***Robotics 1***

# Robot components:
## Exteroceptive sensors

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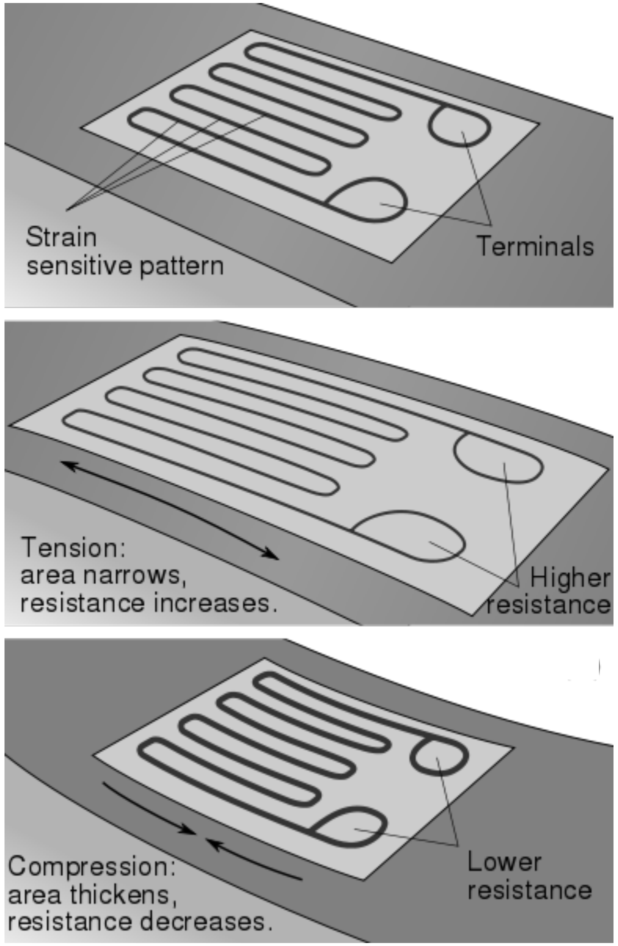
# Summary

- 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 (⇒ moved to AMR course!)
  - infrared (IF)
  - ultrasound (US)
  - laser
  - with structured light
- vision
- examples of robot sensor equipment
- 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: it uses the variation of the resistance $R$ of a metal conductor when its length $L$ and/or cross-section $S$ vary

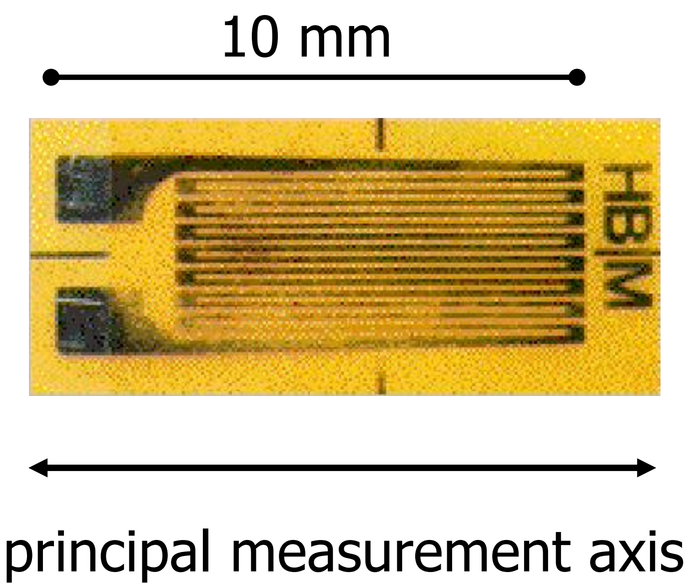



$$\frac{\partial R}{\partial L} > 0 \qquad \frac{\partial R}{\partial S} < 0$$

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

temperature

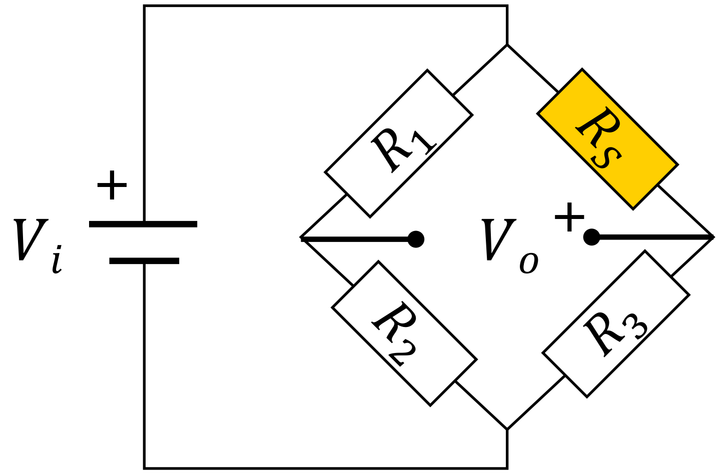
# Strain gauges




$$\text{Gauge-Factor} = \text{GF} = \frac{\Delta R/R}{\Delta L/L}$$ strain $\varepsilon$

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

Wheatstone single-point quarter-bridge
(for accurately measuring resistance)



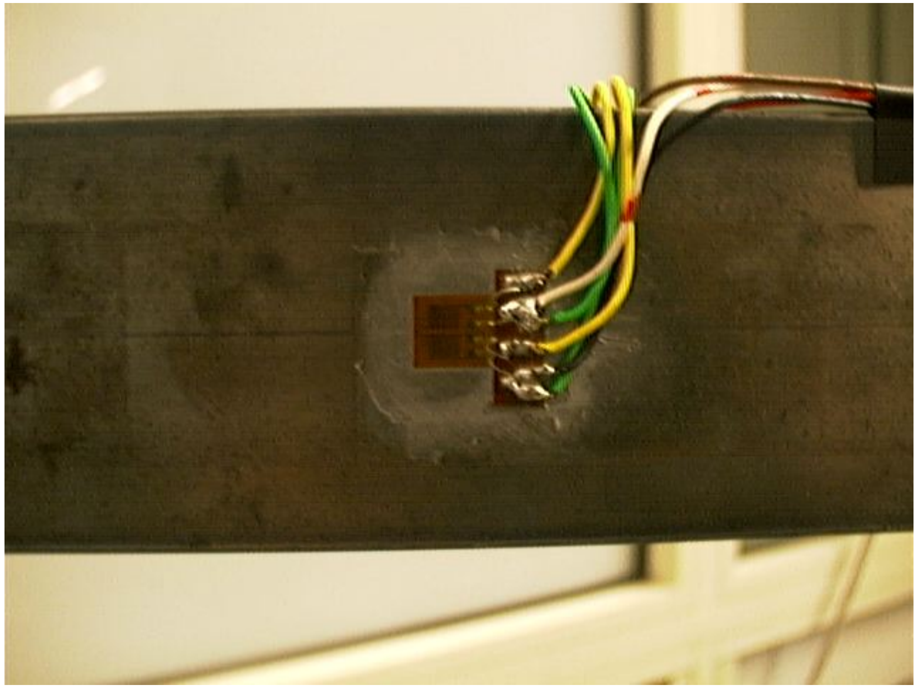

- $R_1, R_2, R_3$ very well matched ($\approx R$)
- $R_S \approx R$ at rest (no stress)
- two-point bridges have 2 strain gauges connected oppositely (↗ sensitivity)

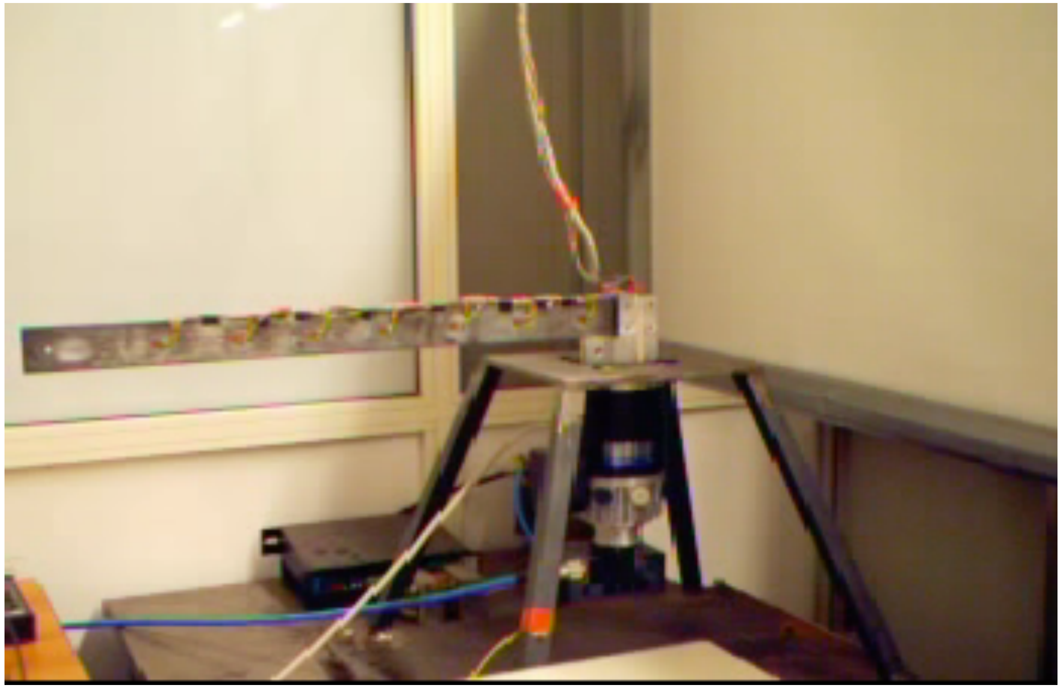
if $R_1$ has the same dependence on $T$ of $R_S$ thermal variations are automatically compensated

$$\boxed{V_0 = \left(\frac{R_3}{R_3 + R_s} - \frac{R_2}{R_1 + R_2}\right) V_i}$$

# Strain gauges in flexible arms

video



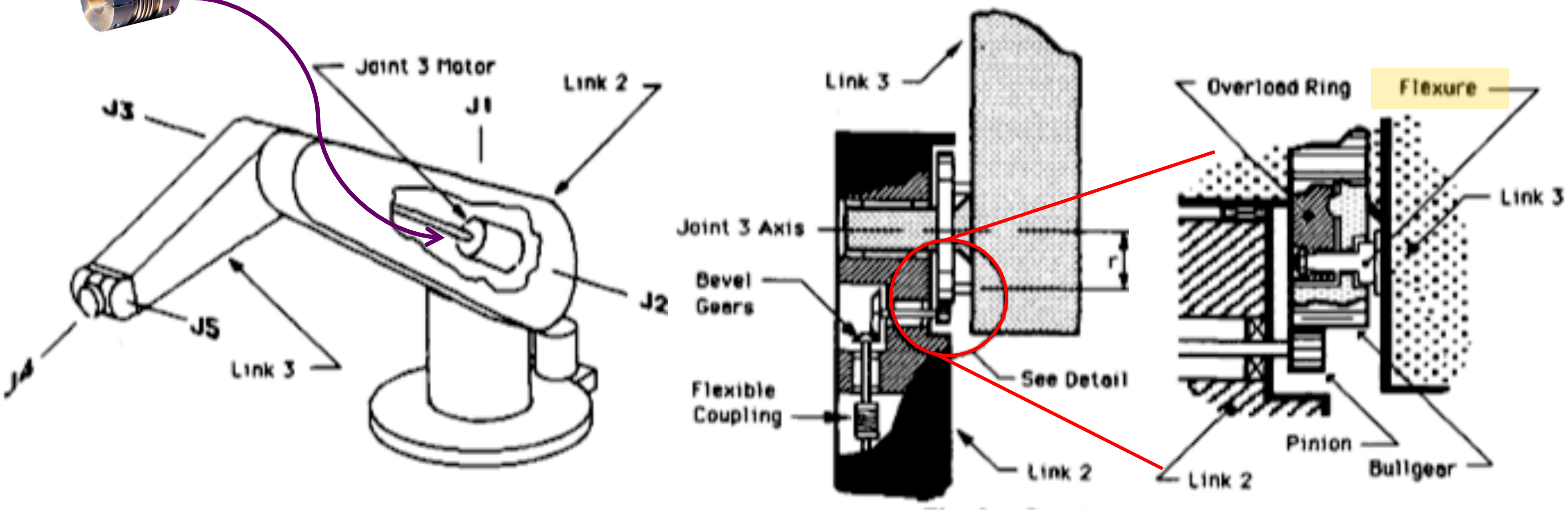


7 strain gauges glued[1] to a flexible aluminum beam (a robot "link") measuring its local "curvature" in dynamic bending during slew motions (a proprioceptive use of these sensors)

[1] by cyanoacrylic glue

# Torque sensor at robot joints

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

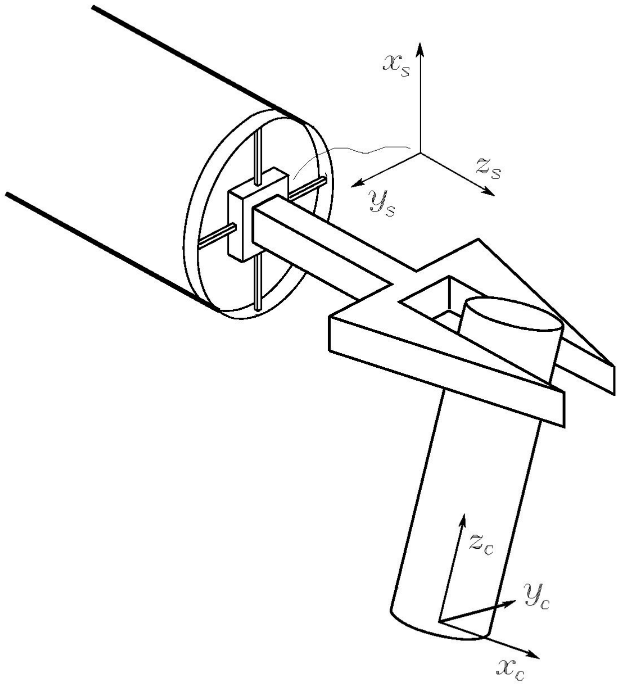


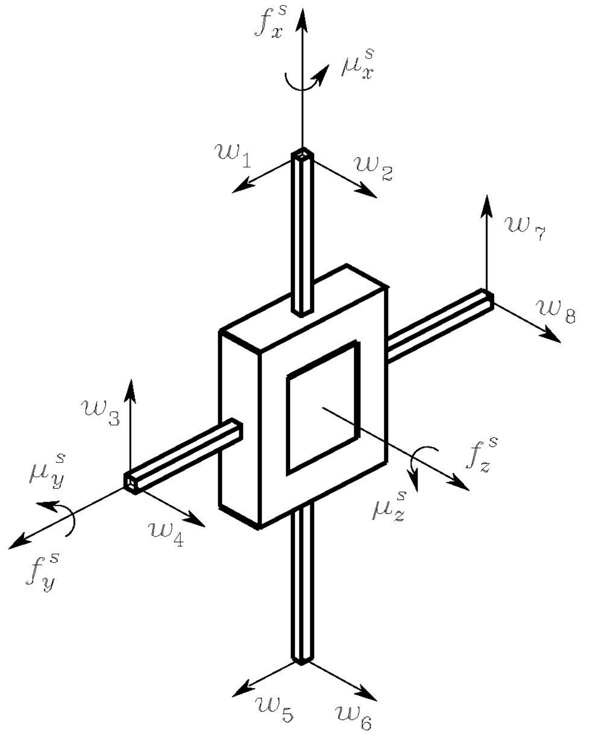

strain gauge mounted to “sense” the axial deformation
of the transmission shaft of joint #3 (elbow) in a PUMA 500 robot
(again, a proprioceptive use of this sensor)

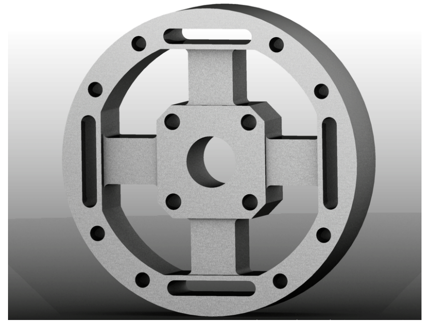
# Force/torque sensor at robot wrist

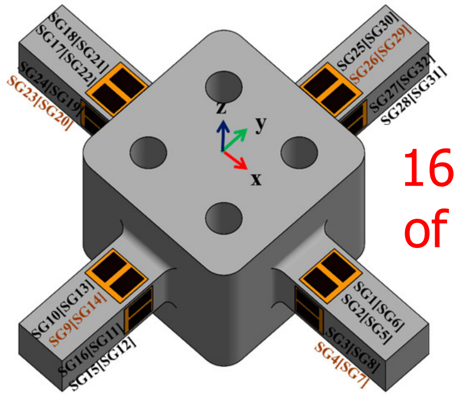
- a device (with the outer form of a cylinder), typically located between the last robot link and its end-effector
- top and bottom plates are mechanically connected by a number of deformable elements subject to strain under the action of forces and moments
- there should be at least one such element 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 $N \geq 6$ 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






16 pairs of SG !!

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

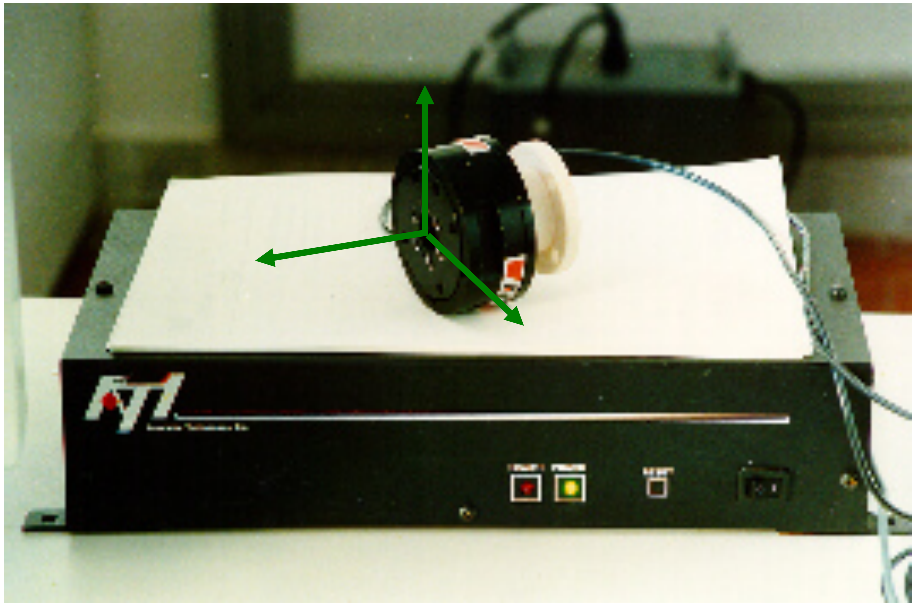
# 6D force/torque sensors

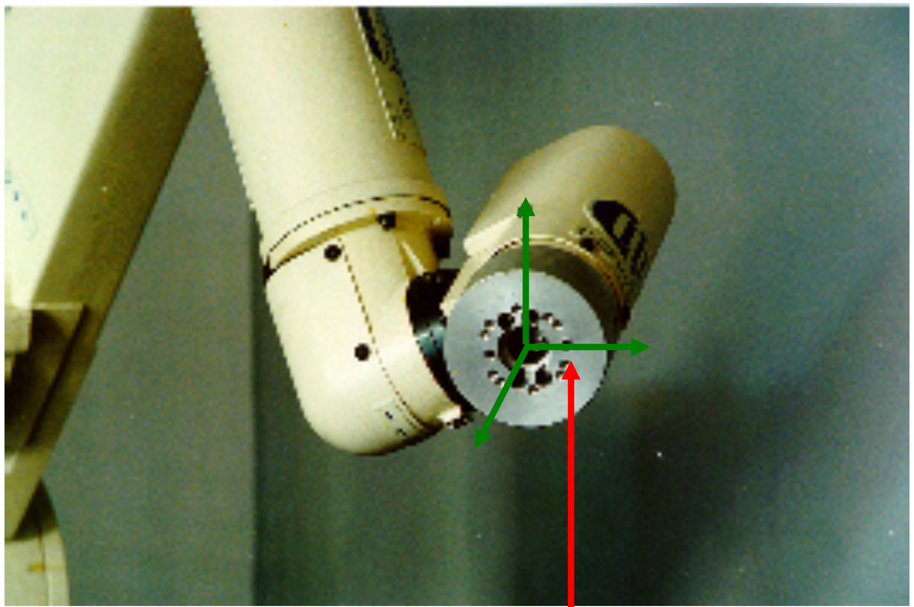
- ATI series
- cost (in 2016): about 6 K€ for Mini45 model + 700 € DAQ card

| 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

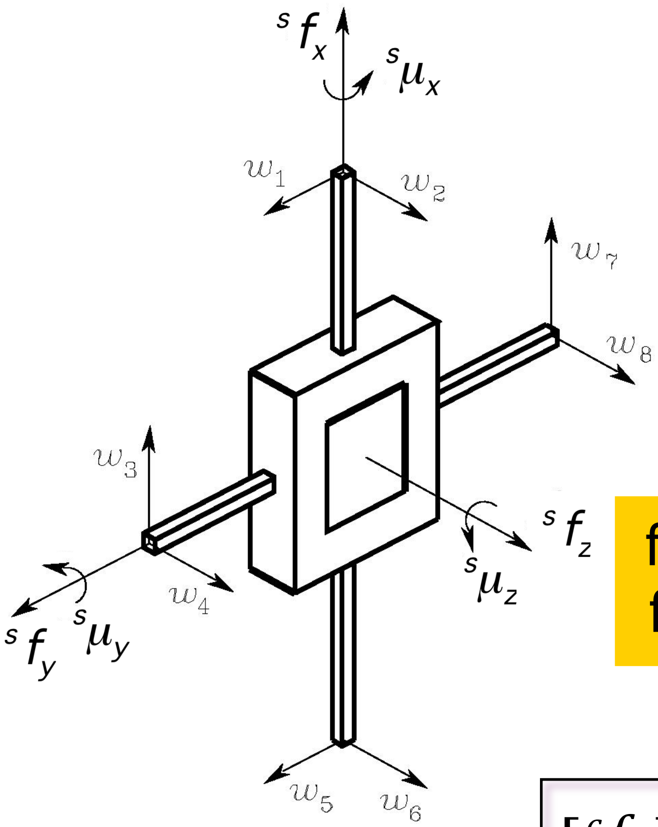
- electronic processing unit and mounting on an industrial robot (Comau Smart 3 robot, 6R kinematics)





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

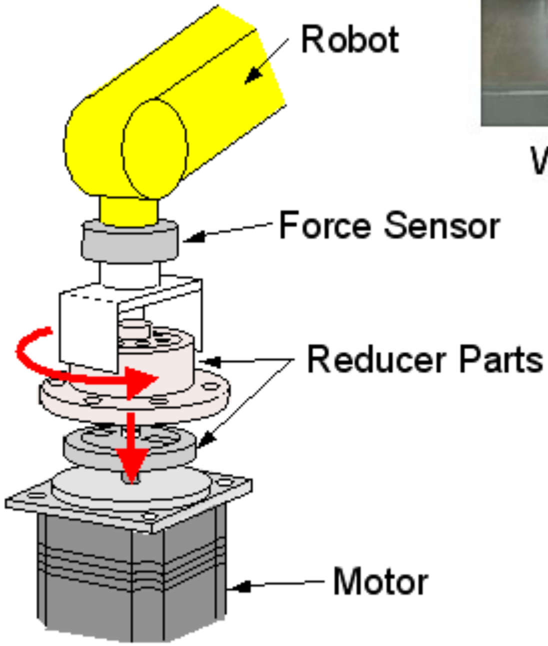
$$\begin{bmatrix} {}^c f_c \\ {}^c\mu_c \end{bmatrix} = \begin{bmatrix} {}^cR_s & O \\ S({}^c r_{cs})\,{}^cR_s & {}^cR_s \end{bmatrix} \begin{bmatrix} {}^s f_s \\ {}^s\mu_s \end{bmatrix}$$

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

# Typical uses of a F/T sensor

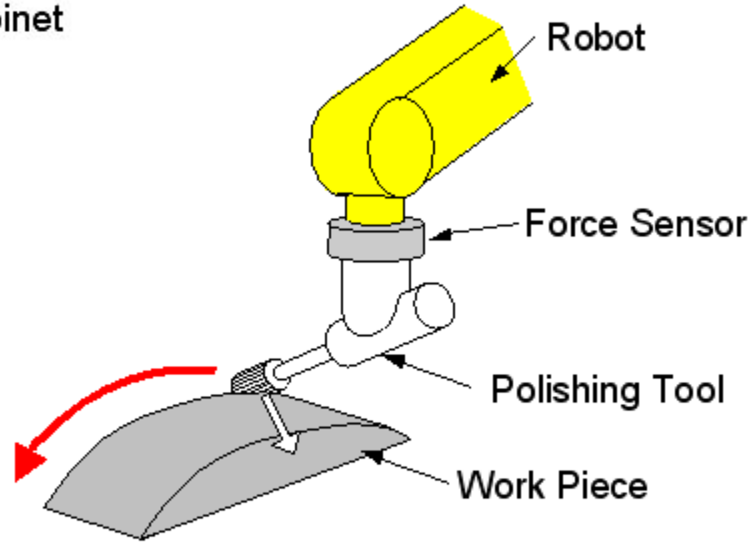
Washstand

Metal Cabinet




Phase matching by force sensing

Gear Parts



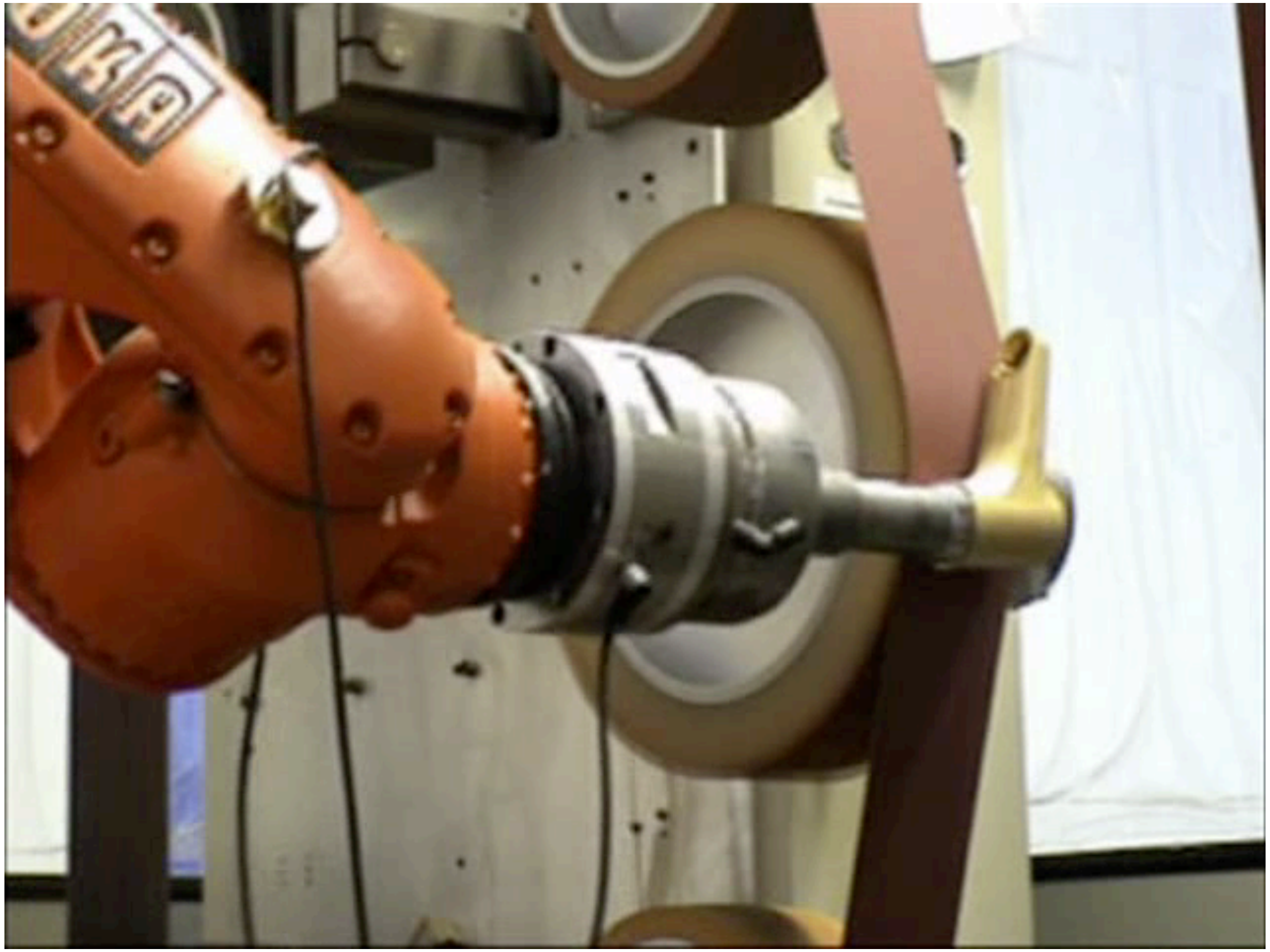

Following with constant pushing force

# Active assembly with F/T sensor

video

ABB robot with ATI F/T sensor

# Surface finishing with F/T sensor



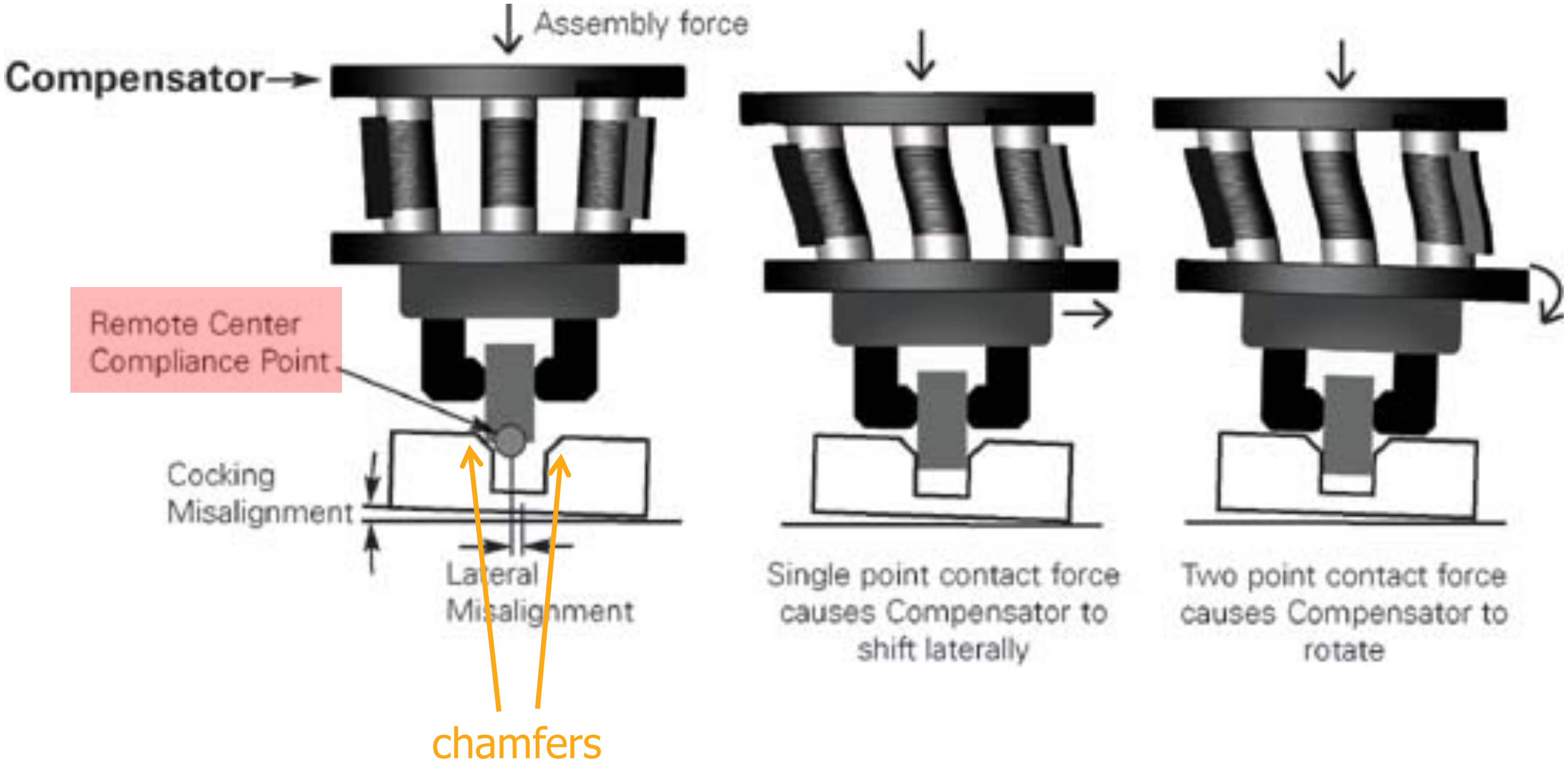

video

KUKA robot with F/T sensor

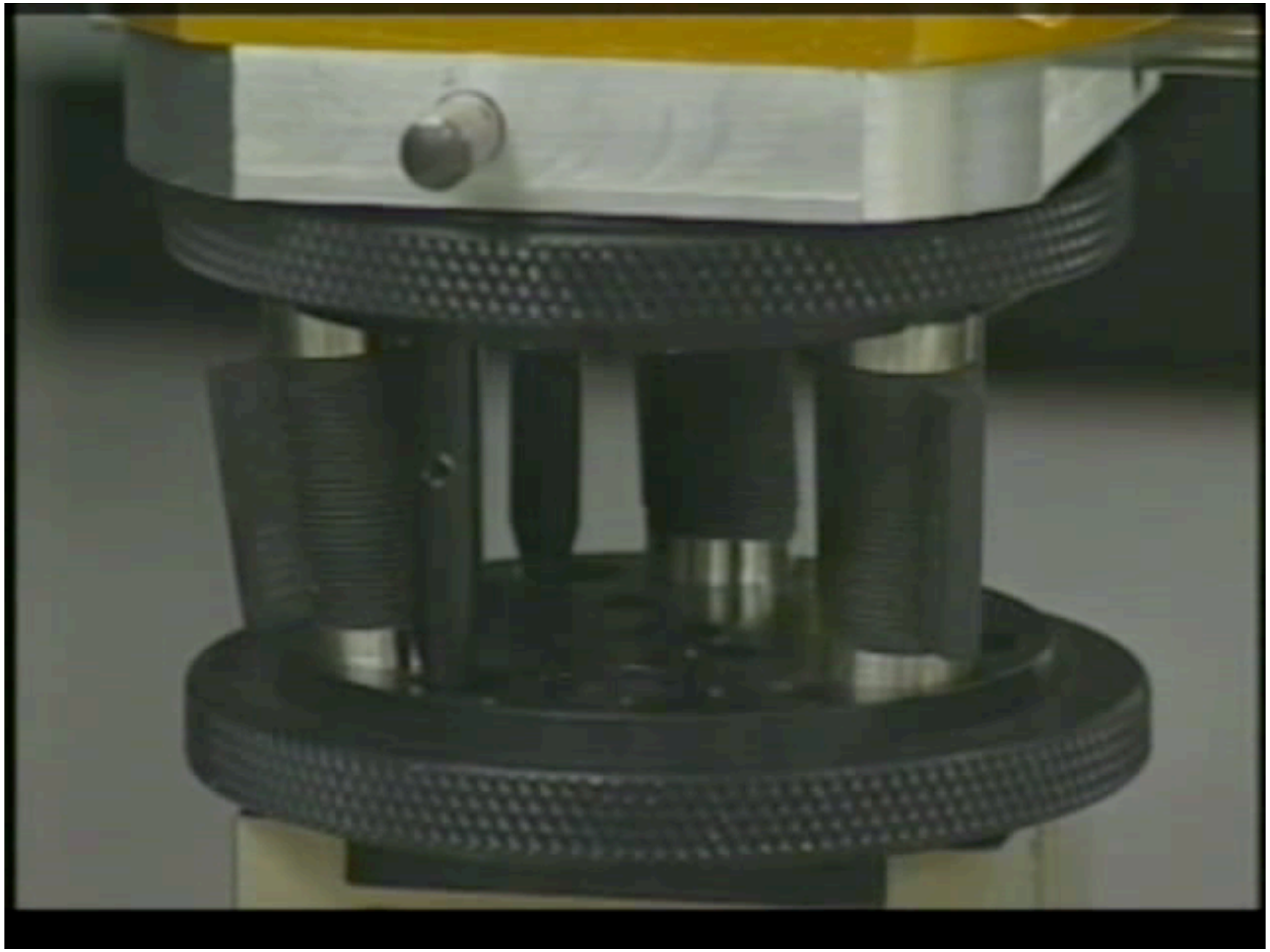
# Passive RCC device

- 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

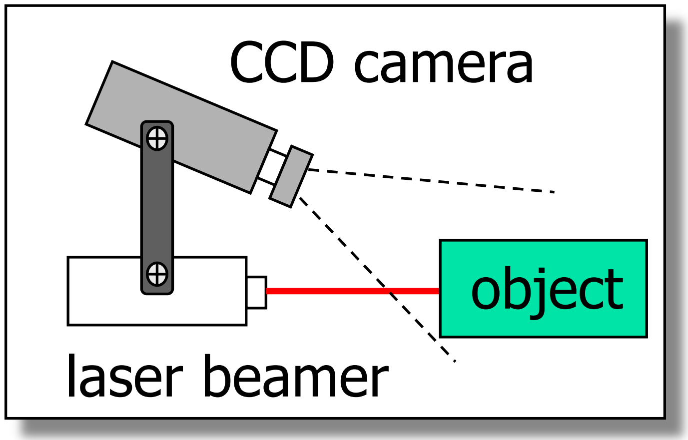


video

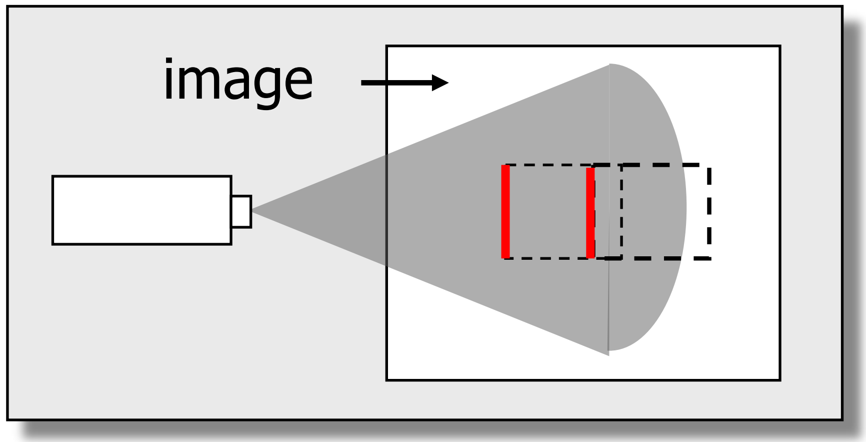
RCC by ATI Industrial Automation
http://www.ati-ia.com

# Proximity/distance sensors - 4

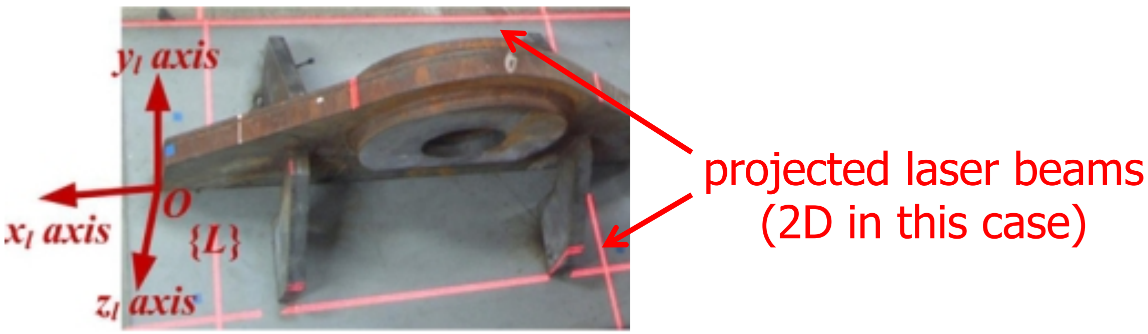
- structured light: a laser beam (coherent light source) is projected on the environment, and its planar intersection with surrounding objects is detected by a (tilted) camera
- the position of the "red pixels" on the camera image plane is in trigonometric relation with the object distance from the sensor



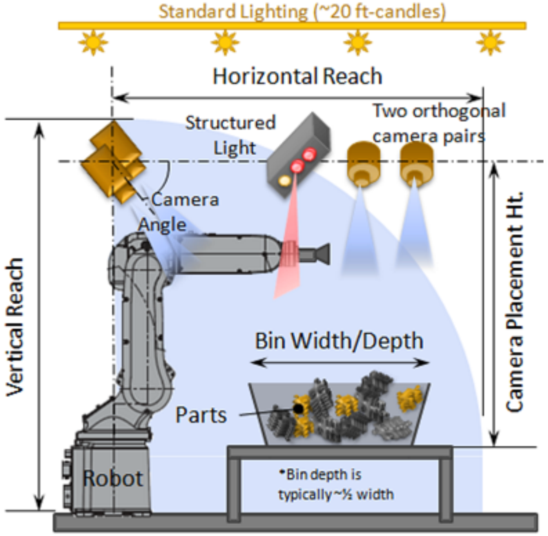

side view



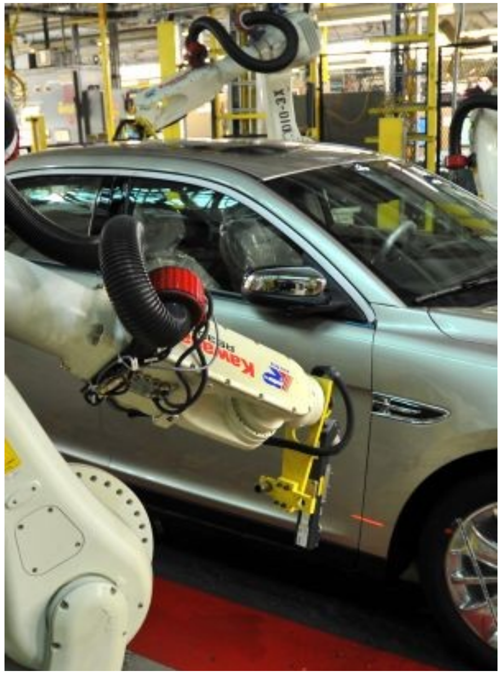

top view



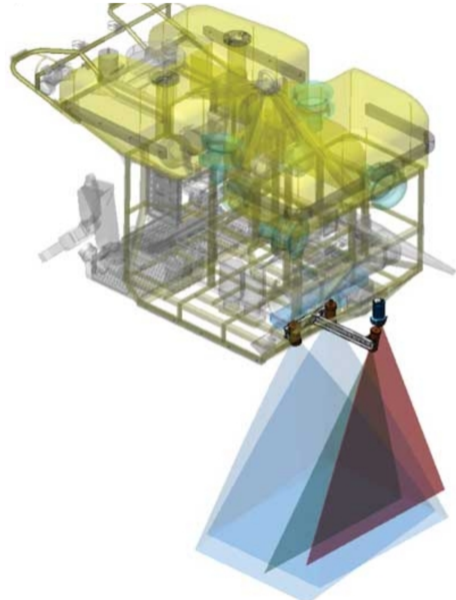
# Use of structured light sensors

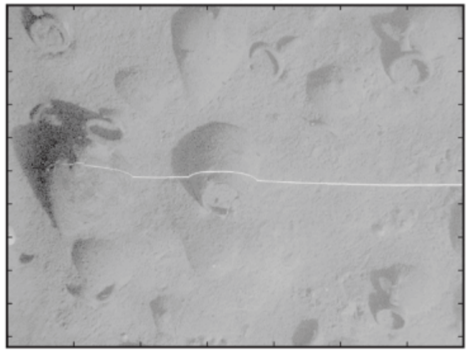



Random bin picking of 10-30 parts/minute (with surface inspection) with a 6R industrial robot, two pairs of cameras and a structured light sensor [Universal Robotics]



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





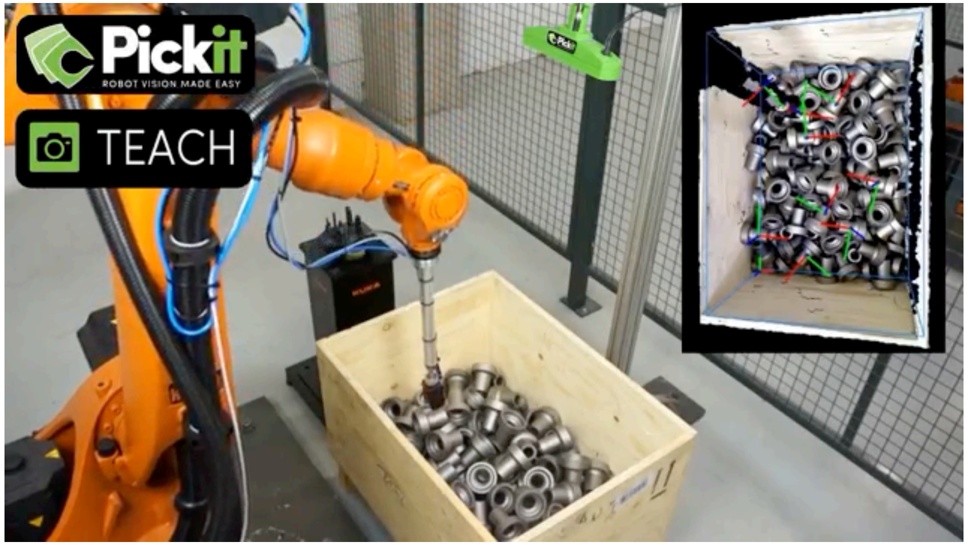
Hercules ROV + structured-laser-light imaging system for high-resolution bathymetric underwater maps [Univ. Rhode Island]

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

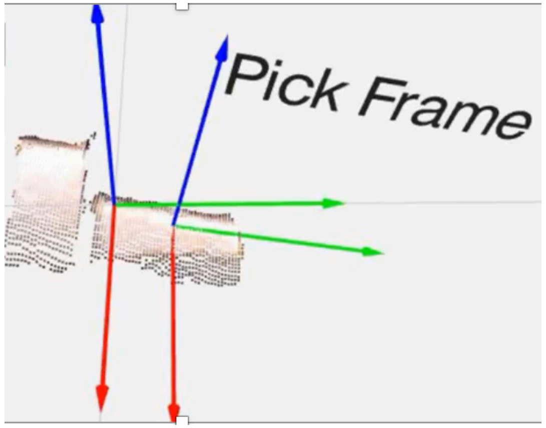
# Robotic bin picking
## using vision and structured light

video

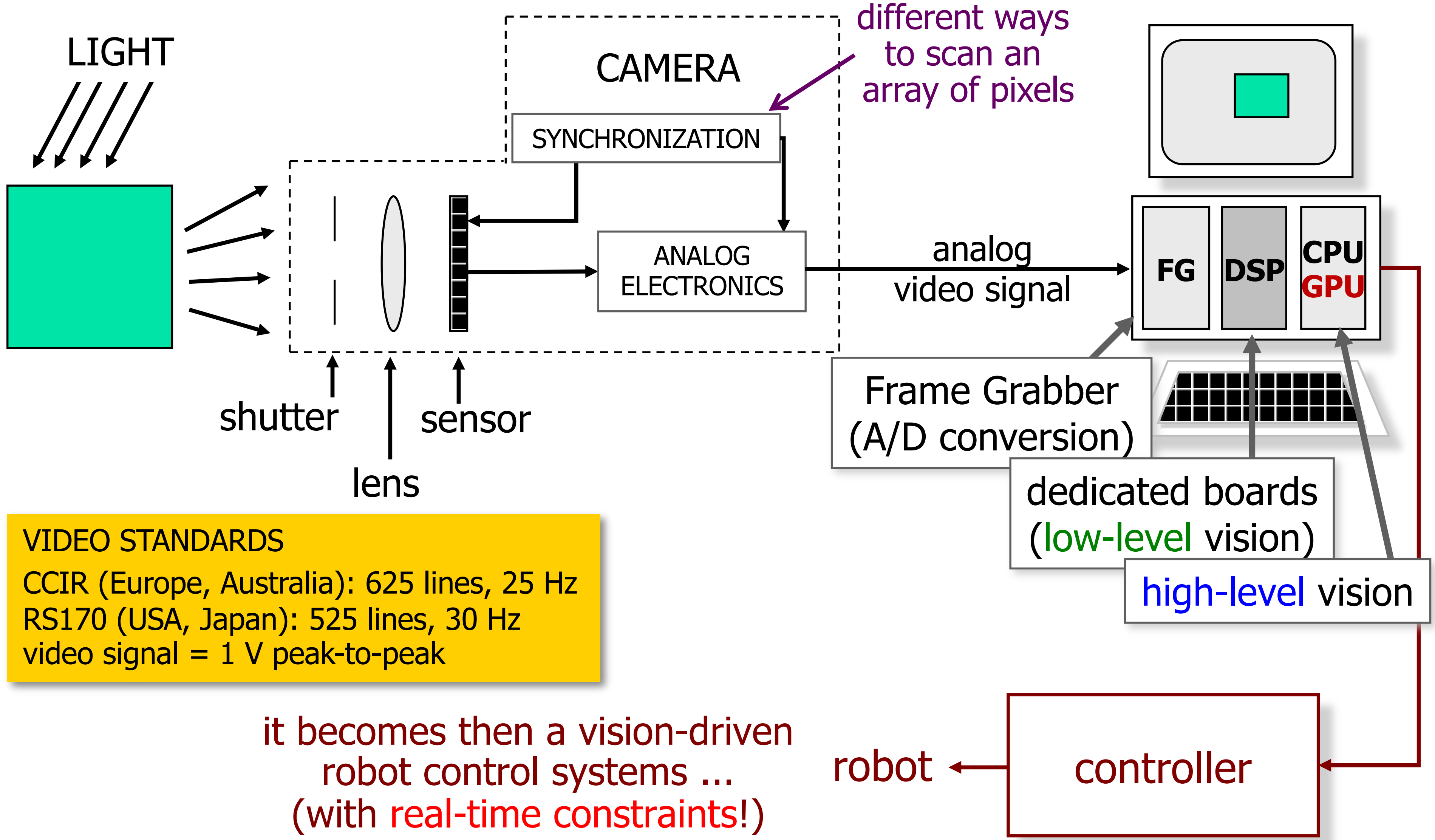
video





# Vision systems

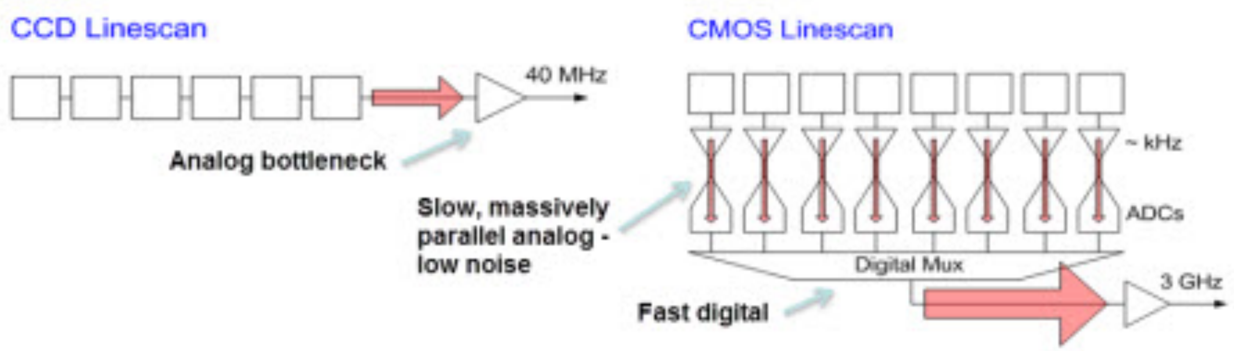



VIDEO STANDARDS
CCIR (Europe, Australia): 625 lines, 25 Hz
RS170 (USA, Japan): 525 lines, 30 Hz
video signal = 1 V peak-to-peak

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); "integrated" charges "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 possibility of random access to each pixel

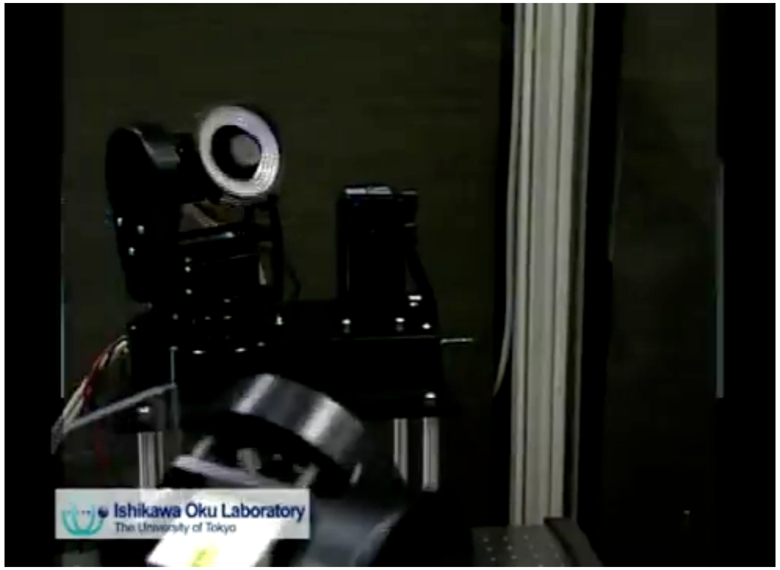


# CMOS versus CCD

- reduction of fabrication costs of CMOS imagers
- better spatial resolution of elementary sensors
  - CMOS: 1M pixel, CCD: $768 \times 576$ 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 have been on the market since much longer time

# Fast image processing for fast motion control

video




video

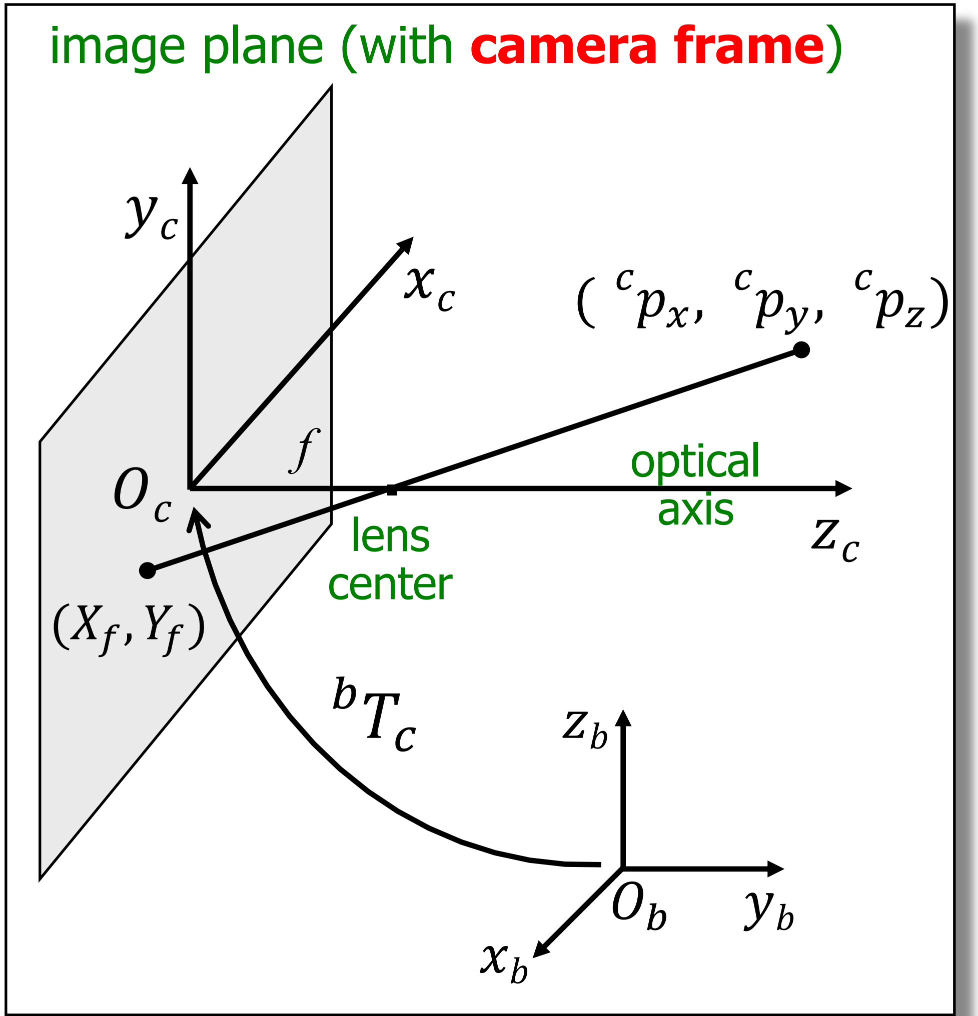
video

- 1 KHz vision frame rate
- 1 KHz robot control rate

  @ Ishikawa Lab – U Tokyo

  (2007-09)

# Perspective transformation
## with pinhole camera model




**1. in metric units**

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

**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

pixel/metric scaling factor

**3. LINEAR MAP in homogeneous coordinates**

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

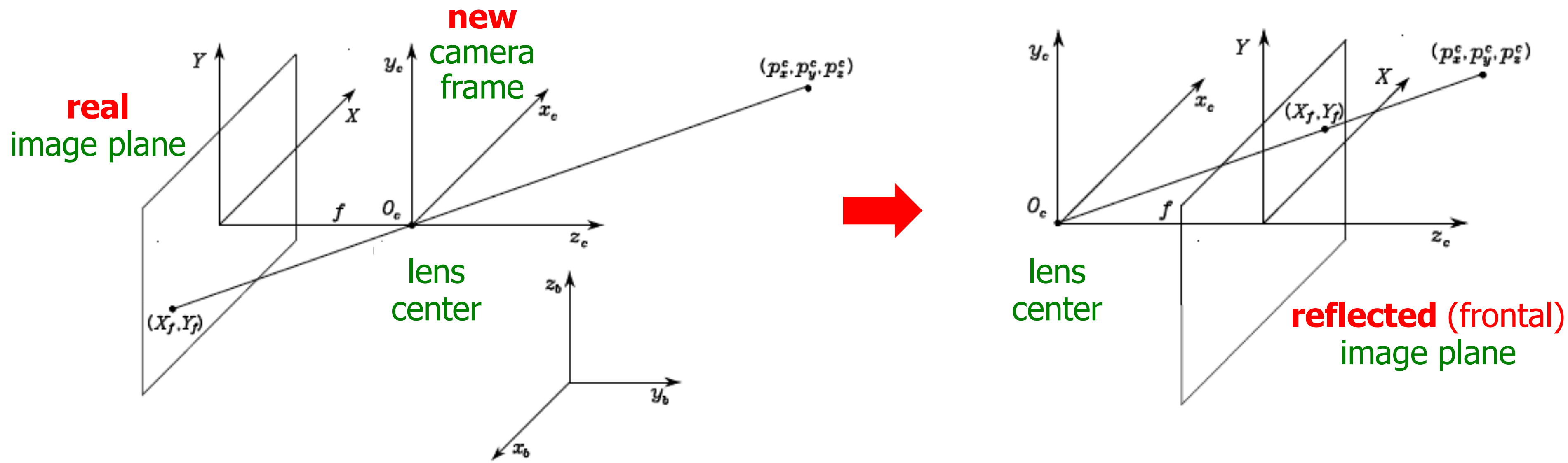
$$\Omega = \begin{bmatrix} \alpha_x & 0 & X_0 & 0 \\ 0 & \alpha_y & Y_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/f & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

calibration matrix

$$\boxed{H = \Omega \cdot {}^c T_b}$$

intrinsic and extrinsic parameters

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



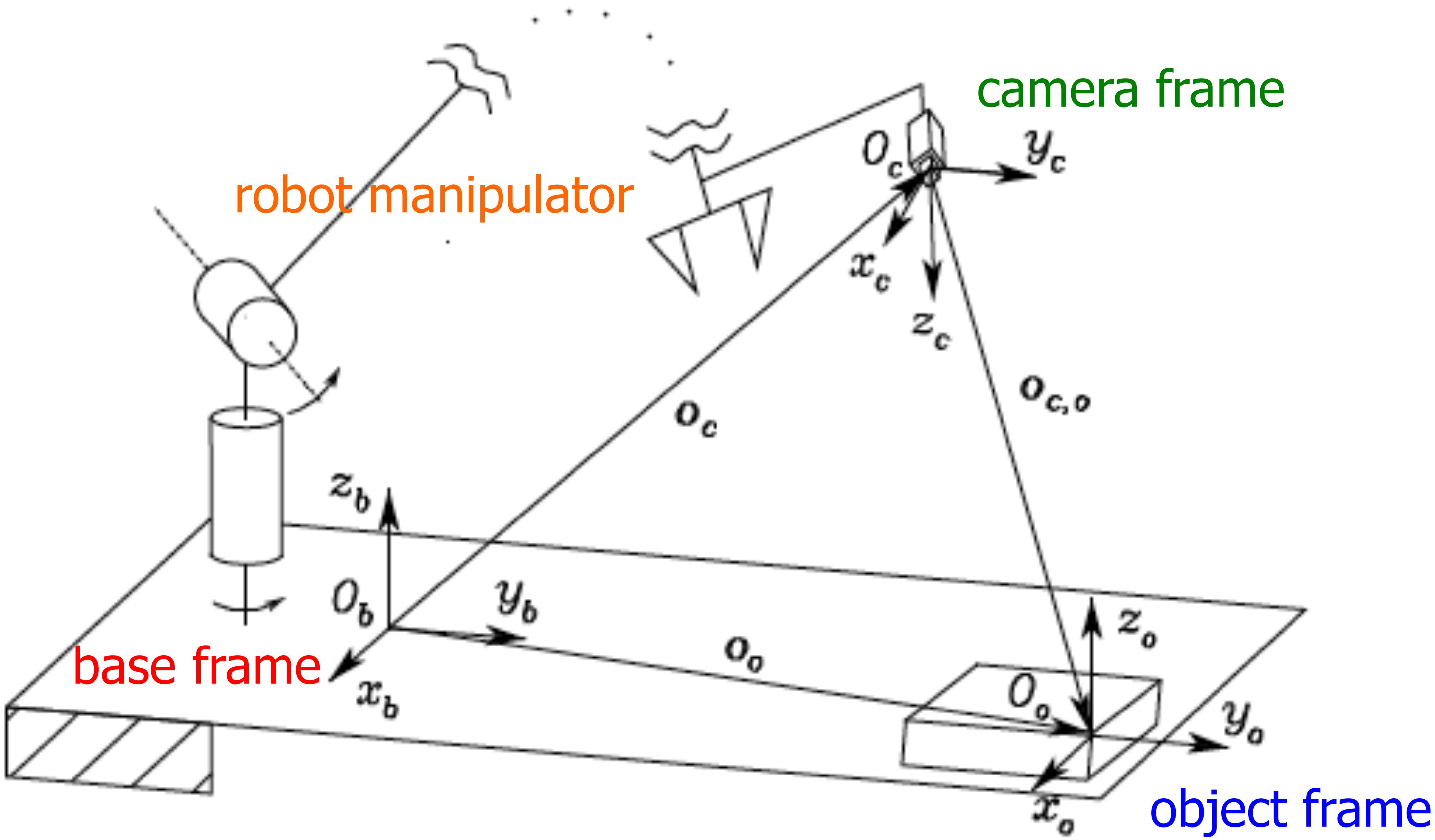

1. in metric units $\quad X_f = -\dfrac{f\,{}^c p_x}{{}^c p_z} \quad Y_f = -\dfrac{f\,{}^c p_y}{{}^c p_z} \;\Rightarrow\; X_f = \dfrac{f\,{}^c p_x}{{}^c p_z} \quad Y_f = \dfrac{f\,{}^c p_y}{{}^c p_z}$

2. in pixel $\quad \ldots \;\Rightarrow\; X_I = \dfrac{\alpha_x f\,{}^c p_x}{{}^c p_z} + X_0 \quad Y_I = \dfrac{\alpha_y f\,{}^c p_y}{{}^c p_z} + Y_0$

3. LINEAR MAP in homogeneous coordinates $\quad \ldots \;\Rightarrow$

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

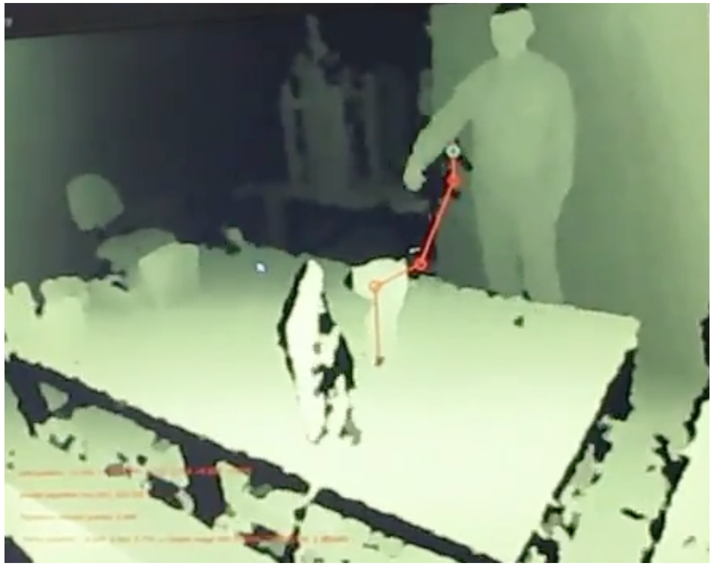
# Eye-in-hand camera




Relevant reference frames for visual-based tasks

# 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

depths

focal length

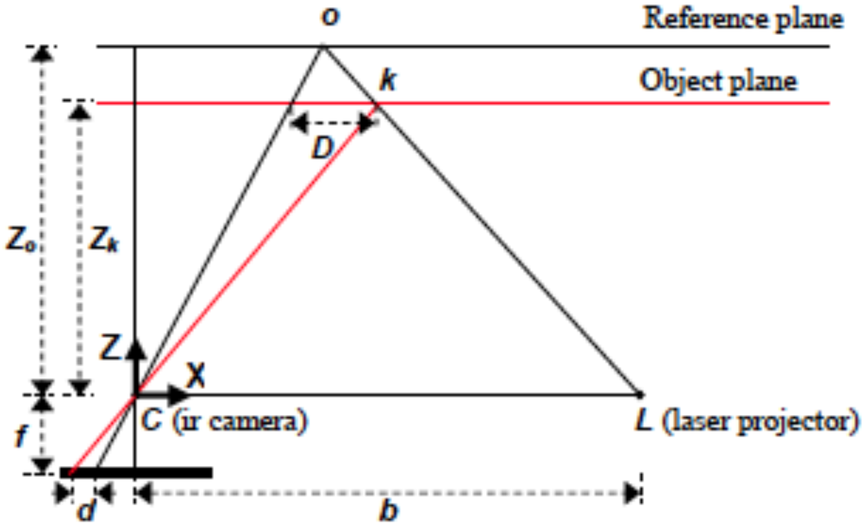



image plane baseline

- 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)

$$\frac{D}{b} = \frac{z_0 - z_k}{z_0} \quad \& \quad \frac{d}{f} = \frac{D}{z_k} \quad \Rightarrow \quad z_k = \frac{z_0}{1 + \dfrac{d}{fb} z_0}$$

$$x_k = -\frac{z_k}{f}(X_k - X_0 + \delta X)$$

$$y_k = -\frac{z_k}{f}(Y_k - Y_0 + \delta Y)$$

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 $X_0, Y_0$)

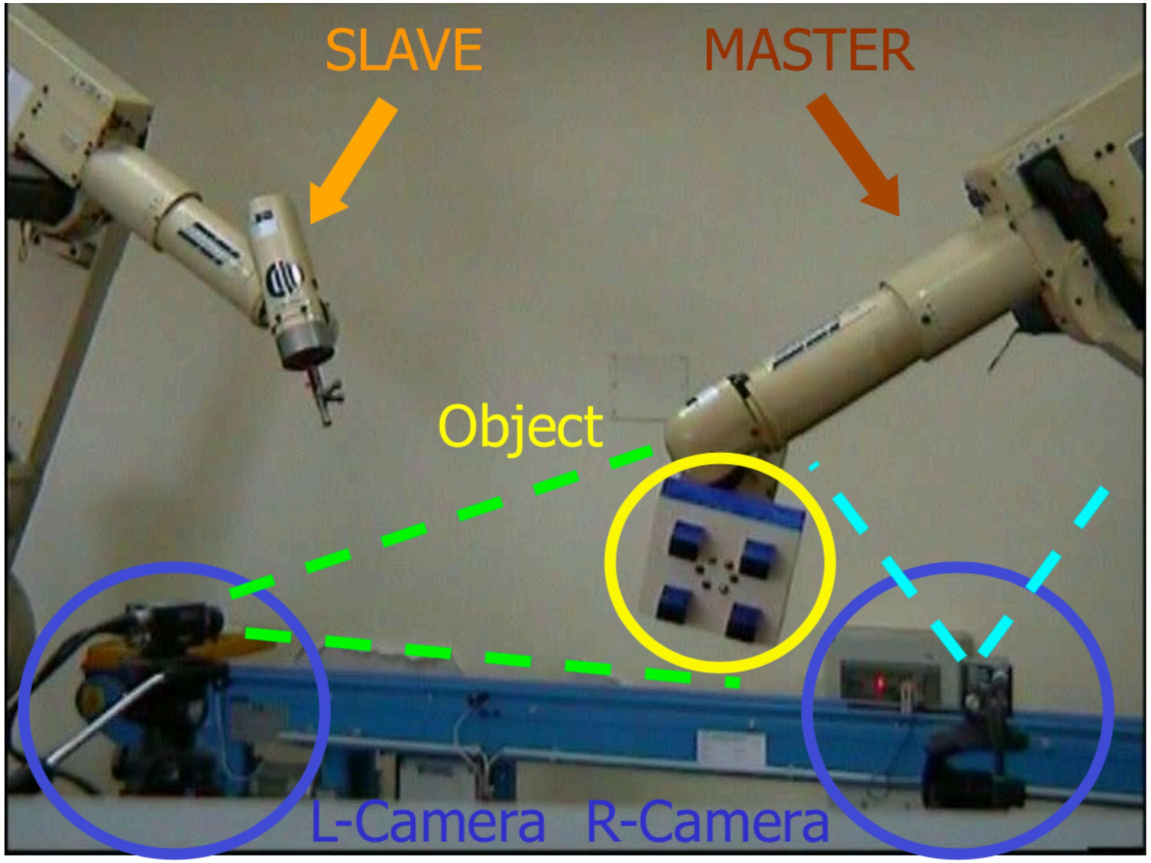
# How Kinect works
## (a 2-minute illustration...)

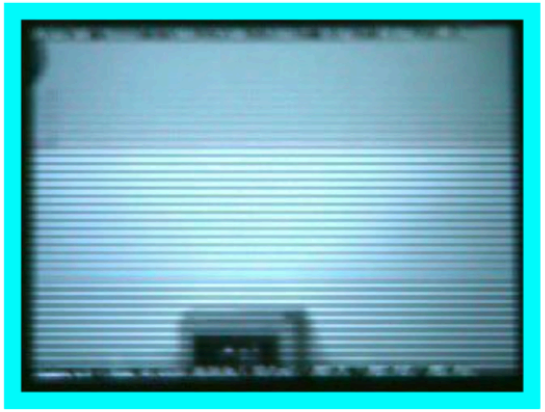

video

http://youtu.be/uq9SEJxZiUg

# Manipulators and vision systems

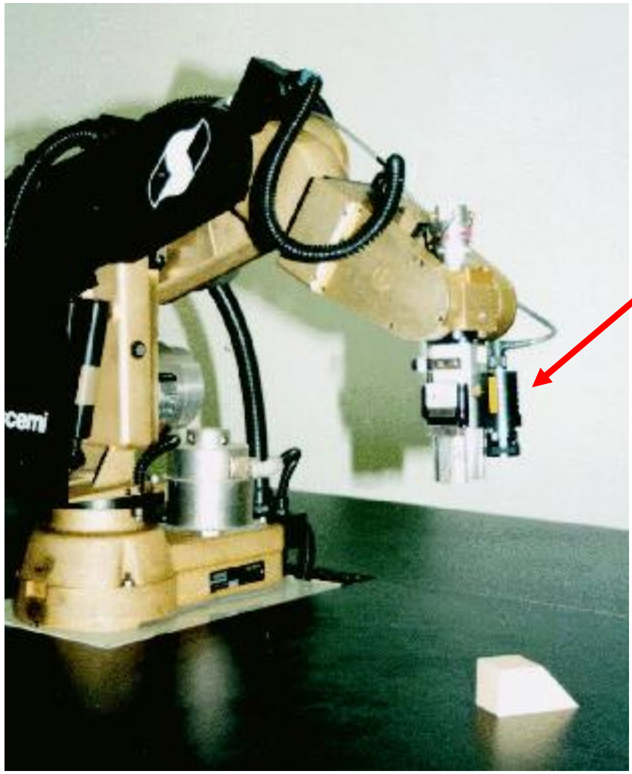
- stereovision with two external cameras, fixed in the environment (eye-to-hand)

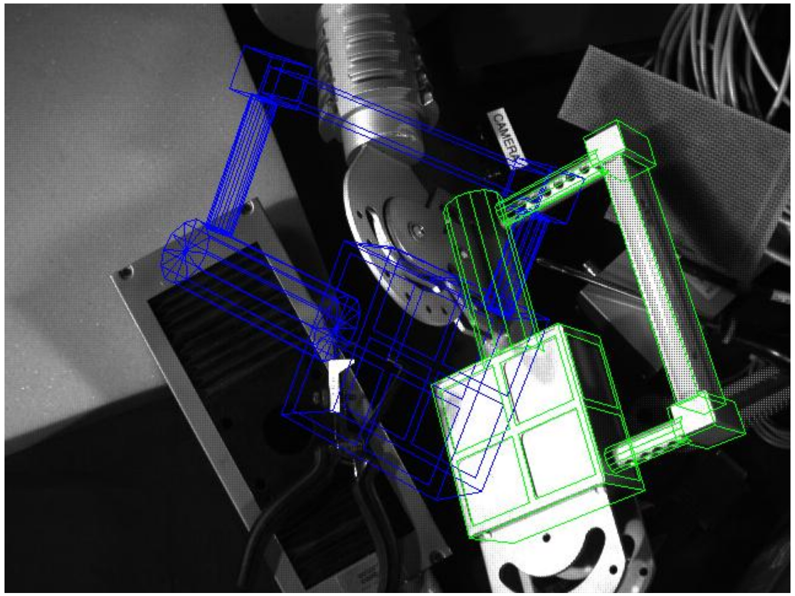


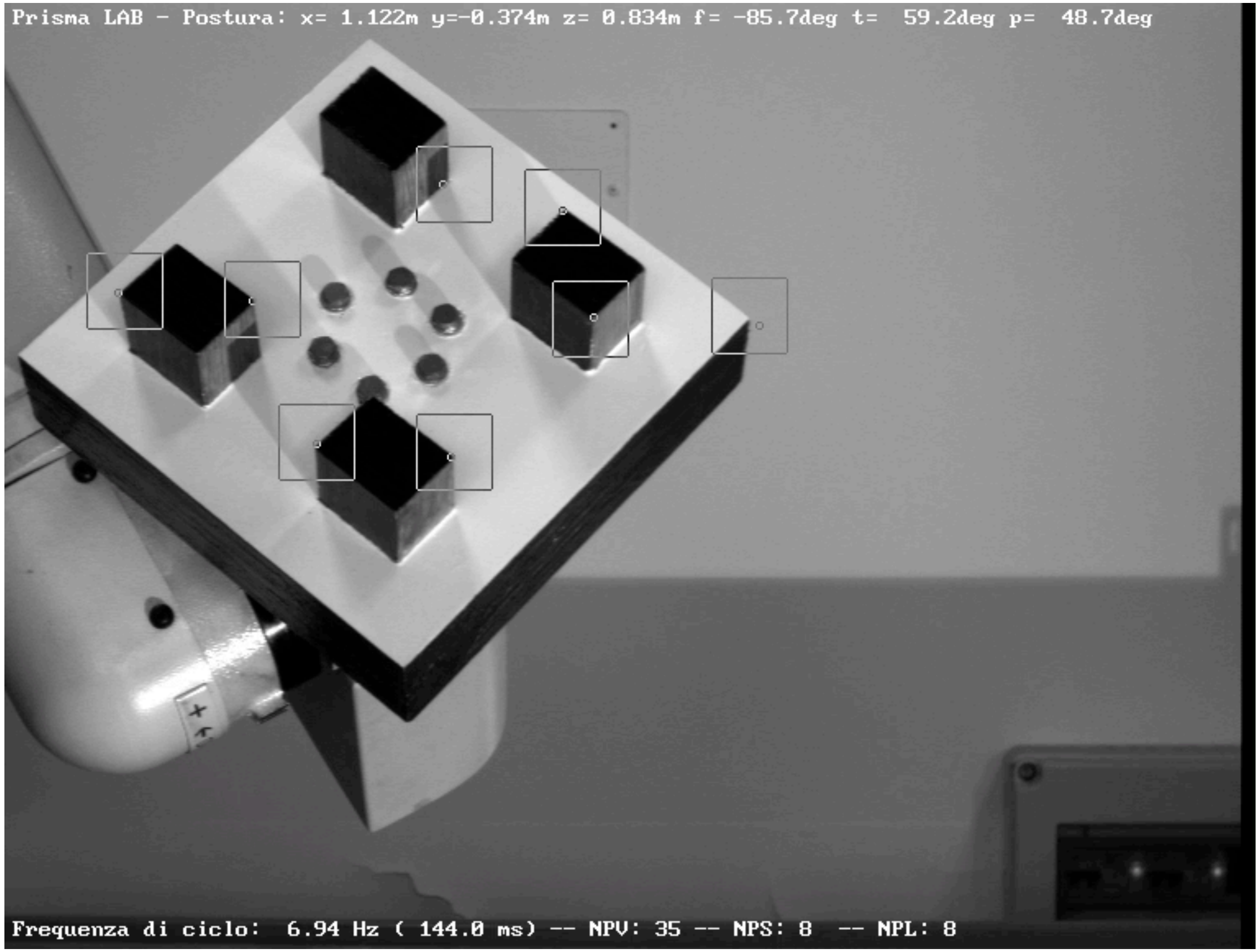
# Manipulators and vision systems

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





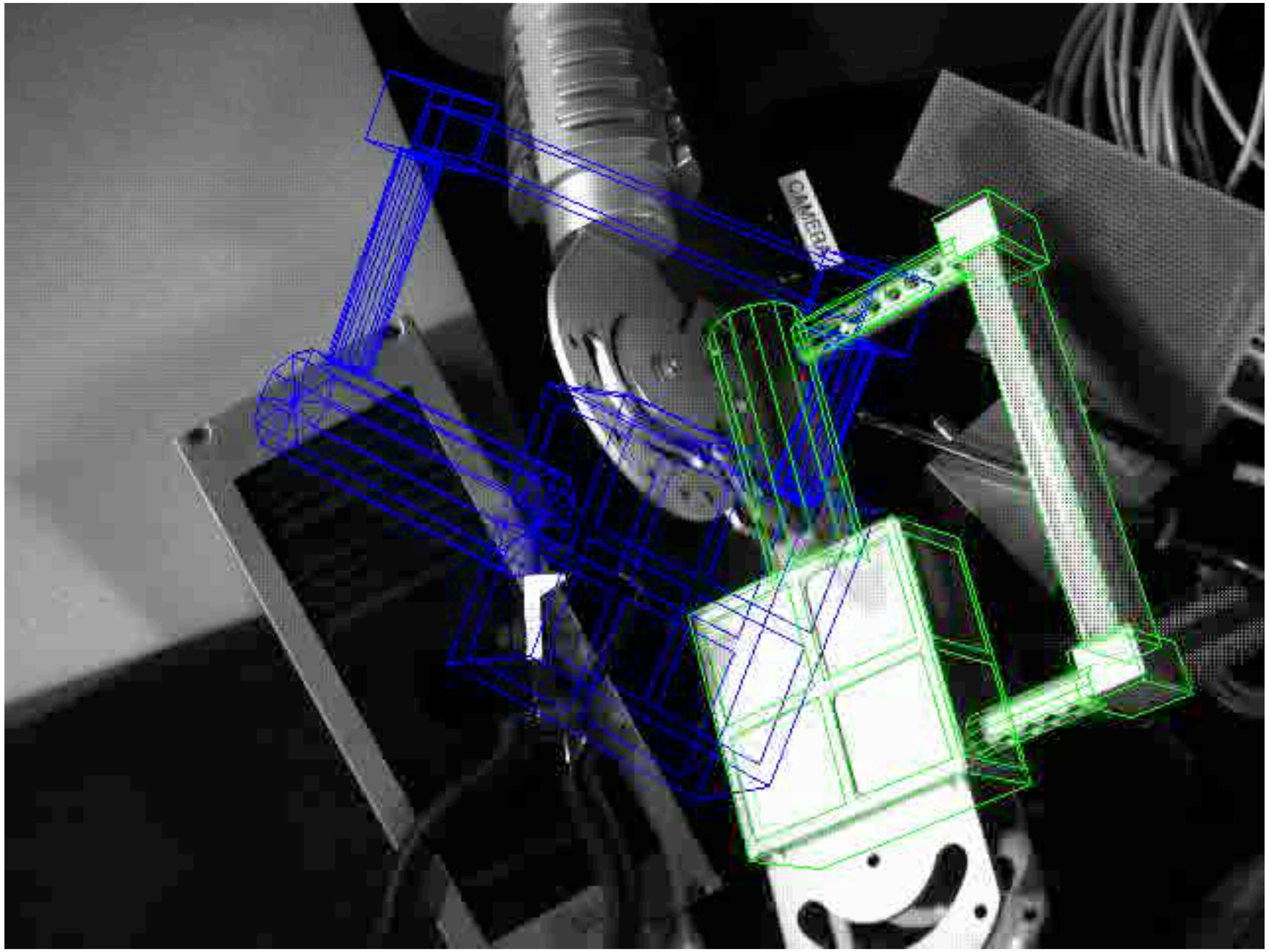
# Visual tracking eye-to-hand




video

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

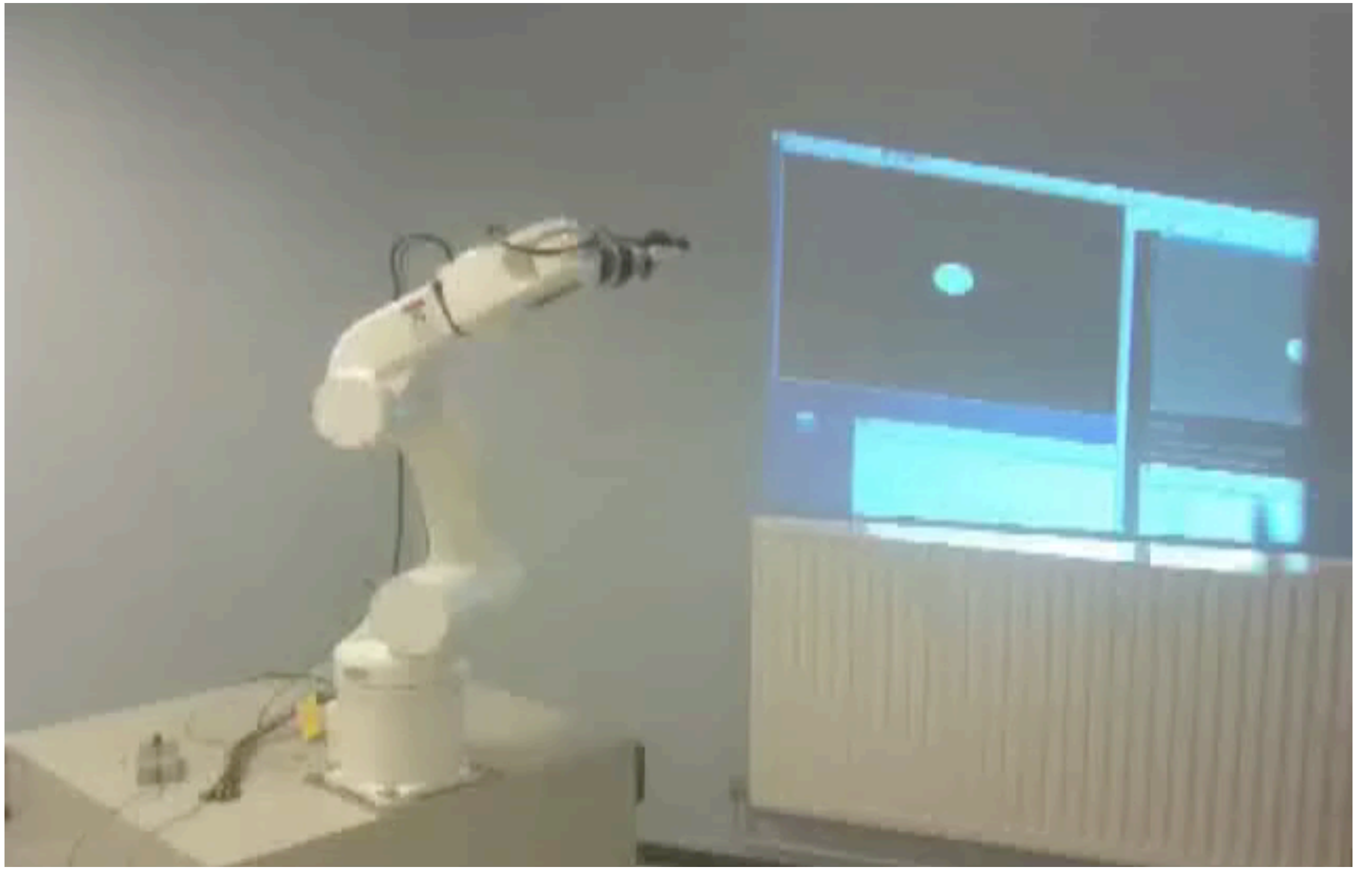
# Visual servoing eye-in-hand




video

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

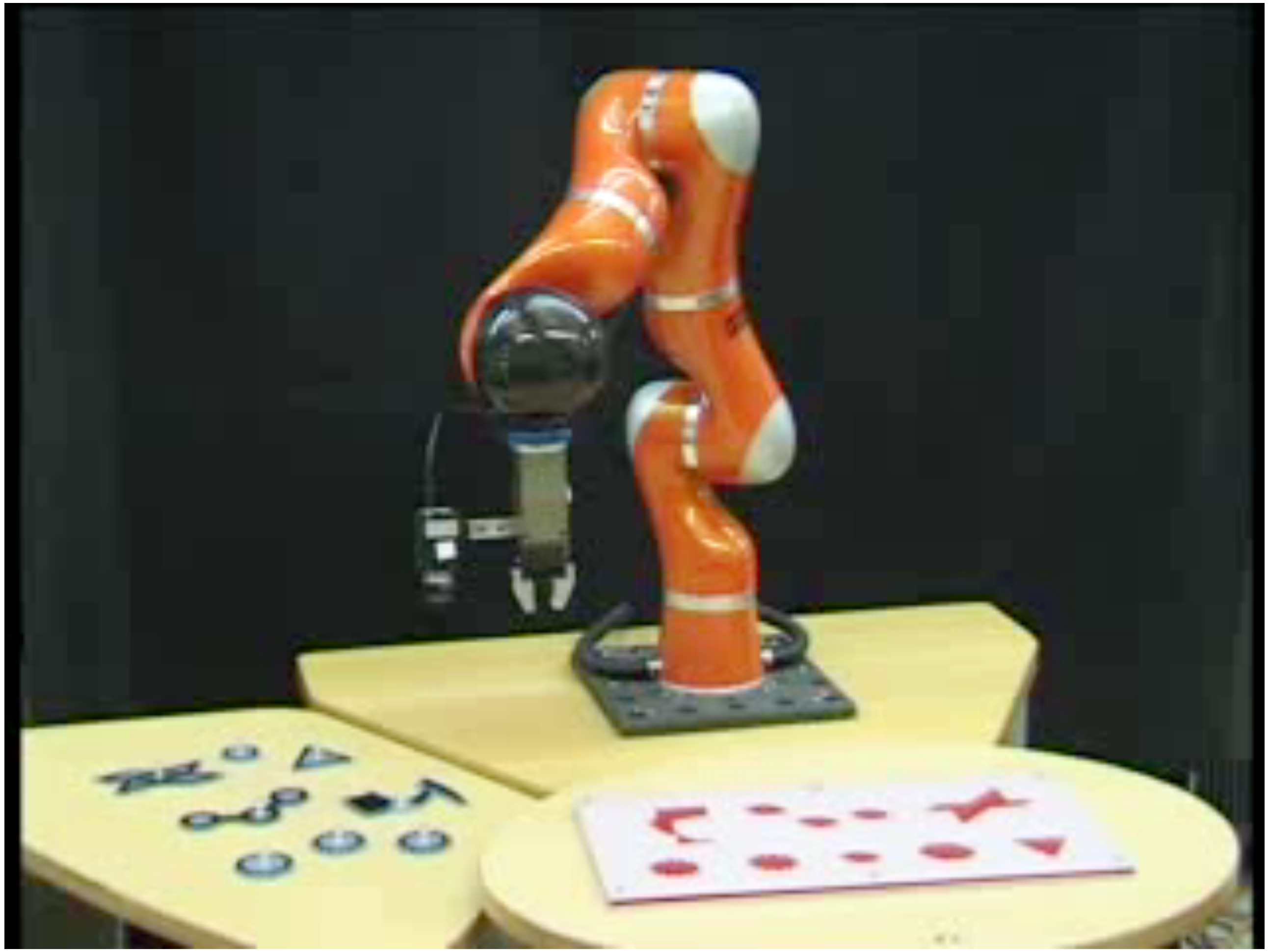
# Visual servoing and redundancy



video

visual servoing of circle feature ($m = 3$: $p_x, p_y, r$) by Adept Viper robot ($n = 6$): redundancy is used for avoiding joint range limits (IRISA/INRIA, Rennes)

# Combined visual/force assembly



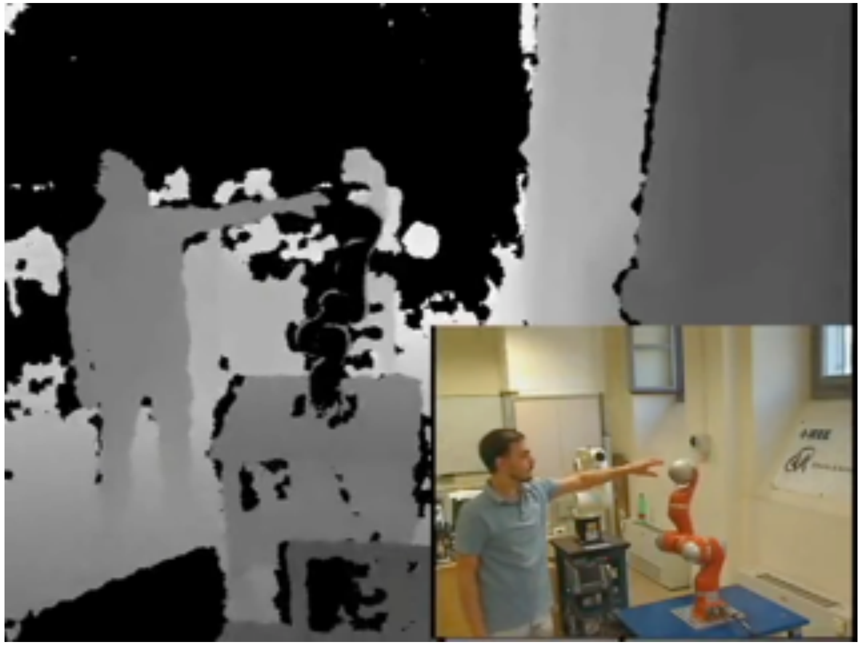
video

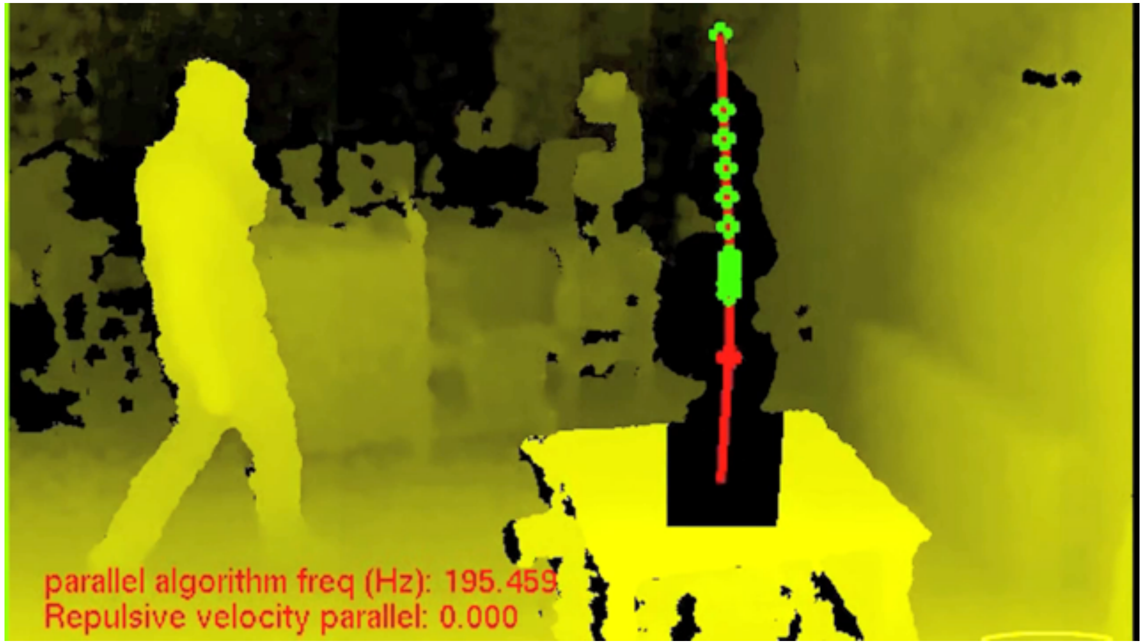
KUKA LWR with eye-in-hand camera and F/T sensor
(DLR, IEEE ICRA'07 demo in Roma)

# On-line distance computation and human-robot coexistence

video

video






monitoring left- and right-hand distance to the robot (at same time)

several control points on robot skeleton used to compute distances and control motion

KUKA LWR with a Kinect monitoring its workspace
(DIAG Robotics Laboratory, EU project SAPHARI, 2013)