese-cross configuration




- diameter ≈ 10 cm
- height ≈ 5 cm
- 50÷500 N (resolution 0.1%)
- 5÷70 Nm (resolution 0.05%)
- sample frequency ≈ 1 KHz

- 4 deformable elements
- two pair of strain gauges are mounted on opposite sides of each element (8 pairs)
- the two gauges of each pair are placed adjacent on the same Wheatstone bridge

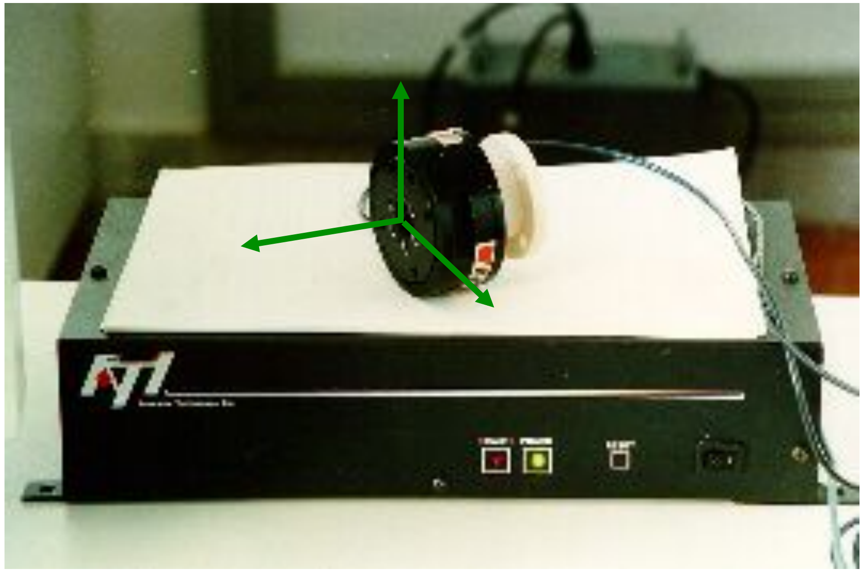
# 6D force/torque sensors

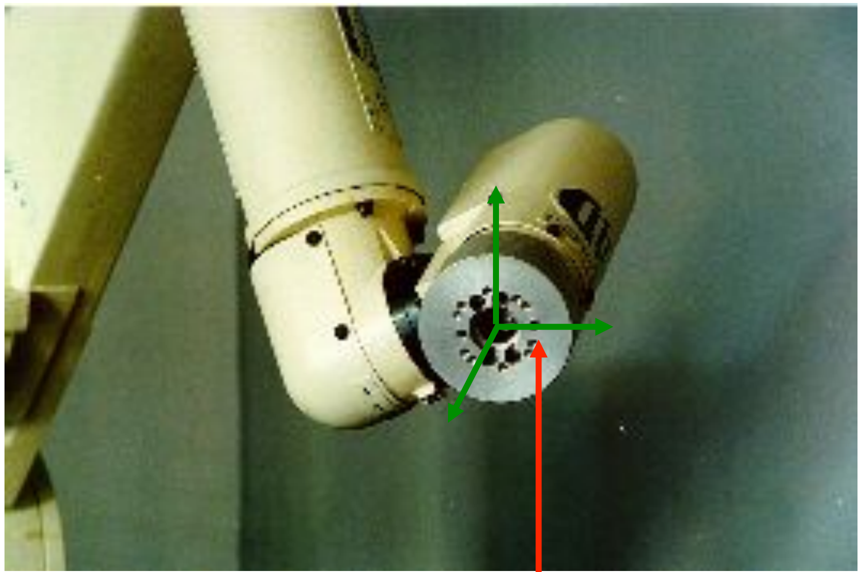
- ATI series
  - cost: about 5 K€ for the Gamma model

| Model | Max Fx,Fy* | Max Tx,Ty* | Weight** | Diameter** | Height** |
|---|---|---|---|---|---|
| Nano17 | ±50 N | ±500 N-mm | 0.0091 kg | 17 mm | 14 mm |
| Nano25 | ±250 N | ±6 N-m | 0.064 kg | 25 mm | 22 mm |
| Nano43 | ±36 N | ±500 N-mm | 0.041 kg | 43 mm | 11 mm |
| Mini40 | ±80 N | ±4 N-m | 0.05 kg | 40 mm | 12 mm |
| Mini45 | ±580 N | ±20 N-m | 0.091 kg | 45 mm | 16 mm |
| Gamma | ±130 N | ±10 N-m | 0.25 kg | 75 mm | 33 mm |
| Delta | ±660 N | ±60 N-m | 0.91 kg | 94 mm | 33 mm |
| Theta | ±2500 N | ±400 N-m | 5 kg | 150 mm | 61 mm |
| Omega160 | ±2500 N | ±400 N-m | 2.7 kg | 160 mm | 56 mm |
| Omega190 | ±7200 N | ±1400 N-m | 6.4 kg | 190 mm | 56 mm |

# 6D force/torque sensor

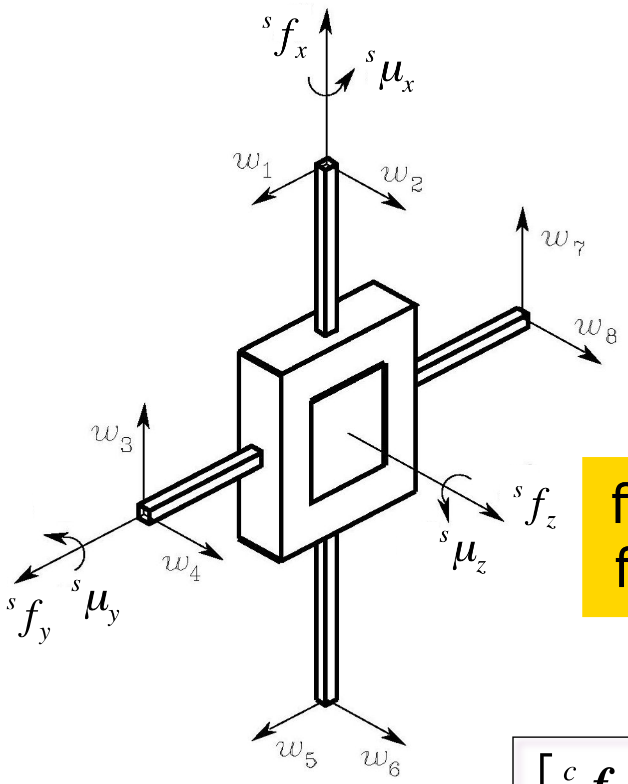
- electronic processing unit and mounting on an industrial robot (Comau Smart 3 robot, 6R kinematics)





mounting flange
(on link 6 of the manipulator arm)

# 6D F/T sensor calibration




$$\begin{bmatrix} ^s f_x \\ ^s f_y \\ ^s f_z \\ ^s \mu_x \\ ^s \mu_y \\ ^s \mu_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_{13} & 0 & 0 & 0 & c_{17} & 0 \\ c_{21} & 0 & 0 & 0 & c_{25} & 0 & 0 & 0 \\ 0 & c_{32} & 0 & c_{34} & 0 & c_{36} & 0 & c_{38} \\ 0 & 0 & 0 & c_{44} & 0 & 0 & 0 & c_{48} \\ 0 & c_{52} & 0 & 0 & 0 & c_{56} & 0 & 0 \\ c_{61} & 0 & c_{63} & 0 & c_{65} & 0 & c_{67} & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \\ w_8 \end{bmatrix}$$

force/torque measured in the frame attached to the sensor

calibration matrix

output of Wheatstone bridges

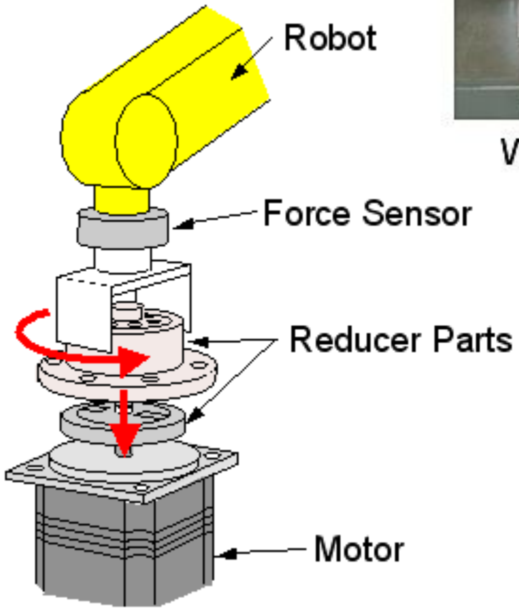
$$\begin{bmatrix} ^c \boldsymbol{f}_c \\ ^c \boldsymbol{\mu}_c \end{bmatrix} = \begin{bmatrix} ^c \boldsymbol{R}_s & \boldsymbol{O} \\ \boldsymbol{S}(^c \boldsymbol{r}_{cs})\, ^c \boldsymbol{R}_s & ^c \boldsymbol{R}_s \end{bmatrix} \begin{bmatrix} ^s \boldsymbol{f}_s \\ ^s \boldsymbol{\mu}_s \end{bmatrix}$$

transformation from the sensor frame to the load/contact frame (at TCP)

# Typical uses of a F/T sensor

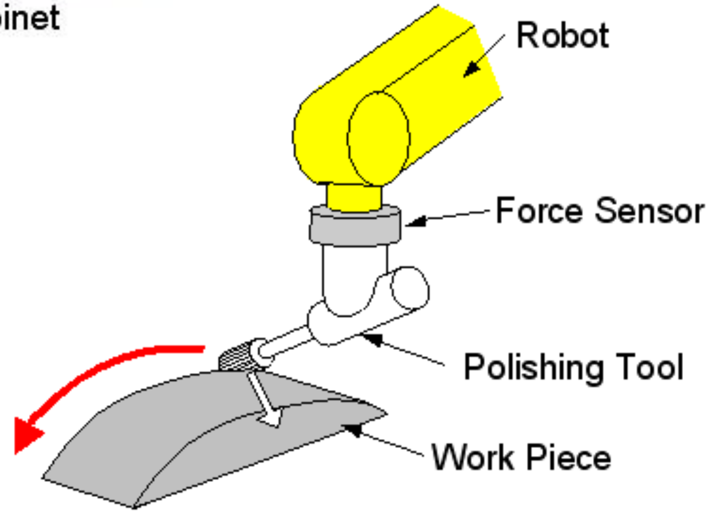
Washstand

Metal Cabinet




Phase matching by force sensing

Gear Parts

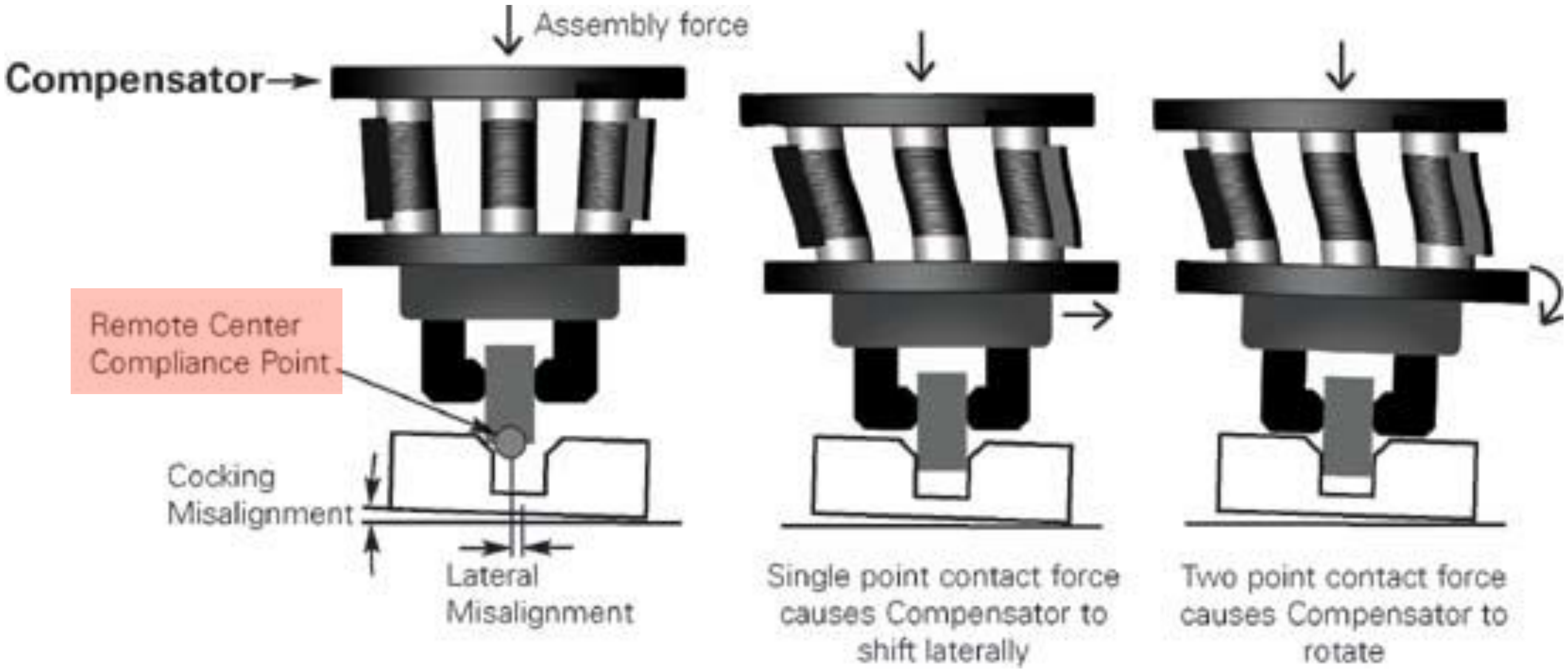



Following with constant pushing force

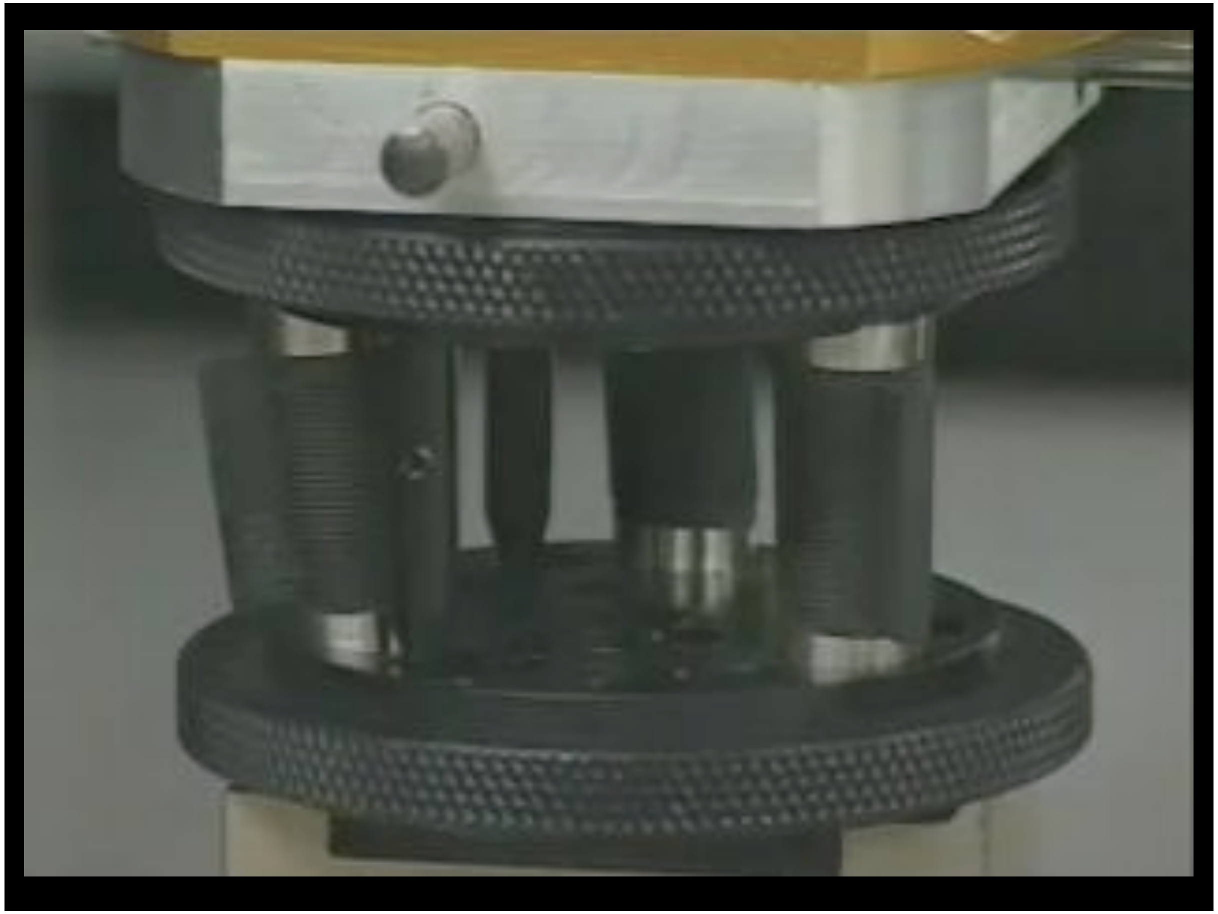
# Passive RCC device

- RCC = Remote Center of Compliance
- placed on the wrist so as to introduce passive "compliance" to the robot end-effector, in response to static forces and moments applied from the environment at the contact area
- mechanical construction yields "decoupled" linear/angular motion responses if contact occurs at or near the RCC point

# Assembly with RCC



# Passive assembly with RCC



video

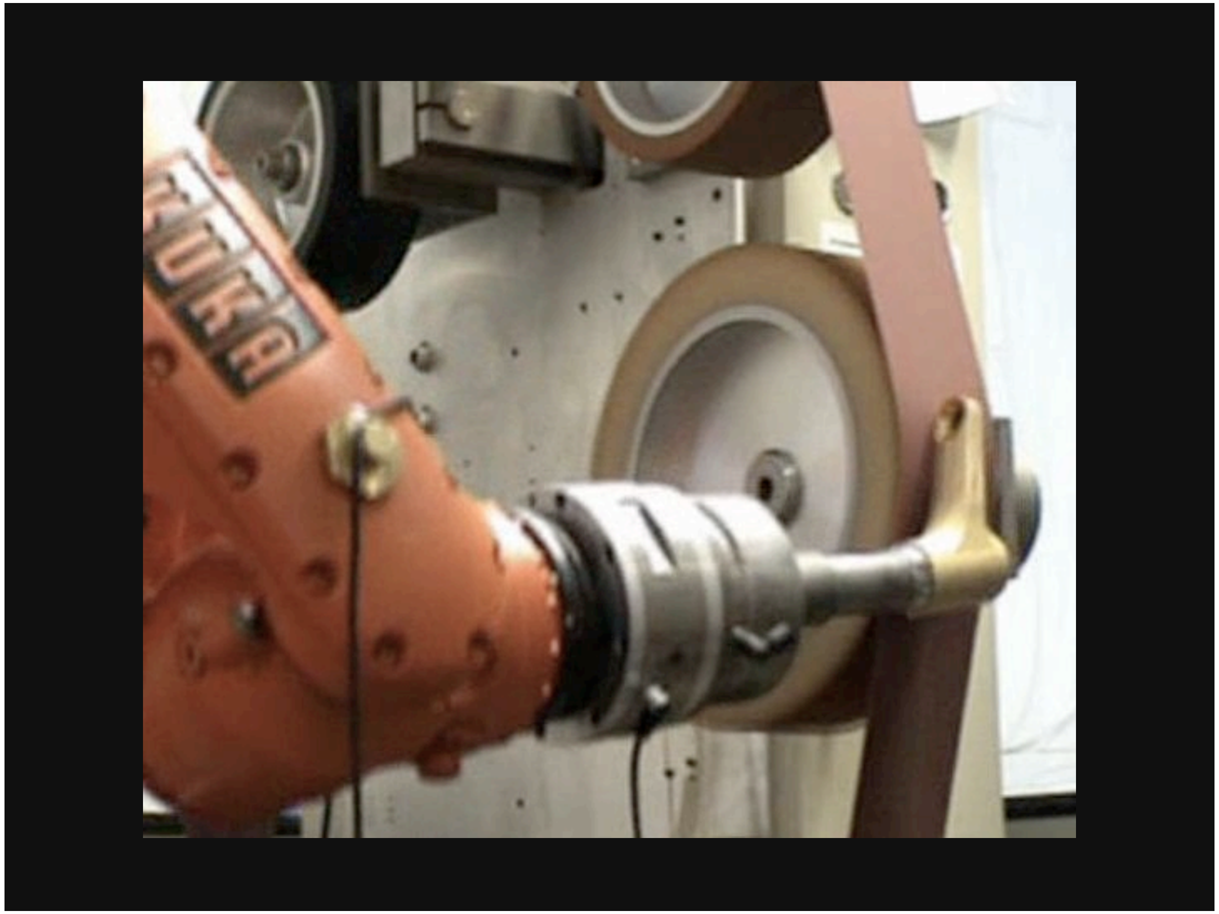
RCC by ATI Industrial Automation
http://www.ati-ia.com

# Active assembly with F/T sensor

video

ABB robot with ATI F/T sensor

# Surface finishing with F/T sensor

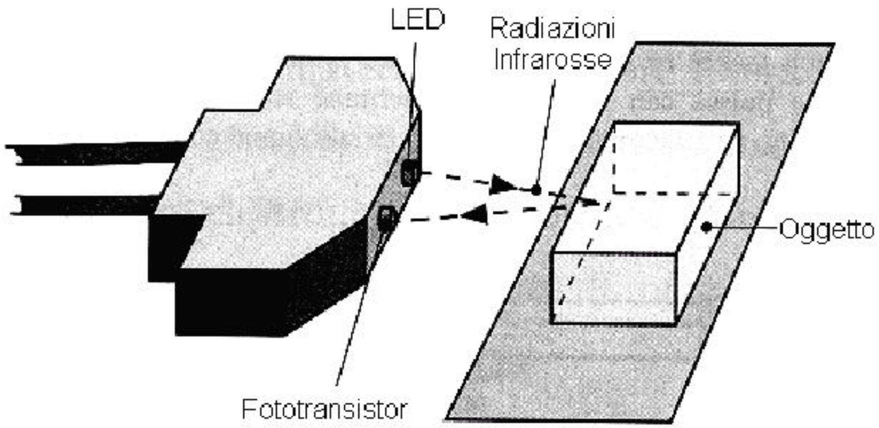



video

KUKA robot with F/T sensor

# Proximity/distance sensors - 1

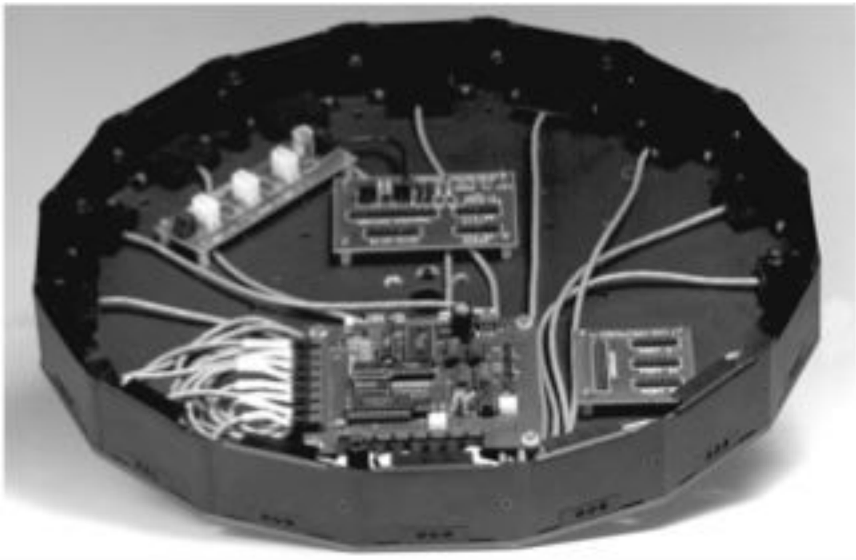
- infrared: a light source (LED) emitting a ray beam (at 850±70 nm) which is then captured by a receiver (photo-transistor), after reflection by an object
- received intensity is related to distance
  - narrow emitting/receiving angle; use only indoor; reflectance varies with object color
- typical sensitive range: 4÷30 cm or 20÷150 cm
- cost: 15 €



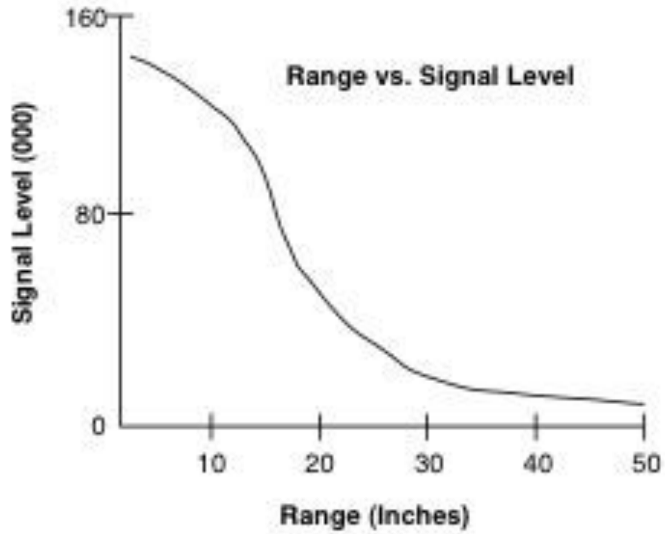

IR sensor
SHARP GP2

# Infrared sensor

example: Sensus 300
on Nomad 200 mobile robot
(power data: 500 mA at 12 V)



ring with 16 IR sensors

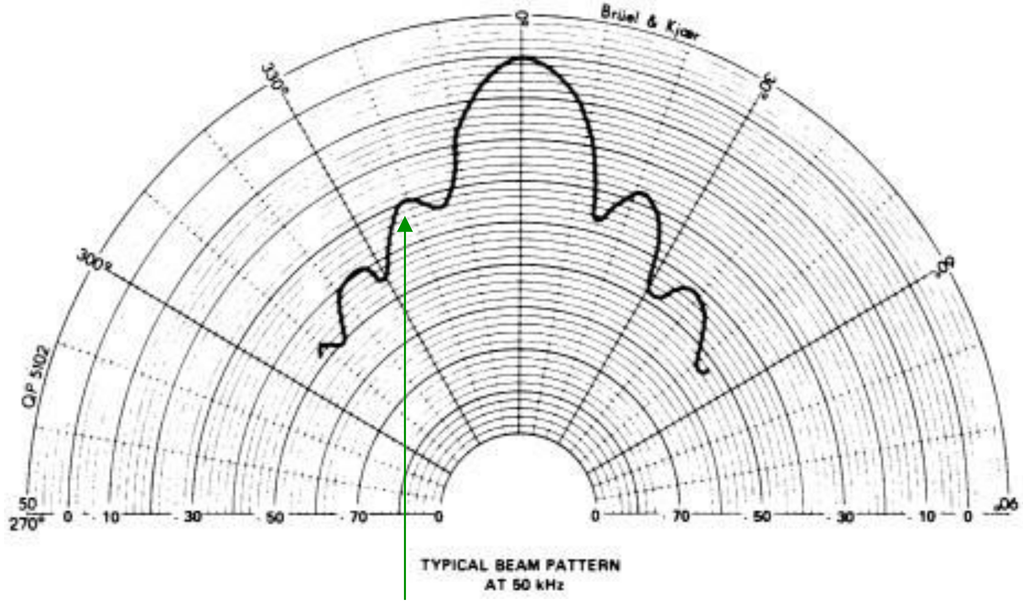



variation of received signal level
as a function of distance

# Proximity/distance sensors - 2

- ultrasound: use of sound wave propagation and reflection (at > 20 kHz, mostly 50 kHz), generated by a piezoelectric transducer excited by alternate voltage ($V \sin \omega t$)
- distance is proportional to the Time-Of-Flight (TOF) along the sensor-object-sensor path

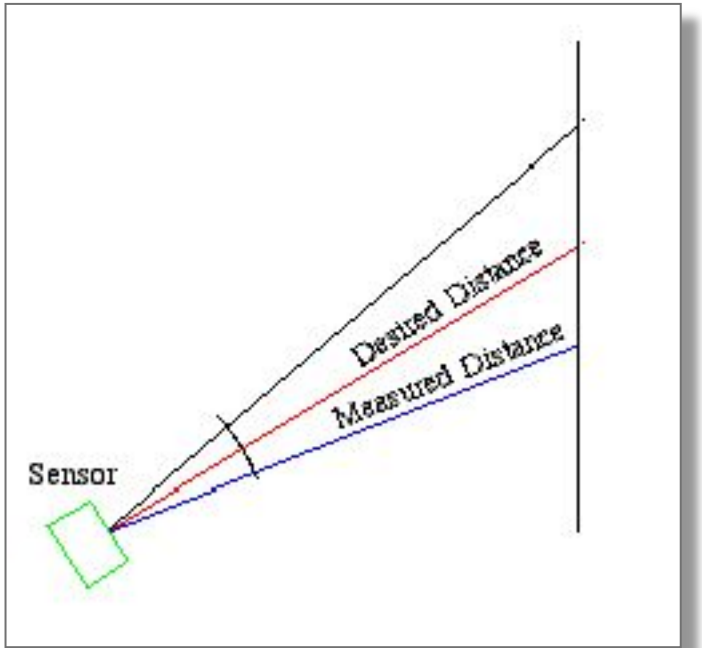
wave emitting angle ≈ 30° allows to detect also obstacles located slightly aside from the front direction (but with uncertainty on their angular position)

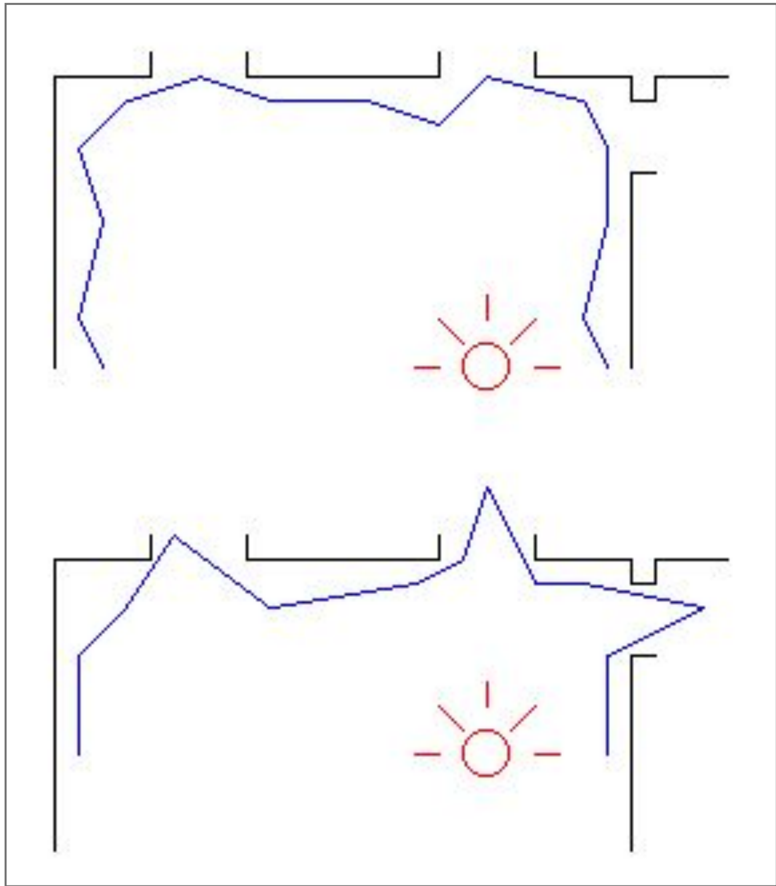



energy lobes

# Ultrasound sensor

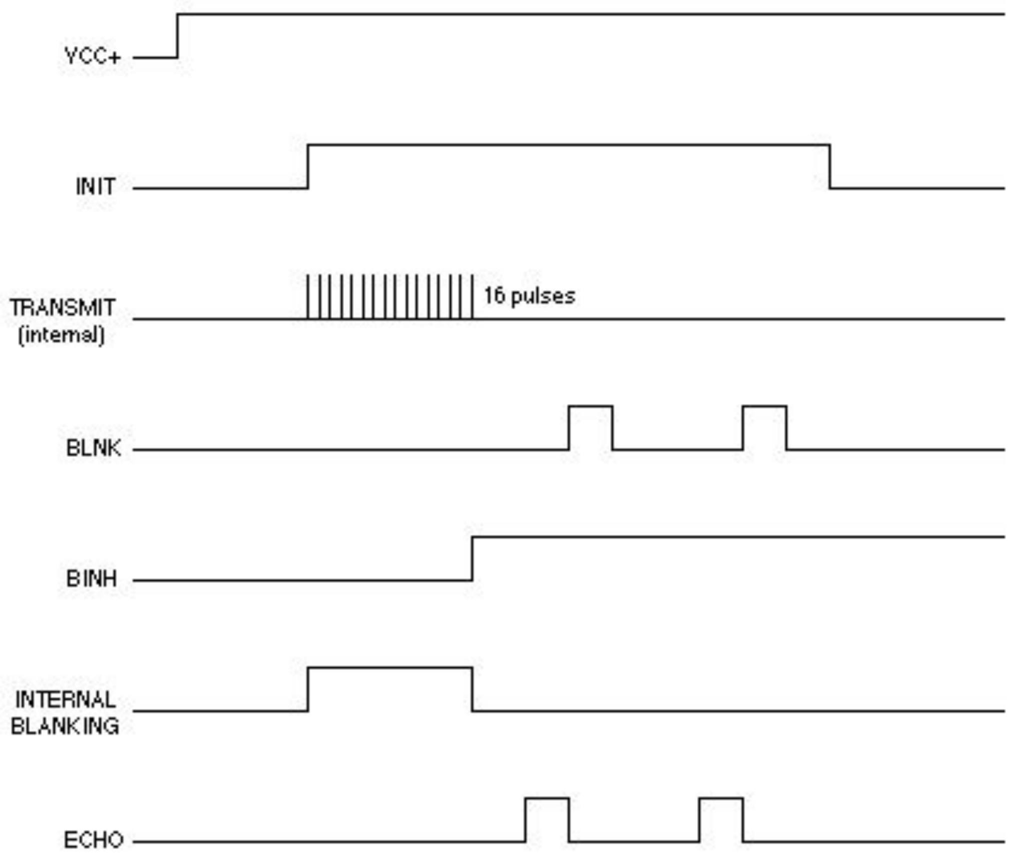
some problems related to US wave propagation



multiple reflections/echoes
absorbing surfaces
mirroring surfaces

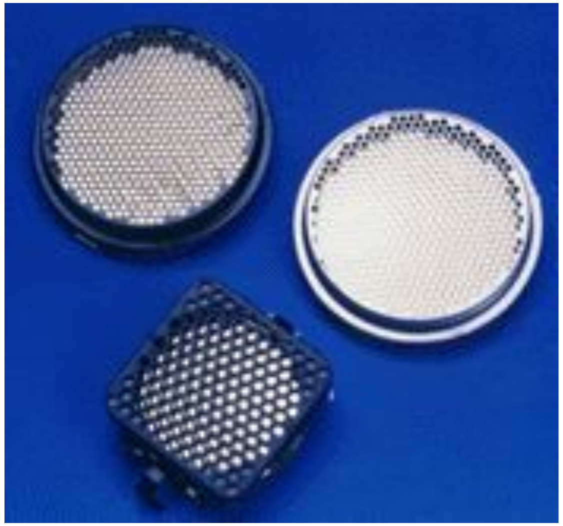
# Range limits for US sensors

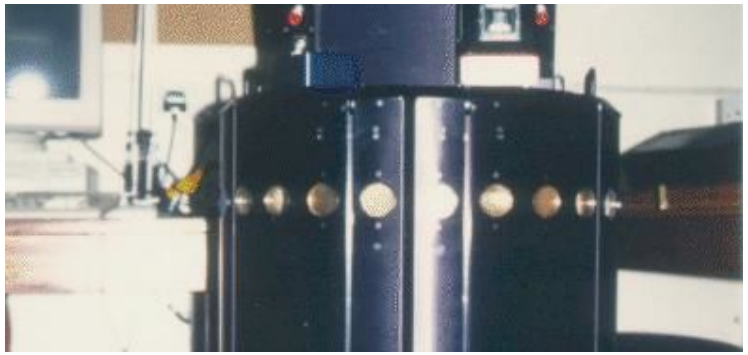



- during US pulses transmission the receiver is disabled, so as to avoid interferences that may lead to false readings
- the same is done after receiving the first echo, so as to avoid multiple reflections from the same object
- this limits the minimum distance that can be detected (> 0.5 m)
- due to angular dispersion during emission, wave energy decreases with $d^2$
- to compensate for this effect, the gain of the receiver is increased over time (up to a limit)
- max detectable distance ≈ 6.5 m

# Polaroid ultrasound sensor

- complete “kit” with trans-receiver and circuitry
- 3.5 ms of TOF for a front obstacle placed at 60 cm of distance
- range: 0.5÷2.5 m
- cost: < 30 €
- typical circular mounting of 16-32 US sensors (with a suitable sequence of activation)



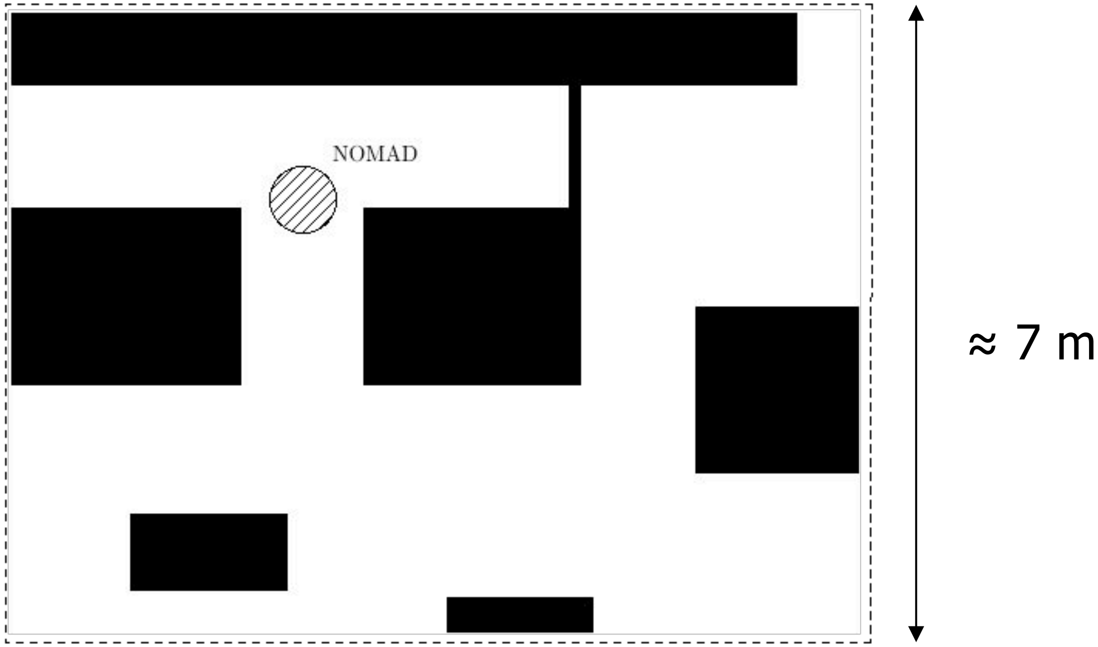


Polaroid USP3

Migatron RPS 409

# Navigation with ultrasound sensing

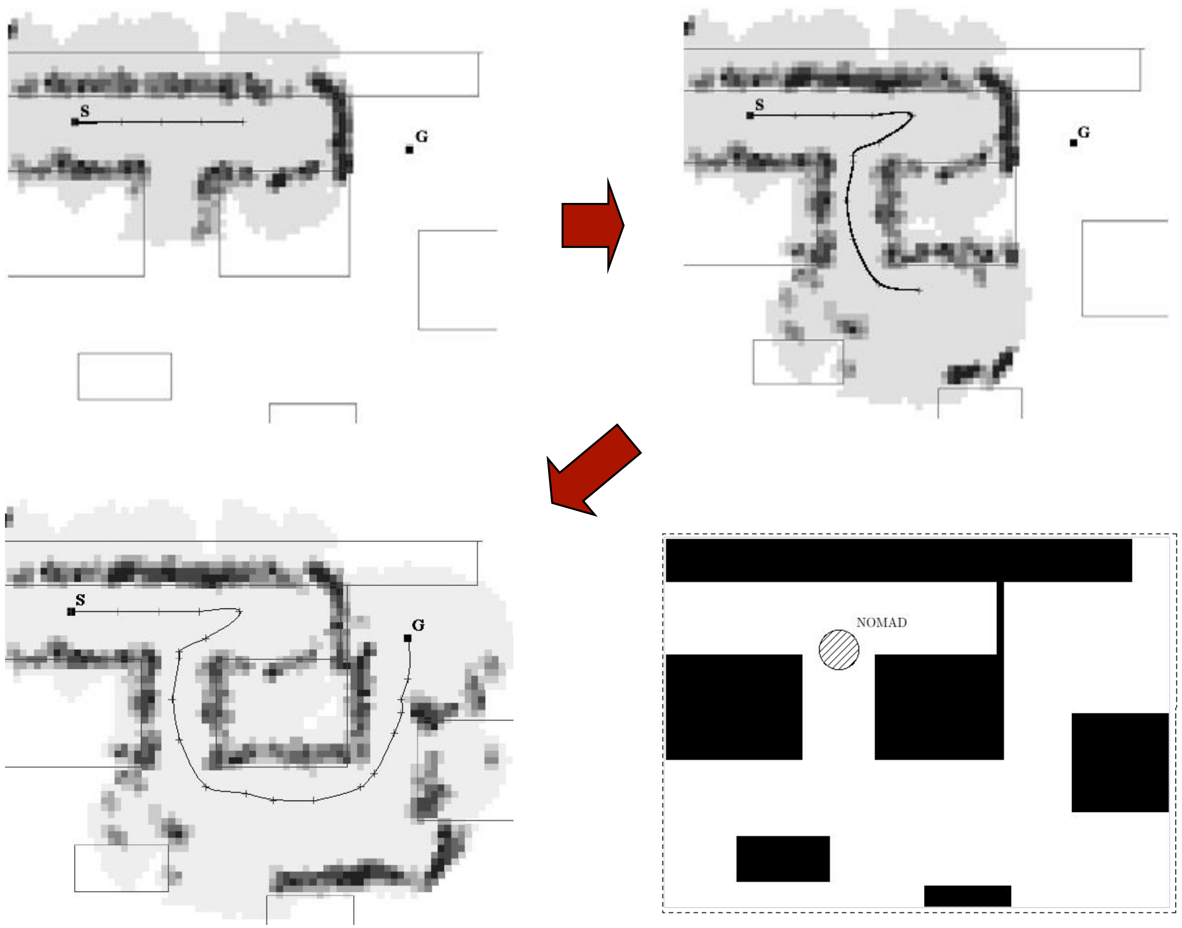
- Nomad 200 with 16 US sensors (plus other not used here)




view of the robot and map of the former DIS Robotics Lab in Via Eudossiana 18
(the map is initially unknown to the robot)

# Navigation with ultrasound sensing

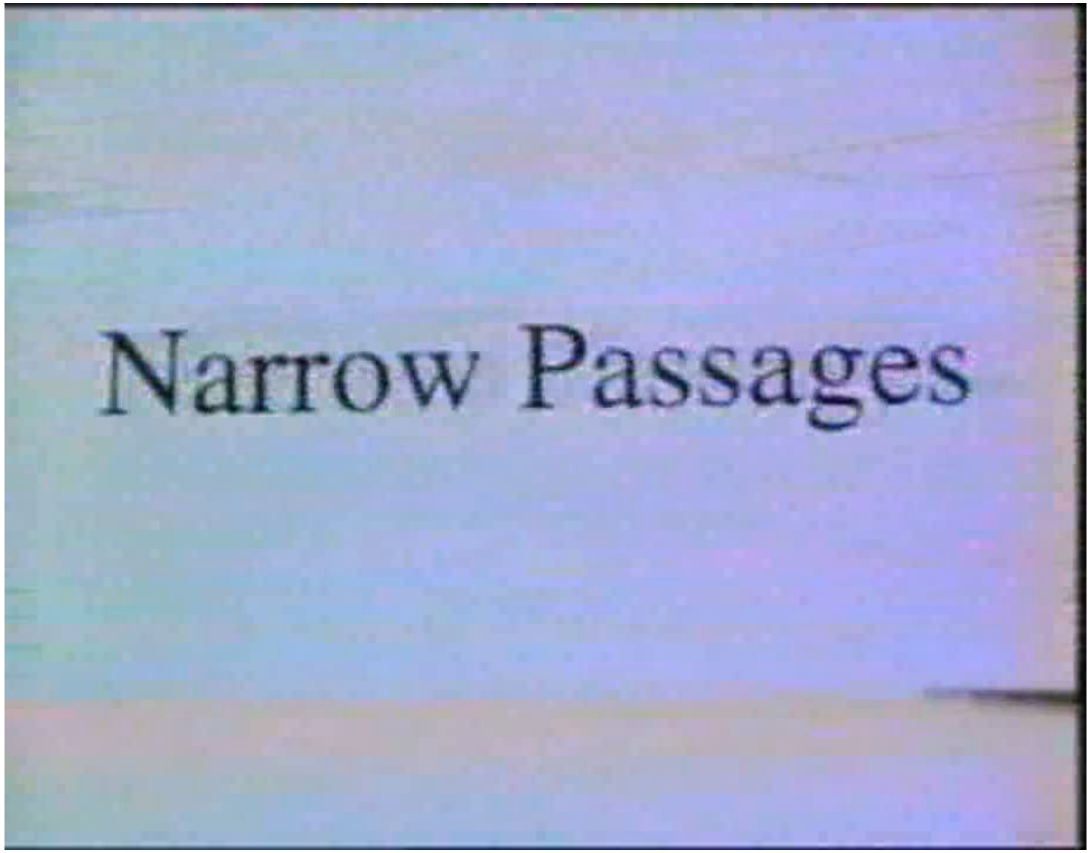
- grid map (unit = 10 cm) obtained by weighting successive data readings from US sensors with fuzzy logic; "aggressive" motion planning with A* search algorithm on graphs; reactive US-based navigation to avoid unexpected obstacles




comparison with the true map

# Narrow passages

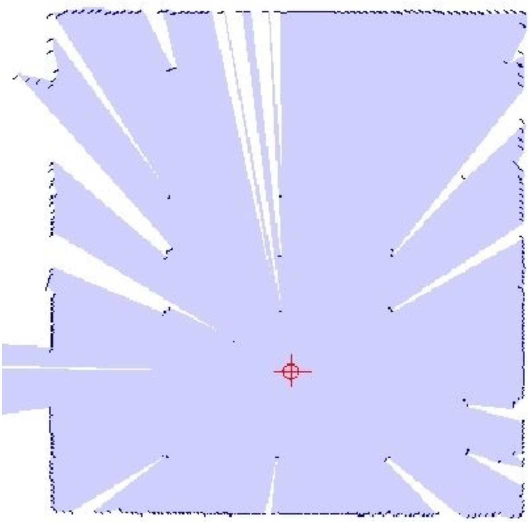
- Nomad 200 navigating with 16 ultrasonic sensors (old Robotics Lab, 1995)




video

# Proximity/distance sensors – 3

- laser scanner: two-dimensional scan of the environment with a radial field of infrared laser beams (laser radar)
  - time between transmission and reception is directly proportional to the distance to the object (Time-of-Flight)

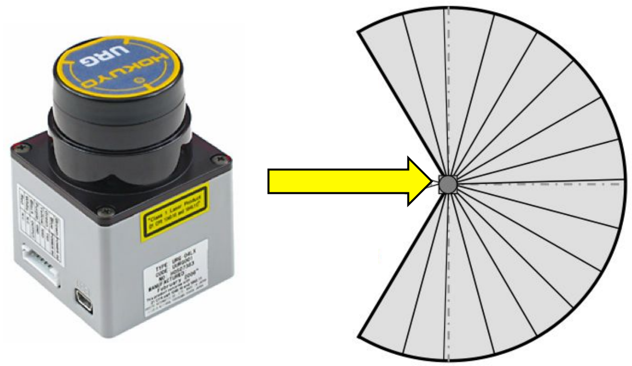


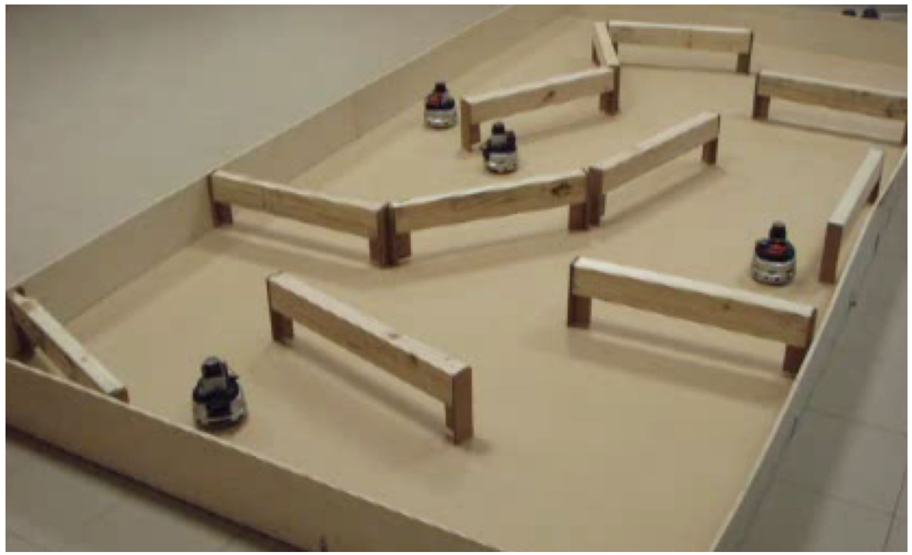
- Sick LMS 200
  - wide angular range: max 180°
  - high angular resolution: 0.25°-0.5°-1°(can be set by user)
  - response time: 53-26-13 msec (depending on resolution)
  - large range: 10 m up to 50÷80 m
  - depth resolution: ±15 mm
  - interface: RS-232, RS-422
  - used to be quite expensive (about 5000 €, this model now discontinued)


weight: 4.5 kg

# A smaller laser scanner

- Hokuyo URG-04X
  - size: 50×50×70 mm
  - weight: 160 g
  - angular range: max 240°
  - angular resolution: 0.36°
  - response: 100 msec/scan
  - range: 0.02÷4 m
  - depth resolution:
    ±1 cm (up to 1 m)
    ±1% (beyond 1 m)
  - interface: RS-232, USB 2.0
  - supply: 5V DC
  - cost: 900 € (1140 US$)
    - 2 years ago was 1750 € ...

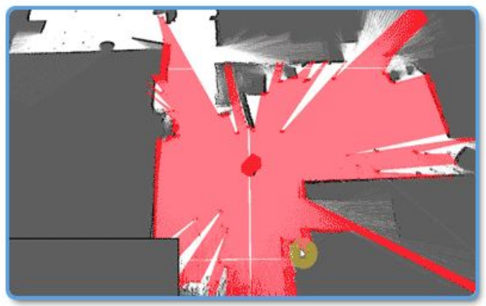




4 small Khepera with Hokuyo sensors
@ DIAG Robotics Lab

# Rotating laser scanner

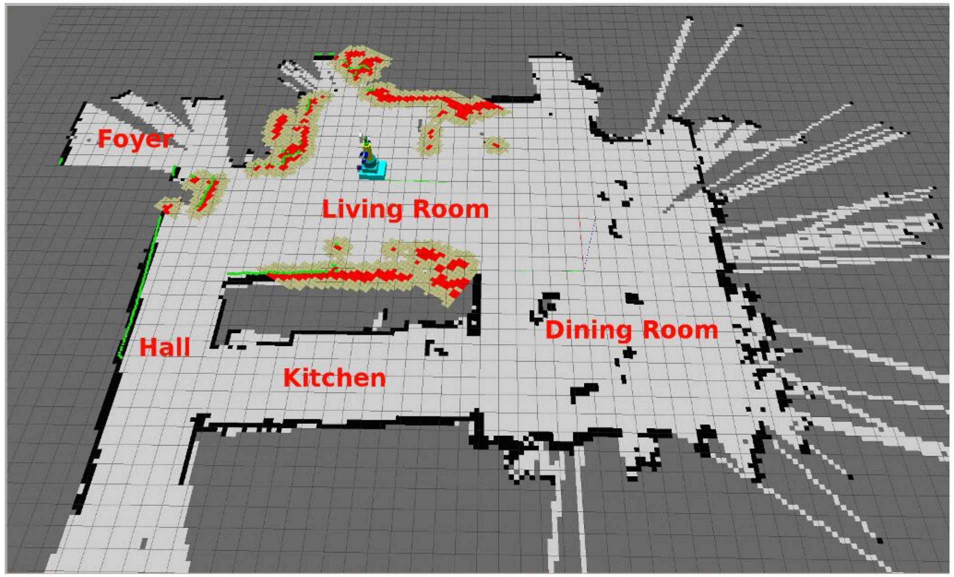
- RoboPeak RPLidar A1M1
  - 360° 2D-scan, 6 m measurement range
  - size: 70×98.5×60 mm
  - weight: 200 g
  - variable scanning rate: 2÷10 Hz
    - by varying the motor PWM signal
  - angular resolution: ≈ 1° @5.5 Hz rate
    - 2000 samples/s @5.5 Hz rate
  - depth resolution: ±20 mm (0.2% of current depth)
  - cost: 315 € (399 US$) in development kit
  - ROS & SLAM ready

Realtime ICP-SLAM based on RPLIDAR

# Localization and mapping

- SLAM (Simultaneous Localization and Mapping) with a laser scanning sensor mounted on a mobile robot




- An "extended" state estimation problem: determine at the same time
  I. a map of the environment (sometimes, of its "landmarks" only)
  II. the robot location within the map

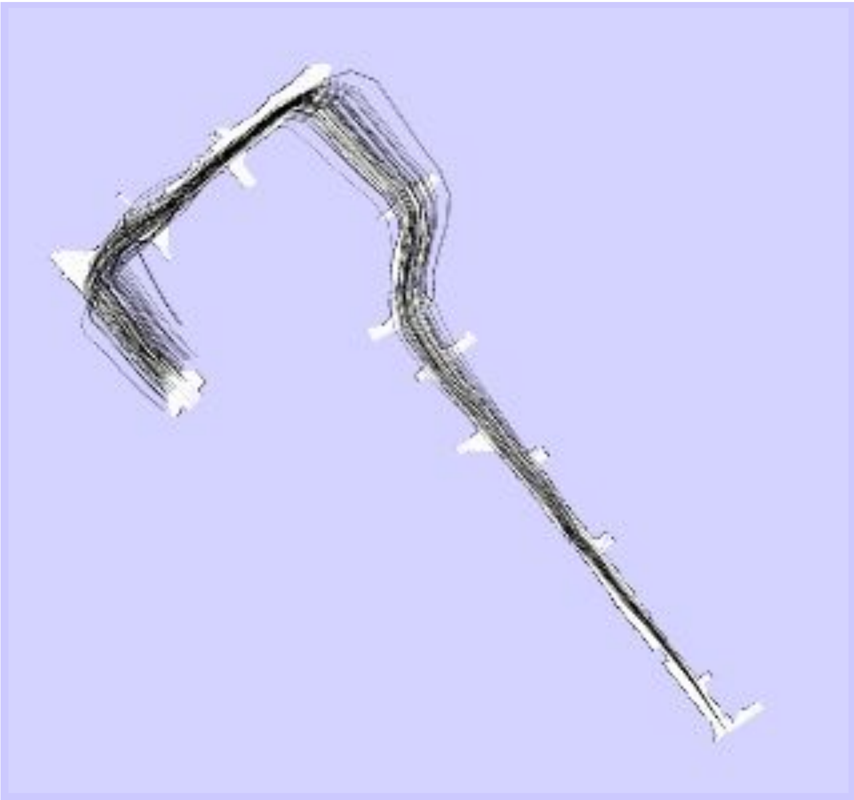
  using an incremental, iterative measurement process (large scale data)

# Localization and mapping

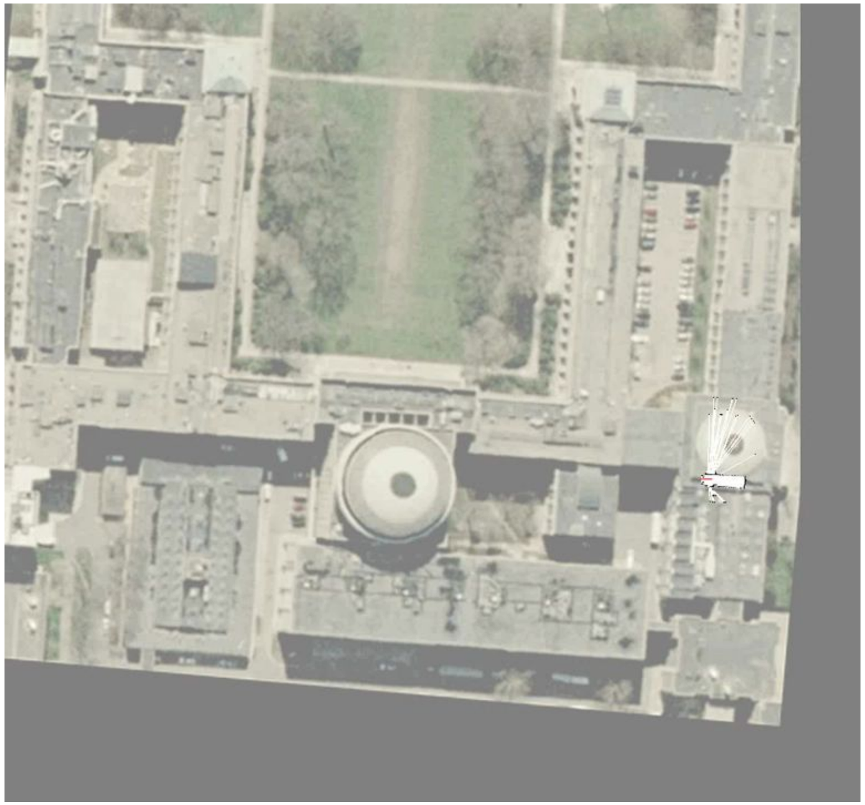
illustrating the benefit of "loop closure" on long range data (map correction)

video

video



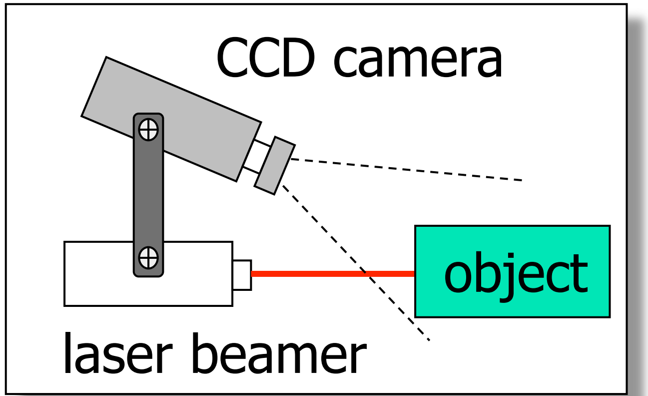
single loop



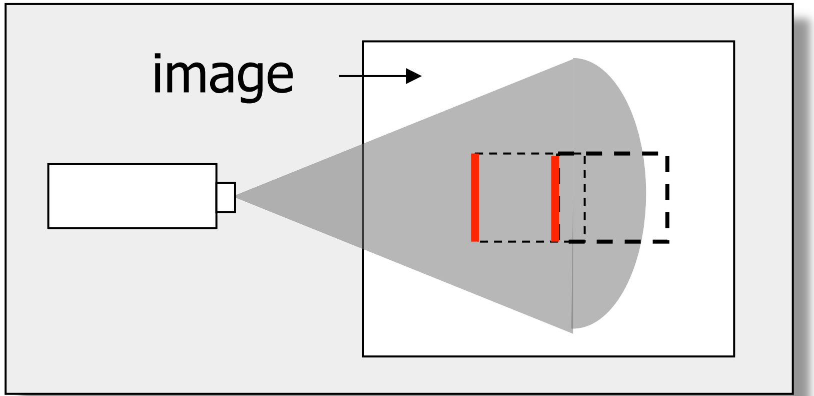
multiple loops (MIT Campus)

# Proximity/distance sensors - 4

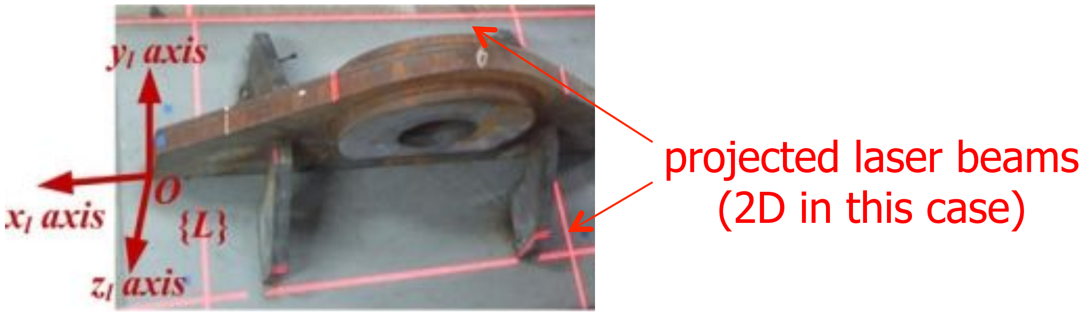
- structured light: a laser beam (coherent light source) is projected on the environment, and its planar intersection with surrounding objects is detected by a (tilted) camera
- the position of the "red pixels" on the camera image plane is in trigonometric relation with the object distance from the sensor




side view

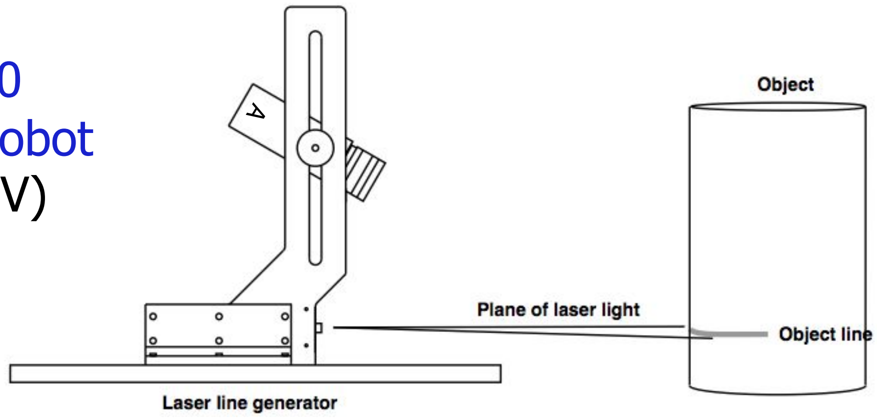


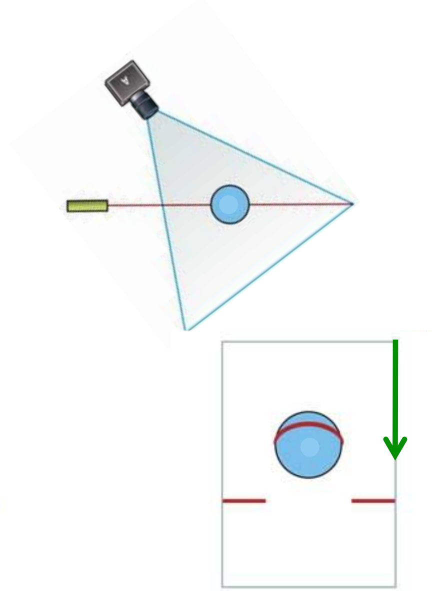

top view



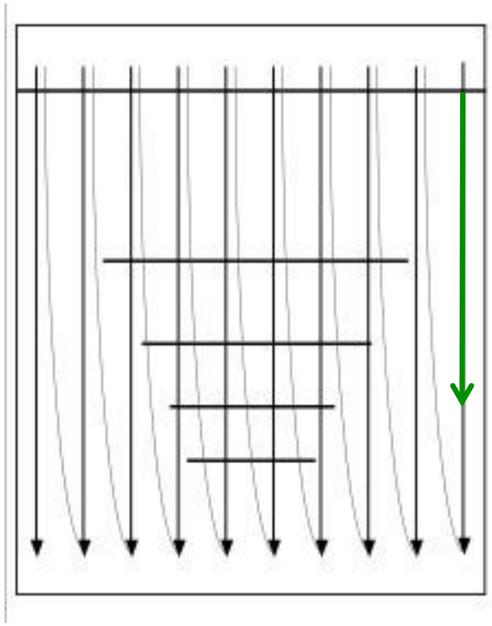
# Structured light sensor

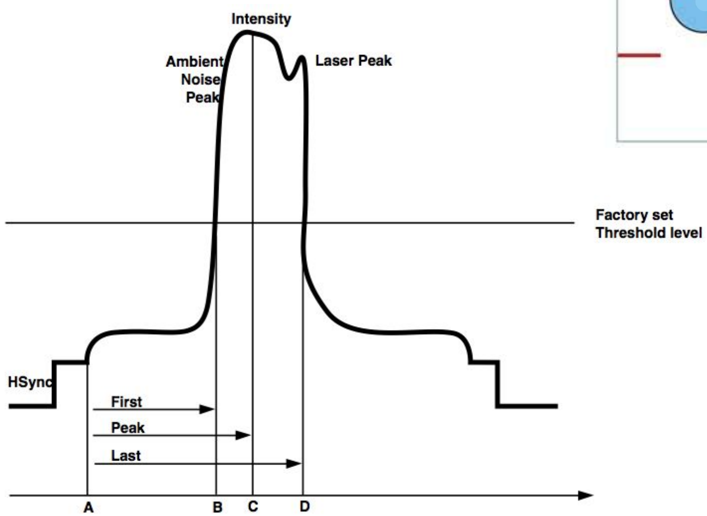
example: Sensus 500
on Nomad 200 mobile robot
(power data: 2A @12V)



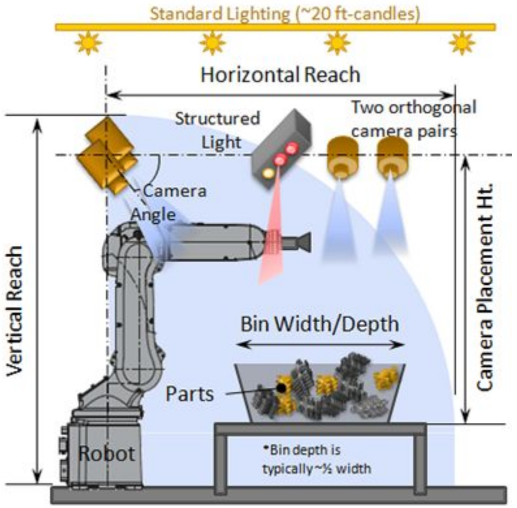
CCD camera with 510×490 pixels (rotated by 90° with respect to the 480 scan lines)



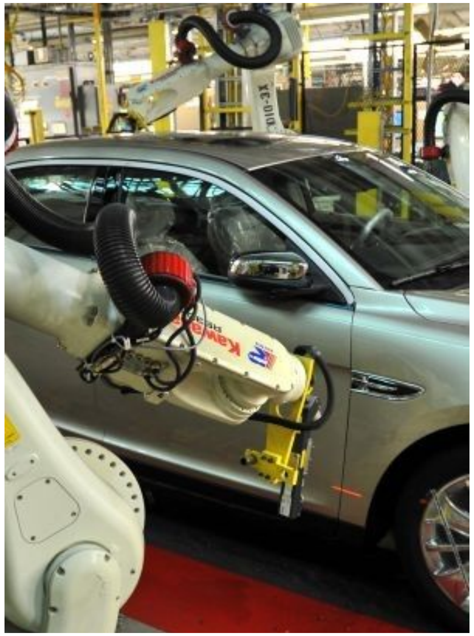



analog signal along a single scan line
with threshold level ⇒ 4 bytes of data:
pixels FIRST, LAST, PEAK; value INTENSITY

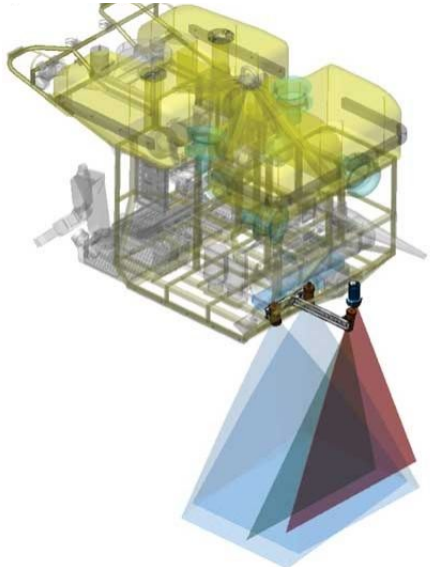
# Use of structured light sensors

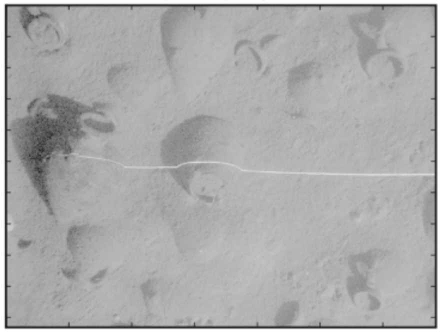



Random bin picking of 10-30 parts/minute (with surface inspection) with a 6R industrial robot, two pairs of cameras and a structured light sensor [Universal Robotics]



Structured light approach to best fit and finish car bodies (down to 0.1 mm) for reducing wind noise [Ford Motor Co.]

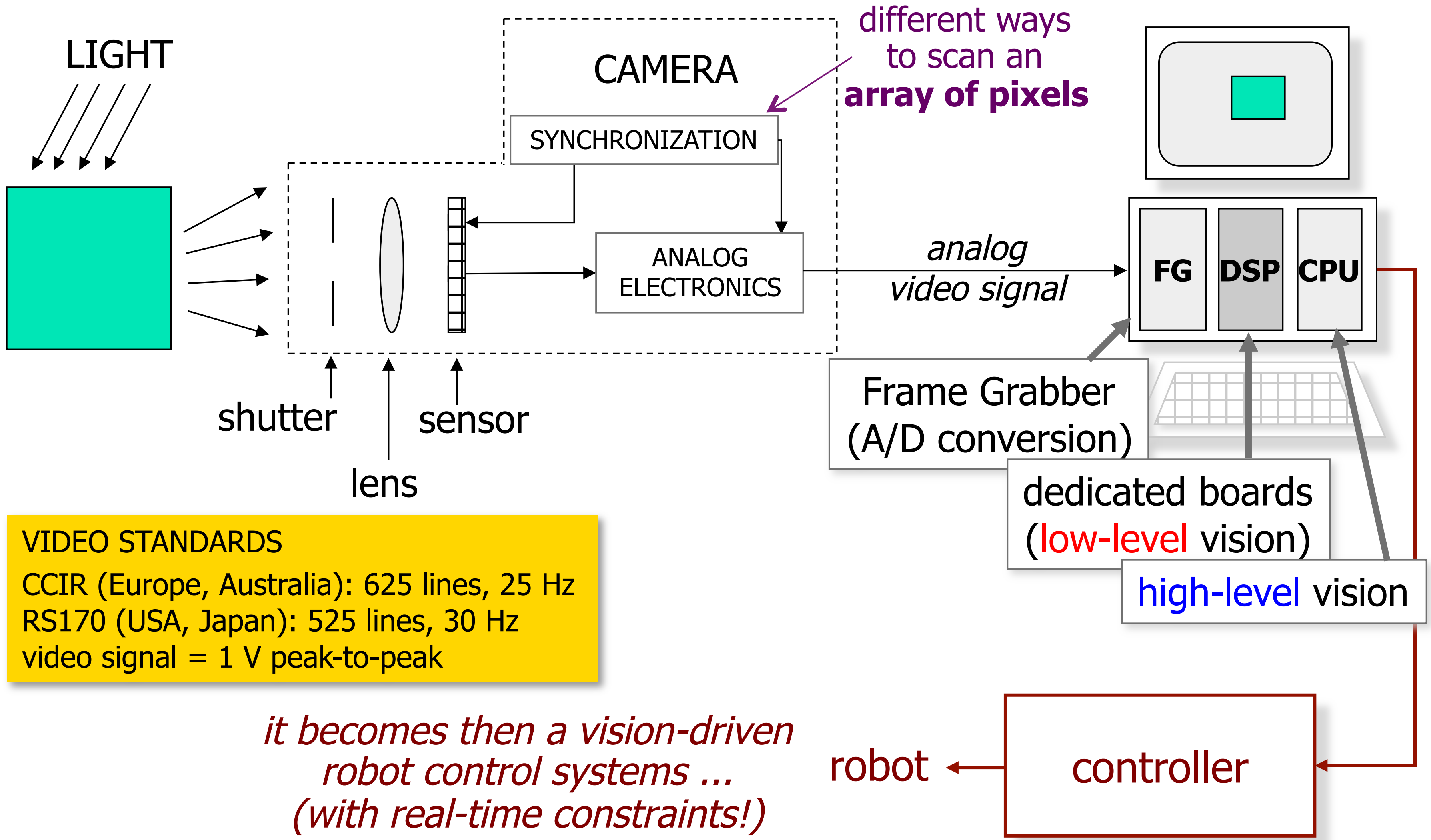




Hercules ROV + structured-laser-light imaging system for high-resolution bathymetric underwater maps [Univ. Rhode Island]

Virtobot system for post-mortem 3D optical scanning of human body & image-guided needle placement [Univ. Zürich]

# Vision systems

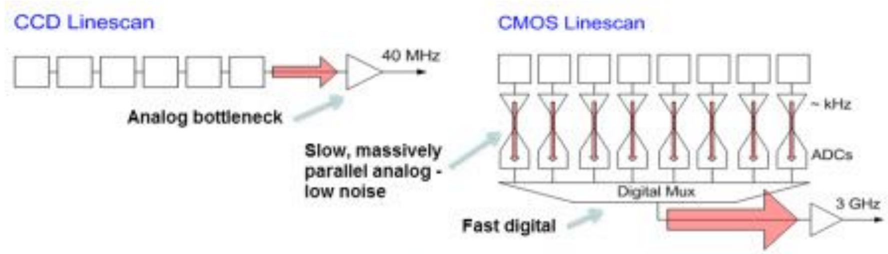



VIDEO STANDARDS
CCIR (Europe, Australia): 625 lines, 25 Hz
RS170 (USA, Japan): 525 lines, 30 Hz
video signal = 1 V peak-to-peak

*it becomes then a vision-driven robot control systems ... (with real-time constraints!)*

# Sensors for vision

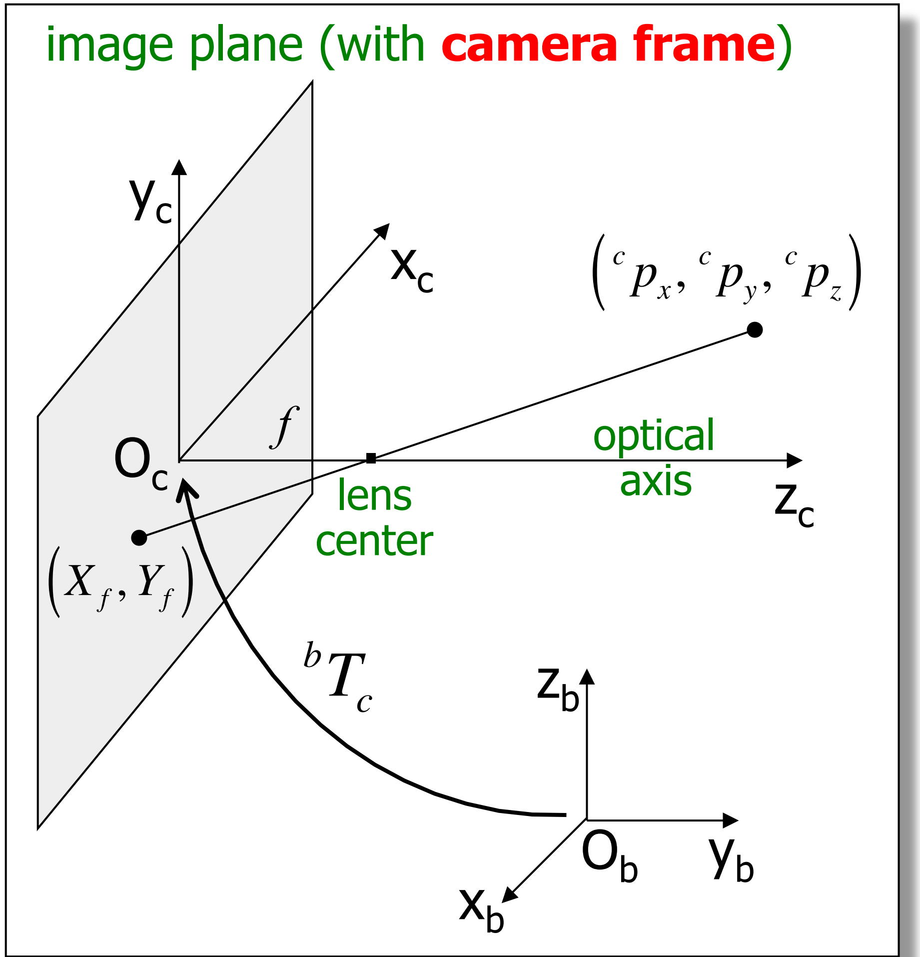
- arrays (spatial sampling) of photosensitive elements (pixel) converting light energy into electrical energy
- CCD (Charge Coupled Device): each pixel surface is made by a semiconductor device, accumulating free charge when hit by photons (photoelectric effect); these "integrated" charges are "read-out" by a sequential process (external circuitry) and transformed into voltage levels
- CMOS (Complementary Metal Oxide Semiconductor): each pixel is a photodiode, directly providing a voltage or current proportional to the instantaneous light intensity, with the possibility of random access to each pixel



# CMOS versus CCD

- reduction of fabrication costs of CMOS imagers
- better spatial resolution of elementary sensors
  - CMOS: 1M pixel, CCD: 768×576 pixel
- faster processing speed
  - 1000 vs. 25 fps (frames per second)
- possibility of integrating "intelligent" functions on single chip
  - sensor + frame grabber + low-level vision
- random access to each pixel or area
  - flexible handling of ROI (Region Of Interest)
- possibly lower image quality w.r.t. CCD imagers
  - sensitivity, especially for applications with low S/N signals
- customization for small volumes is more expensive
  - CCD cameras since much longer on the market

# Perspective transformation




**1. in metric units**

$$X_f = \frac{f\,{}^c p_x}{f - {}^c p_z} \qquad Y_f = \frac{f\,{}^c p_y}{f - p_z^c}$$

**2. in pixel**

$$X_I = \frac{\alpha_x f\,{}^c p_x}{f - {}^c p_z} + X_0$$

$$Y_I = \frac{\alpha_y f\,{}^c p_y}{f - {}^c p_z} + Y_0$$

offsets of pixel coordinate system w.r.t. optical axis ($X_0$, $Y_0$)

pixel/metric scaling factor ($\alpha_x$, $\alpha_y$)

**3. LINEAR MAP in homogeneous coordinates**

$$X_I = \frac{x_I}{z_I} \quad Y_I = \frac{y_I}{z_I} \quad \Rightarrow \quad \begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \Omega \begin{bmatrix} {}^c p_x \\ {}^c p_y \\ {}^c p_z \\ 1 \end{bmatrix}$$

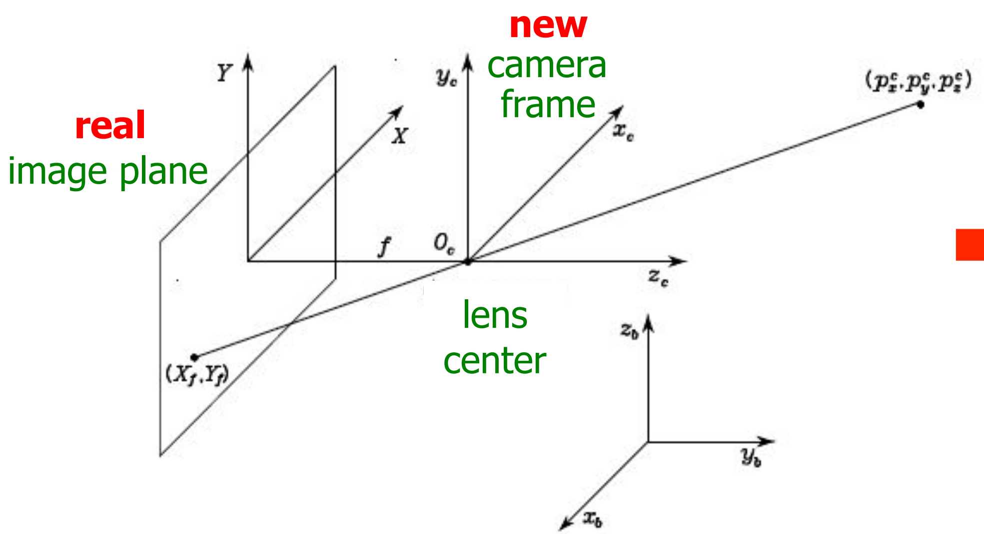
$$\Omega = \begin{bmatrix} \alpha_x & 0 & X_0 & 0 \\ 0 & \alpha_y & Y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/f & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

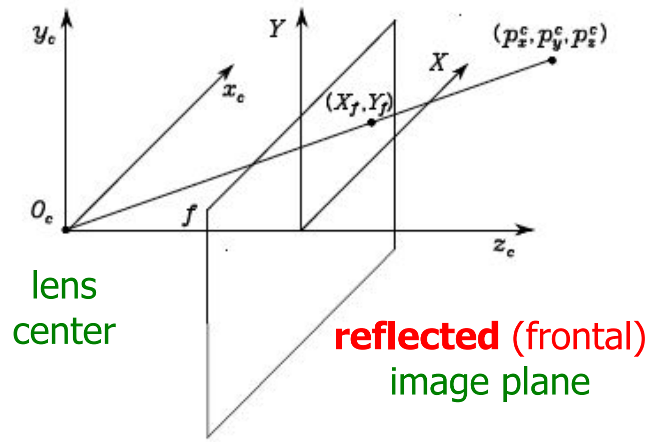
calibration matrix

$$H = \Omega\, {}^c T_b$$

intrinsic and extrinsic parameters

# Perspective transformation
## with camera frame at the lens center



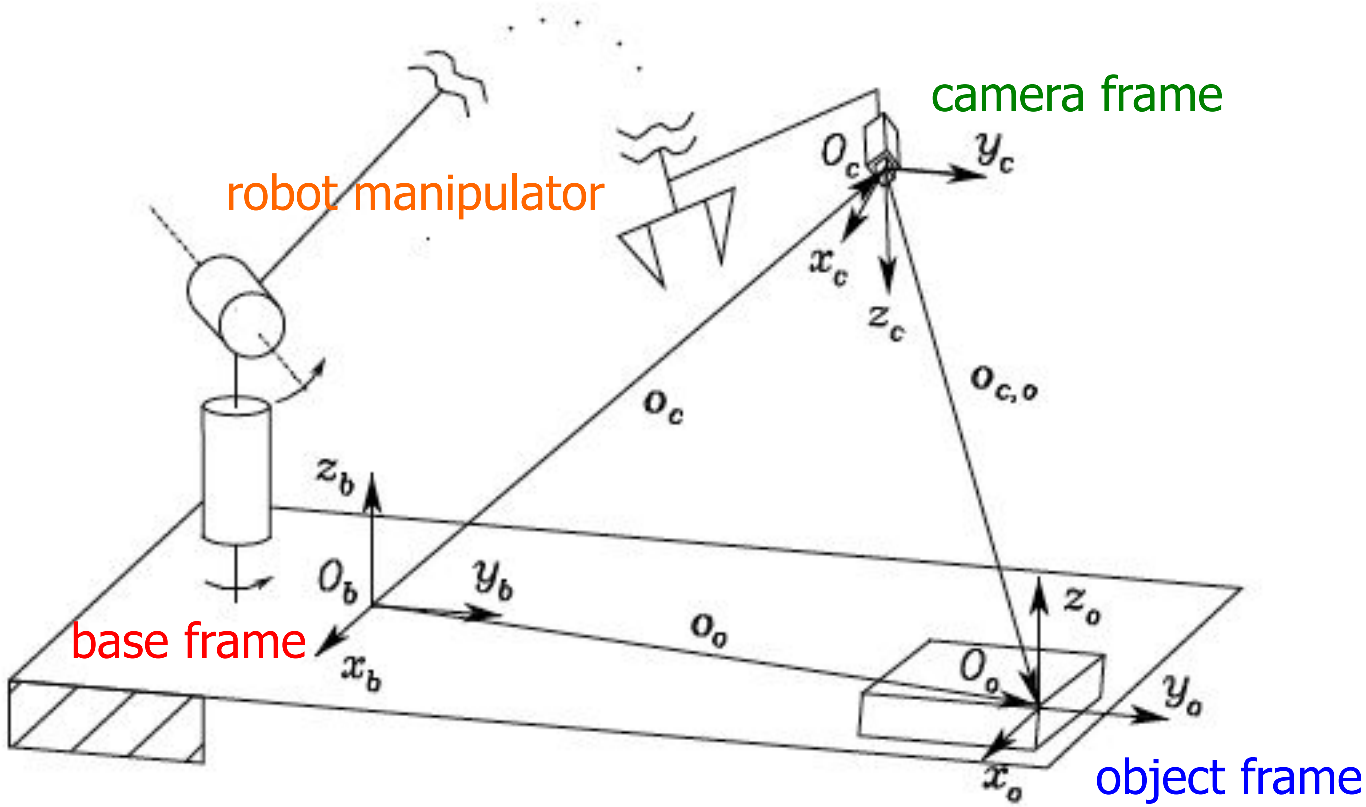

**1. in metric units** $X_f = -\frac{f\,{}^c p_x}{{}^c p_z} \quad Y_f = -\frac{f\,{}^c p_y}{{}^c p_z}$ ➡ $X_f = \frac{f\,{}^c p_x}{{}^c p_z} \quad Y_f = \frac{f\,{}^c p_y}{{}^c p_z}$

**2. in pixel** ... ➡ $X_I = \frac{\alpha_x f\,{}^c p_x}{{}^c p_z} + X_0 \quad Y_I = \frac{\alpha_y f\,{}^c p_y}{{}^c p_z} + Y_0$

**3. LINEAR MAP in homogeneous coordinates** ... ➡

$$\begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \Omega \begin{bmatrix} {}^c p_x \\ {}^c p_y \\ {}^c p_z \\ 1 \end{bmatrix} \qquad \Omega = \begin{bmatrix} \alpha_x f & 0 & X_0 & 0 \\ 0 & \alpha_y f & Y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

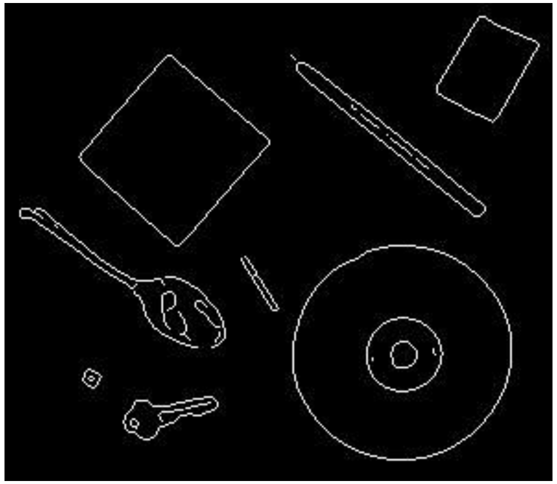
# Eye-in-hand camera



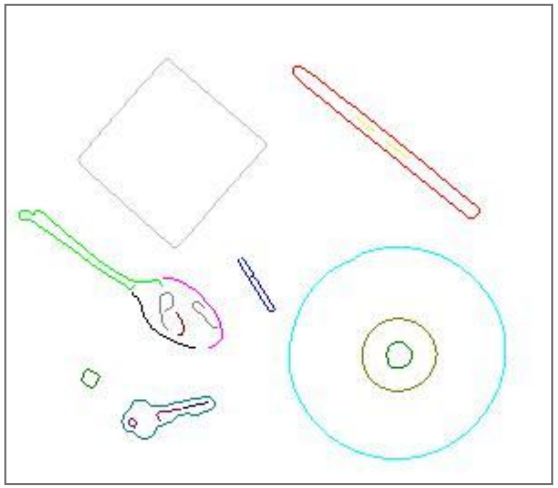

Relevant reference frames for visual-based tasks

# Low-level vision
## contour reconstruction

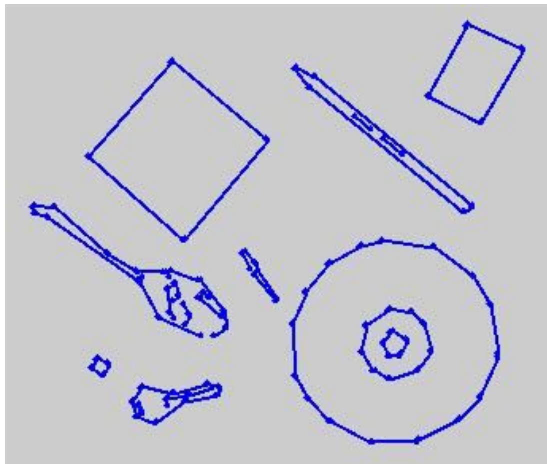
original image



edge detection



adjacent pixels
one the edges
are connected
and labeled with
different colors



linear segments
fitted to the edges

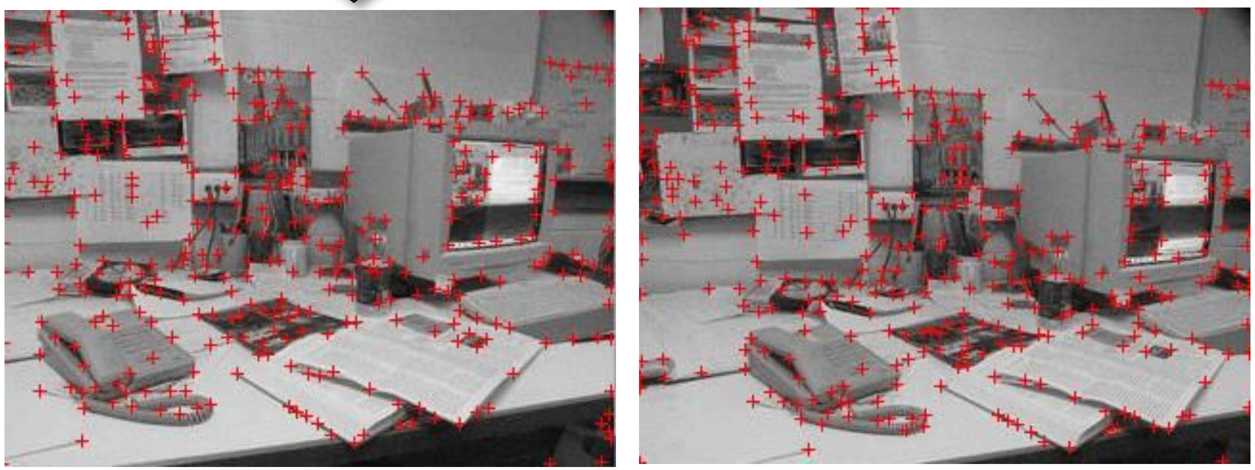
# High-level vision

## features matching in stereovision

goal: find the "fundamental matrix" (rigid transformation between the two images)

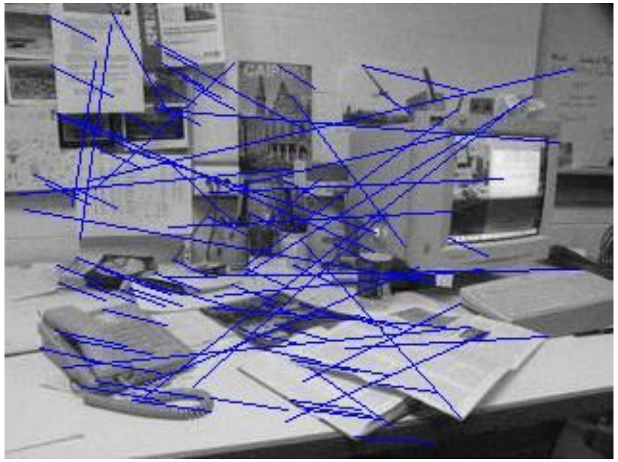
use: visual localization

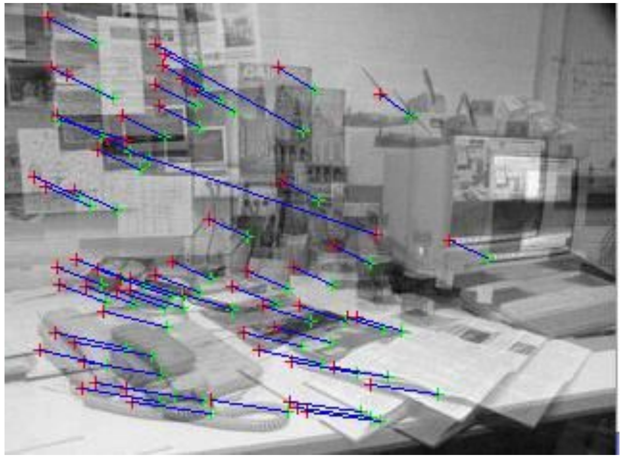
L- and R-views acquired, e.g., by stereocamera Videre (≈5cm)



corners in the two images (in general, "features")

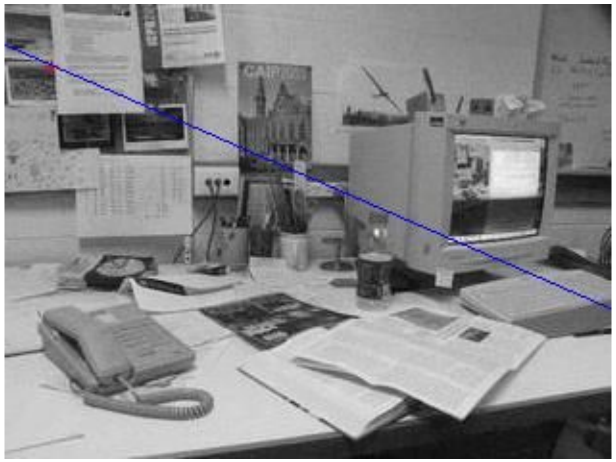
# High-level vision (cont)

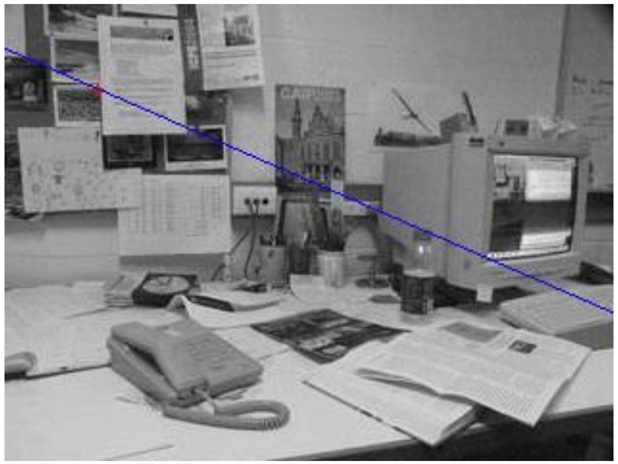




left: correspondence hypotheses used to find the best fitting fundamental matrix
right: inconsistent correspondences are eliminated

corresponding line in the two images

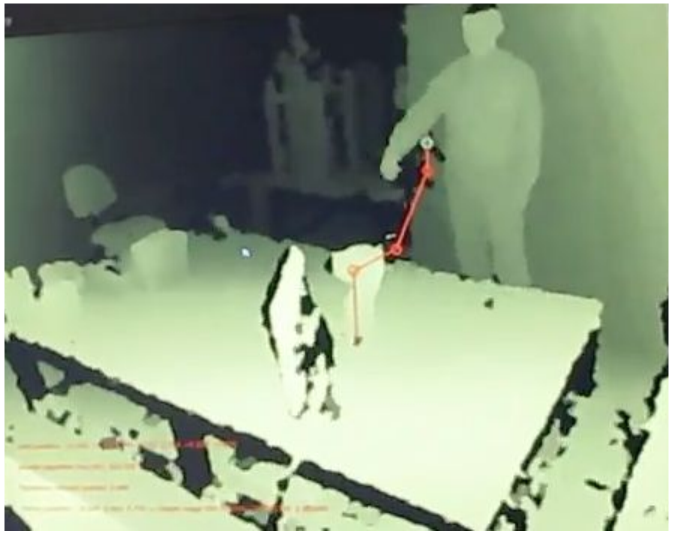




# Kinect

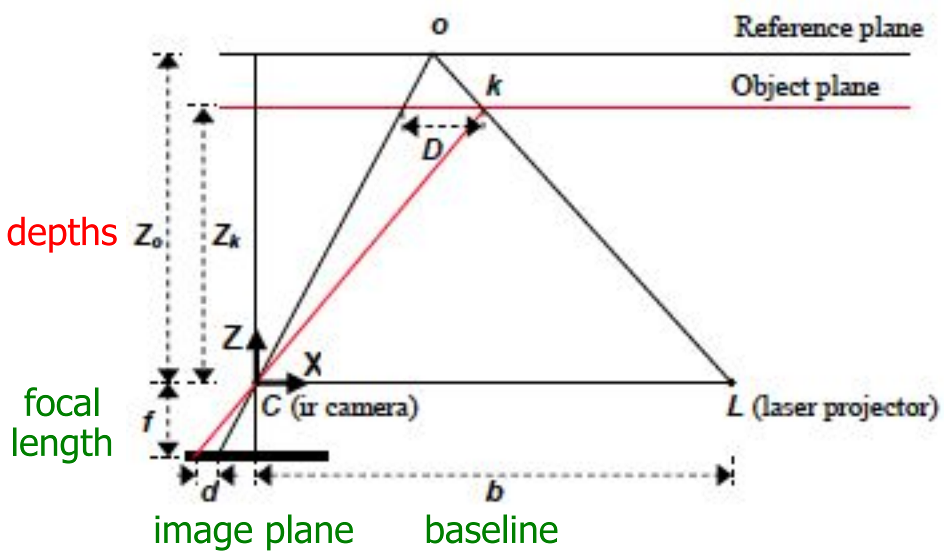
## camera + structured light 3D sensor


- RGB camera (with 640×480 pixel)
- depth sensor (by PrimeSense)
  - infrared laser emitter
  - infrared camera (with 320×240 pixel)
- 30 fps data rate
- range: 0.5÷5 m
- depth resolution: 1cm@2m; 7cm@5m
- cost: < 90 €




"skeleton" extraction and human motion tracking

# Kinect
## Depth sensor operation




- stereo triangulation based on IR source emitting *pseudo-random* patterns
- reference pattern on IR camera image plane acquired in advance from a plane at known distance and coded in H/W
- correlating the disparity $d$ (10 bits) of reference and received object patterns provides the object depth $Z_k$

1. triangulation equations (by similarity of triangles)

$$\frac{D}{b} = \frac{Z_0 - Z_k}{Z_0} \quad + \quad \frac{d}{f} = \frac{D}{Z_k} \quad \Rightarrow \quad Z_k = \frac{Z_0}{1 + \dfrac{d}{f\,b} Z_0}$$

$$X_k = -\frac{Z_k}{f}\left(x_k - x_0 + \delta x\right)$$

$$Y_k = -\frac{Z_k}{f}\left(y_k - y_0 + \delta y\right)$$

2. accurate calibration of sensor

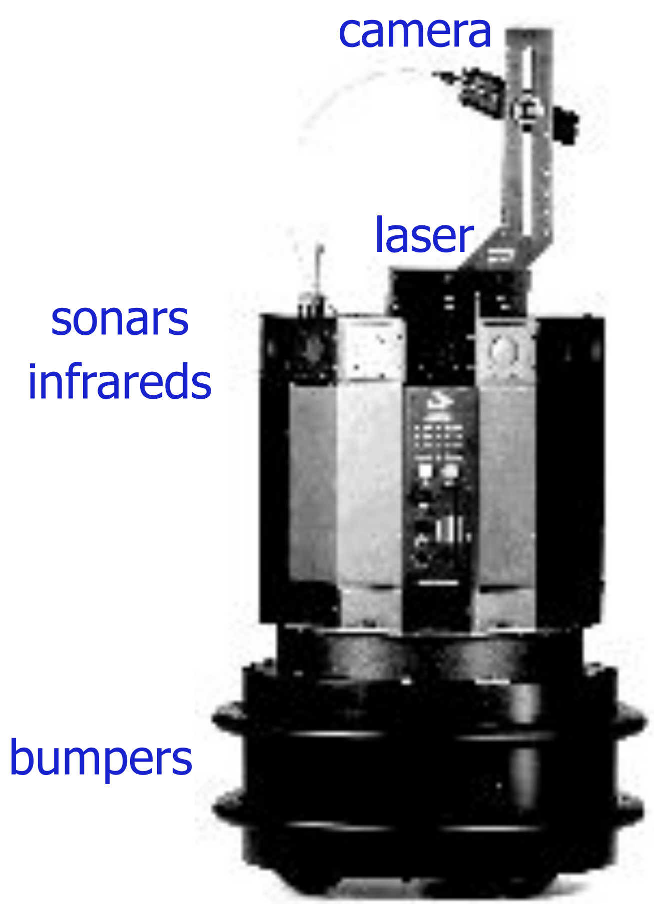
baseline length $b$, depth of reference $Z_0$ + camera intrinsic parameters (focal length $f$, lens distortion coefficients $\delta x, \delta y$, center offsets $x_0, y_0$)

# How Kinect works
## (a 2-minute illustration...)

video

http://youtu.be/uq9SEJxZiUg

# Nomad 200 mobile robot



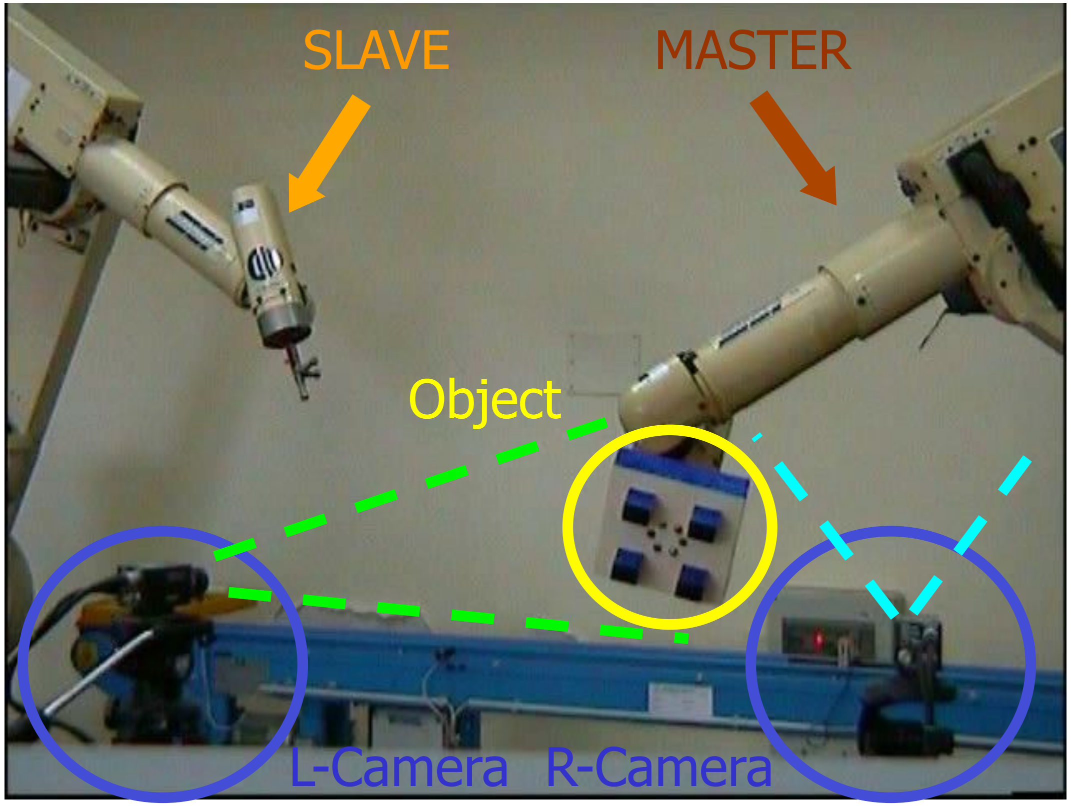

- structured light vision system (laser + CCD camera)
  - 480 scan lines/frame, 30 fps
  - range: 45÷300 cm
- 16 sonar sensors (Polaroid 50 KHz)
  - 25° of field of view
  - range: 40÷640 cm, resolution 1%
- 16 infrared sensors
  - range: ≤ 60 cm, readings every 2.5 msec
- 20 pressure-sensitive bumpers
- radio-ethernet communication

# Magellan Pro mobile robot

- pan-tilt color camera (7 Hz...)
- 16 sonar sensors
- 16 infrared sensors
- 16 pressure-sensitive bumpers
- ethernet radio-link

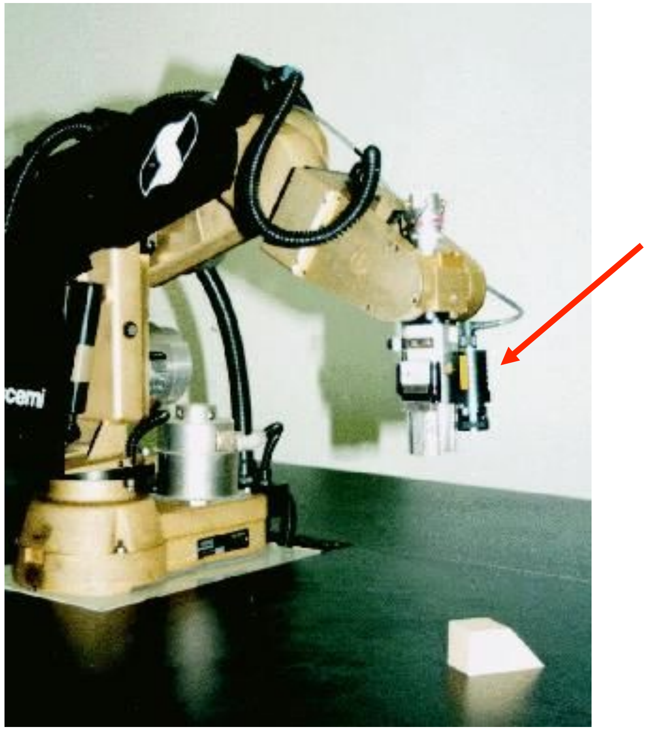
# Manipulators and vision systems

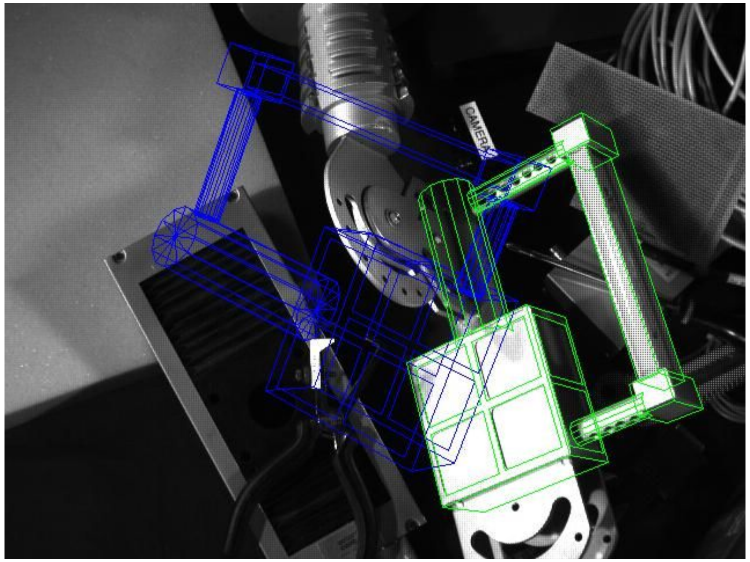
- stereovision with two external cameras, fixed in the environment (eye-to-hand)



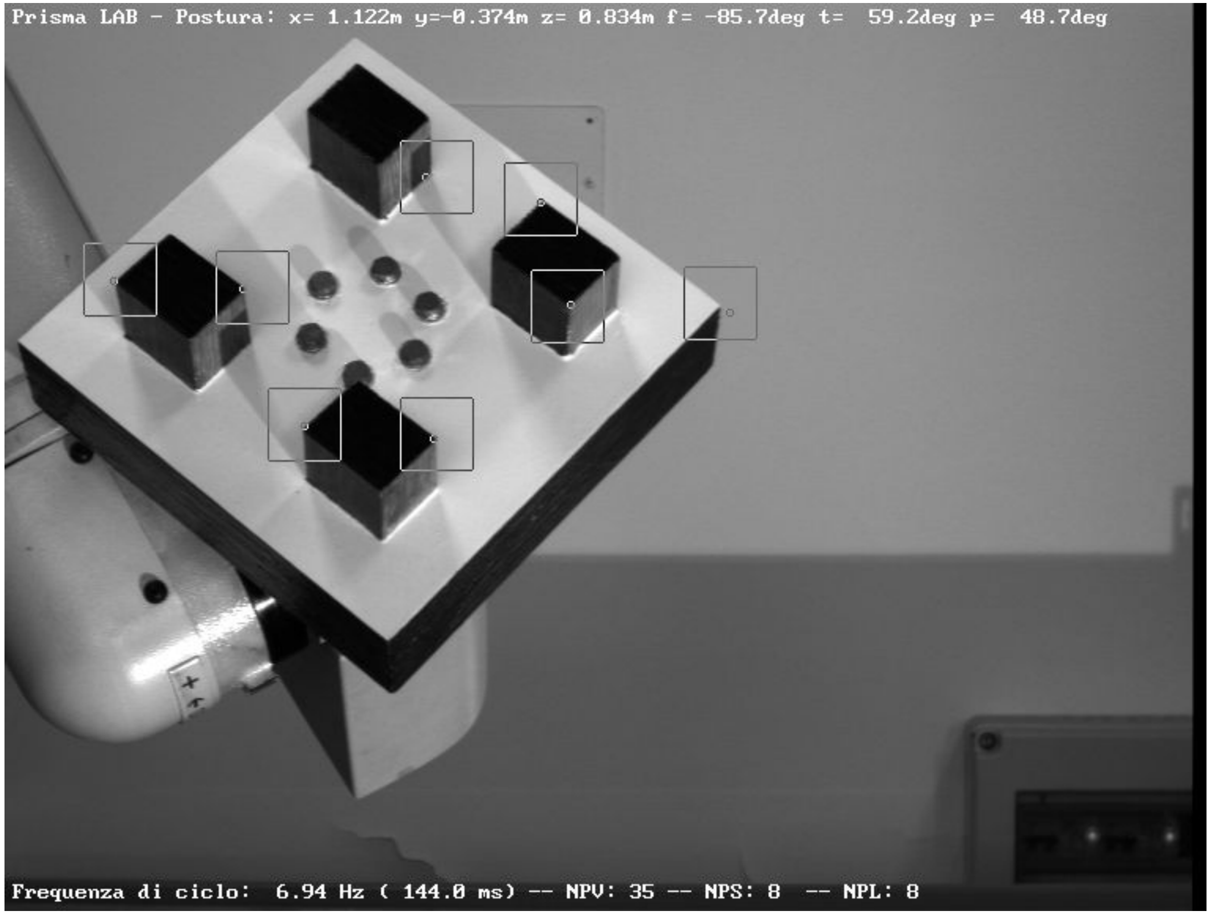

# Manipulators and vision systems

- CCD camera mounted on the robot for controlling the end-effector positioning (eye-in-hand)





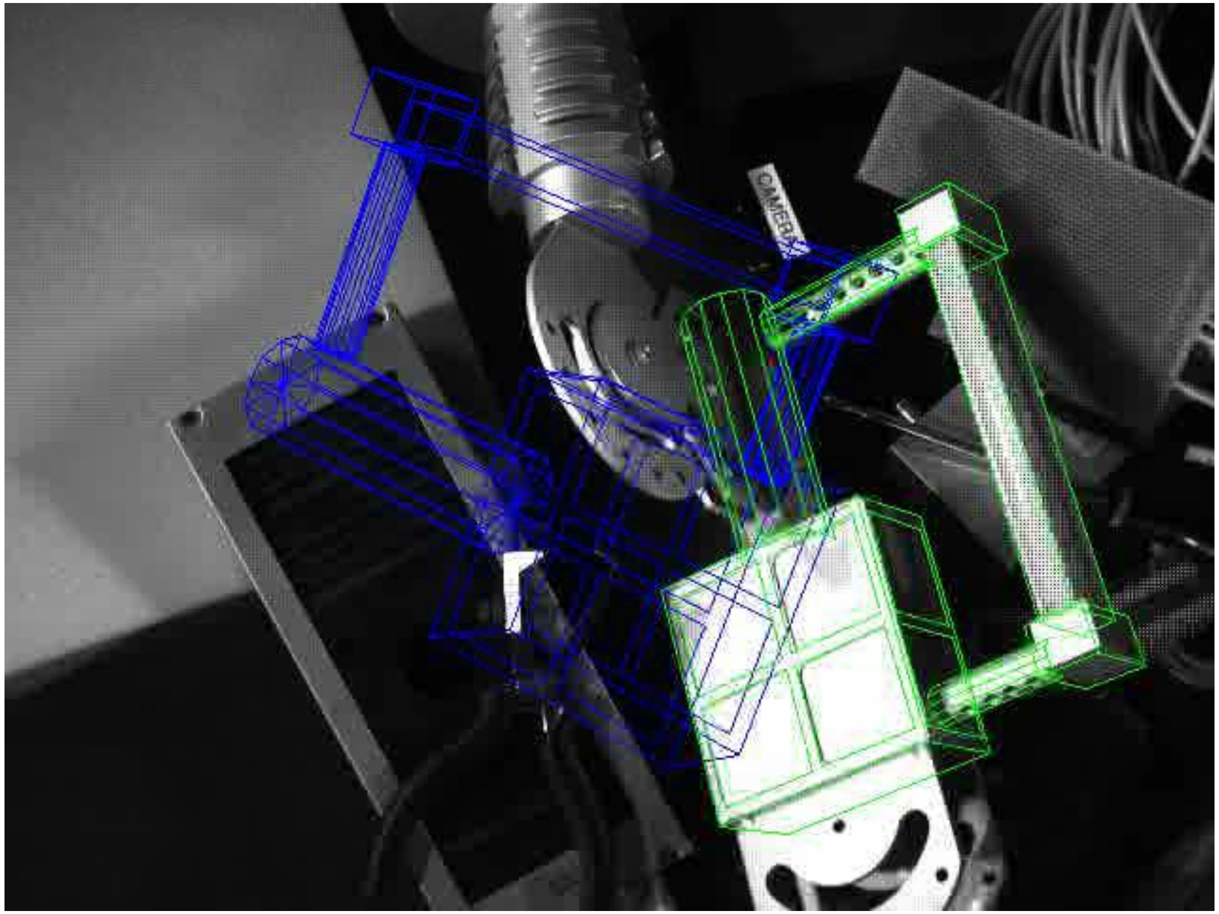
# Visual tracking eye-to-hand




video

COMAU robot with position-based 6D tracking from external camera
(DIS, Università di Napoli Federico II)

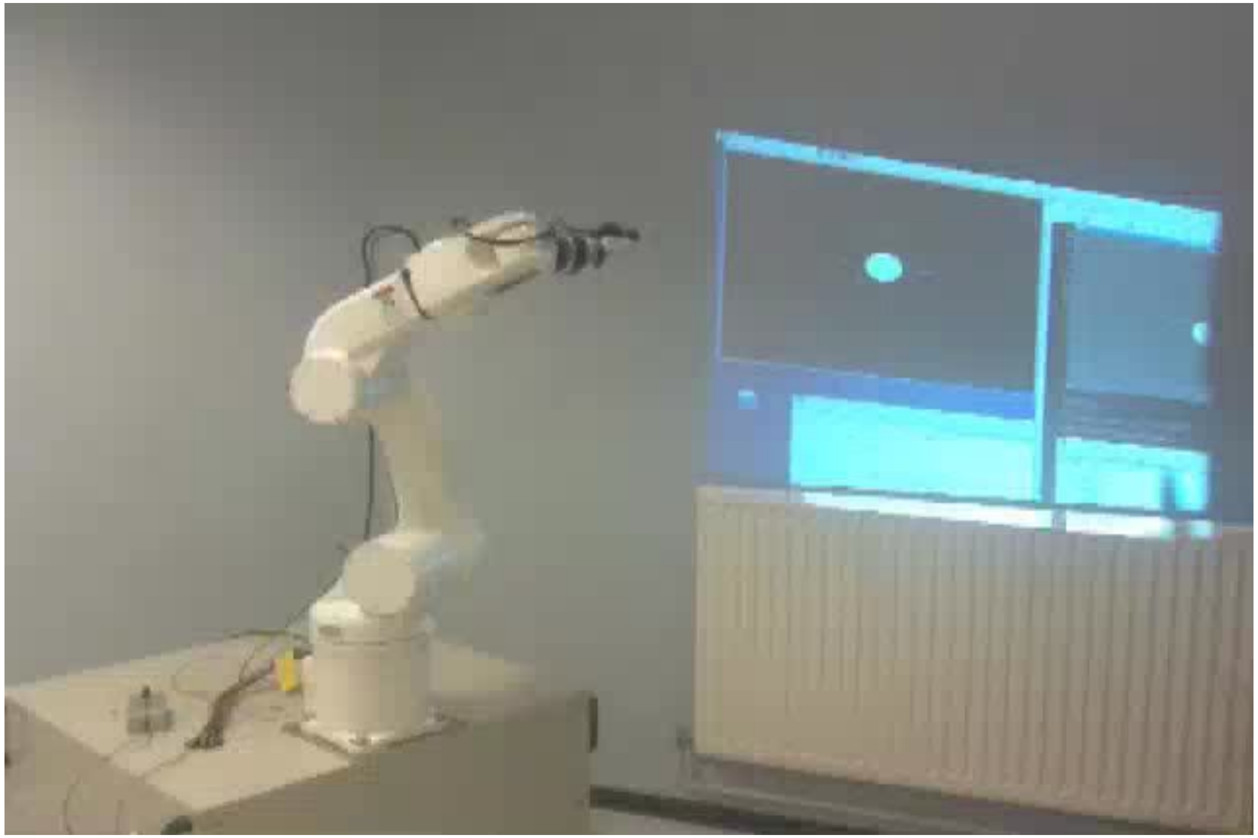
# Visual servoing eye-in-hand




video

Image-based servoing with camera mounted on the robot end-effector
(IRISA/INRIA, Rennes)

# Visual servoing and redundancy



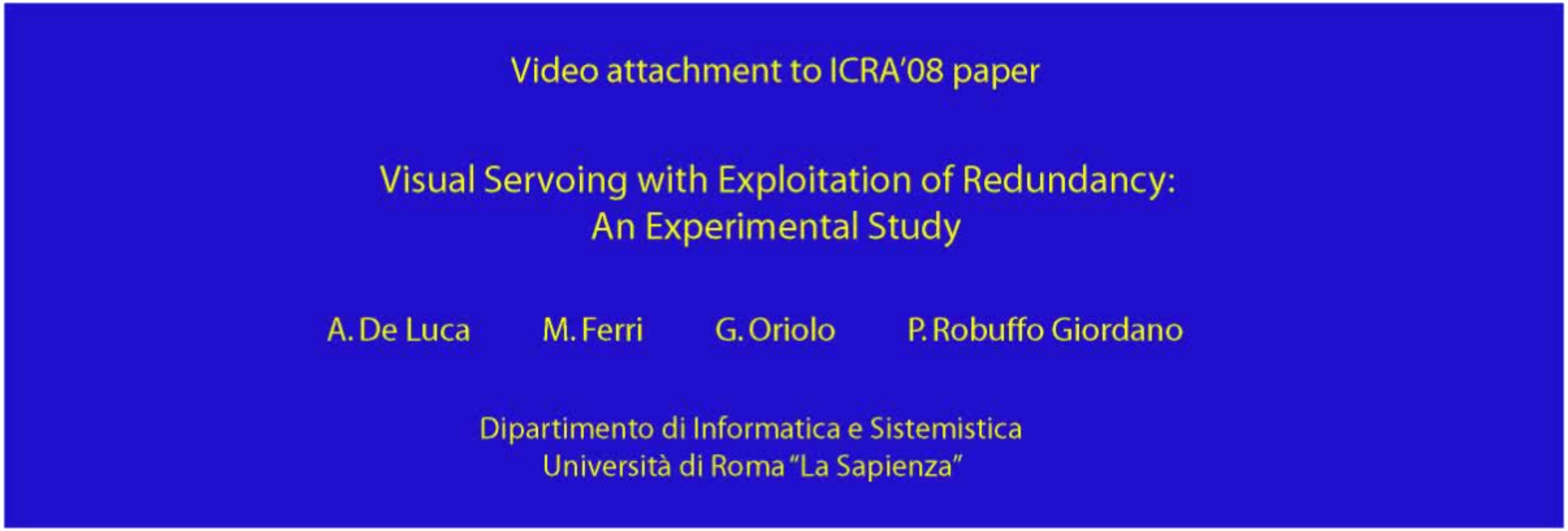
video

Visual servoing of a point feature (m=2) with Adept Viper robot (n=6): redundancy is used for avoiding joint range limits (IRISA/INRIA, Rennes)

# Visual servoing with mobile robot

pan/tilt (2 dof)
web cam at 7Hz
frame rate

video




On-board image-based visual servoing with Magellan mobile robot
(DIS Robotics Laboratory, IEEE ICRA'08)

# Combined visual/force assembly

video

KUKA LWR with eye-in-hand camera and F/T sensor
(DLR, IEEE ICRA'07 demo in Roma)