Robotics 1

Robot components:
Exteroceptive sensors

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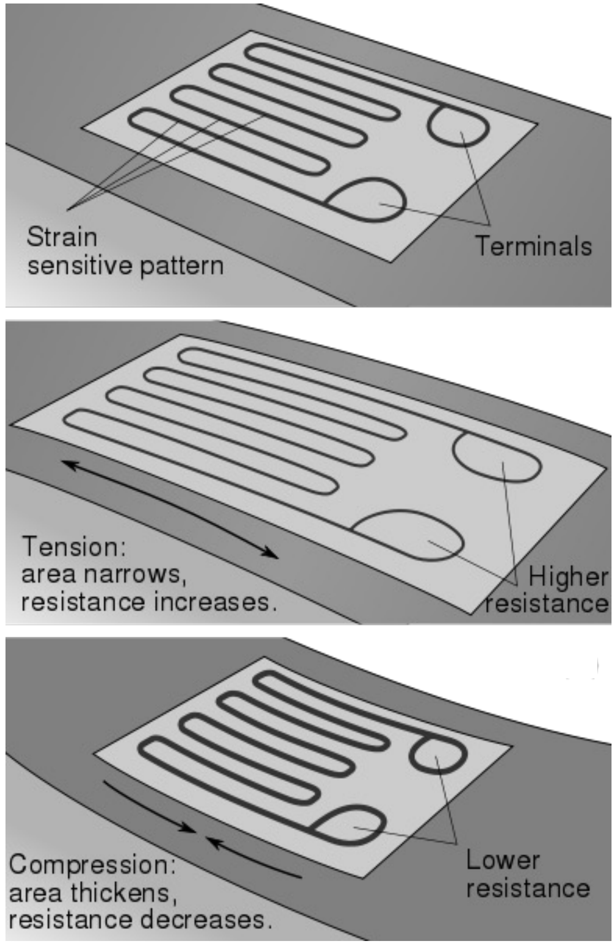
Summary

- 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 and RGB-Depth sensors
- 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

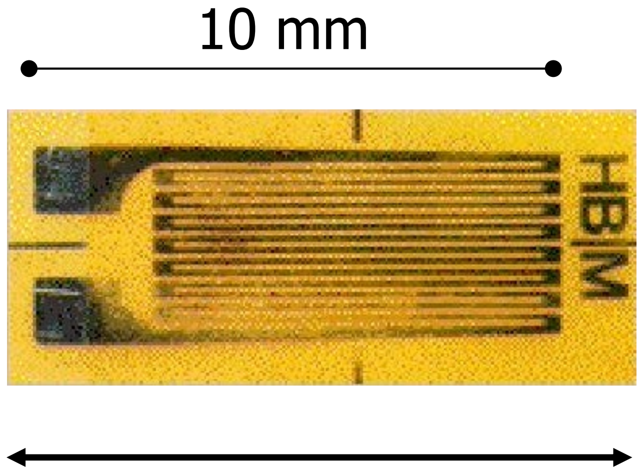


$$\frac{\partial R}{\partial L} > 0 \qquad \frac{\partial R}{\partial S} < 0$$

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

temperature

Strain gauges



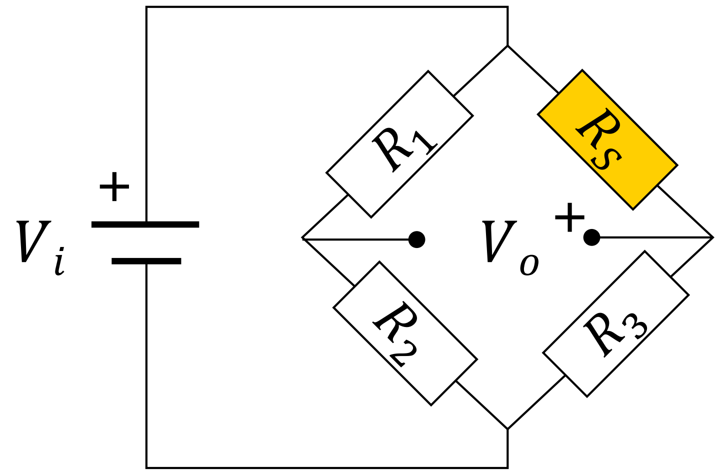
principal measurement axis

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

strain ε

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

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



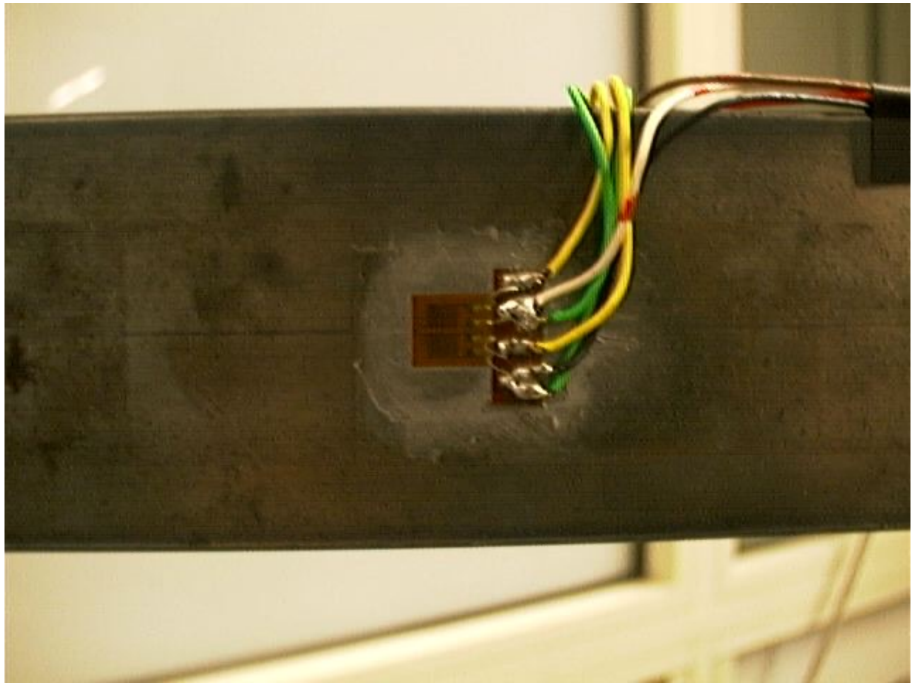
- R_1, R_2, R_3 very well matched ($\approx R$)
- $R_S \approx R$ at rest (no stress)
- two-point bridges have 2 strain gauges connected oppositely (↗ sensitivity)

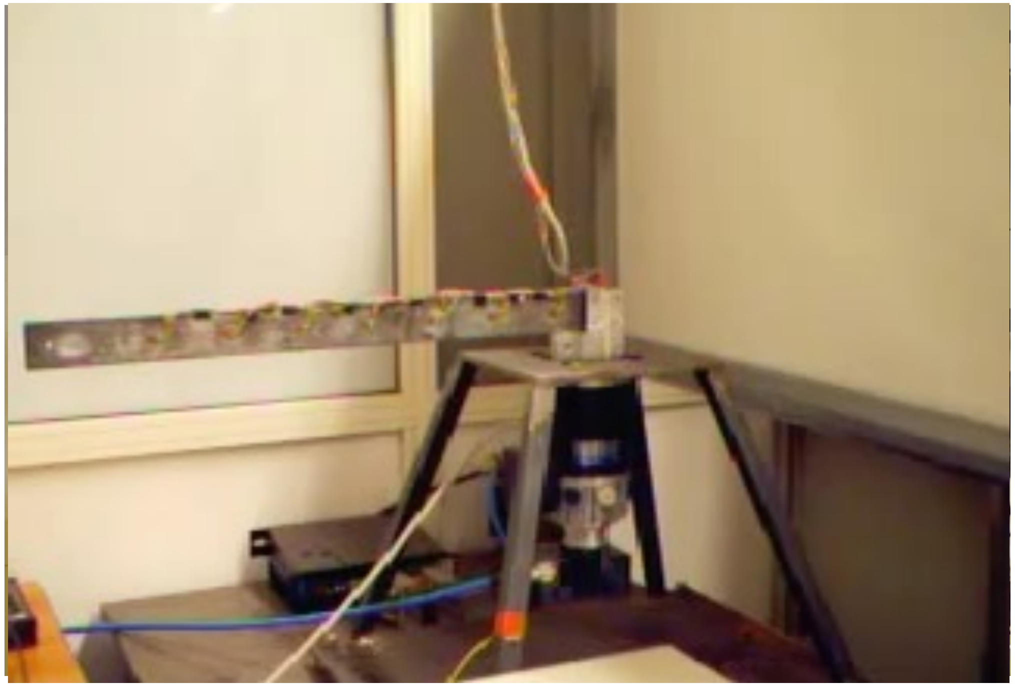
if R_1 has the same dependence on T of R_S
thermal variations will be compensated

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

Strain gauges in flexible arms

video



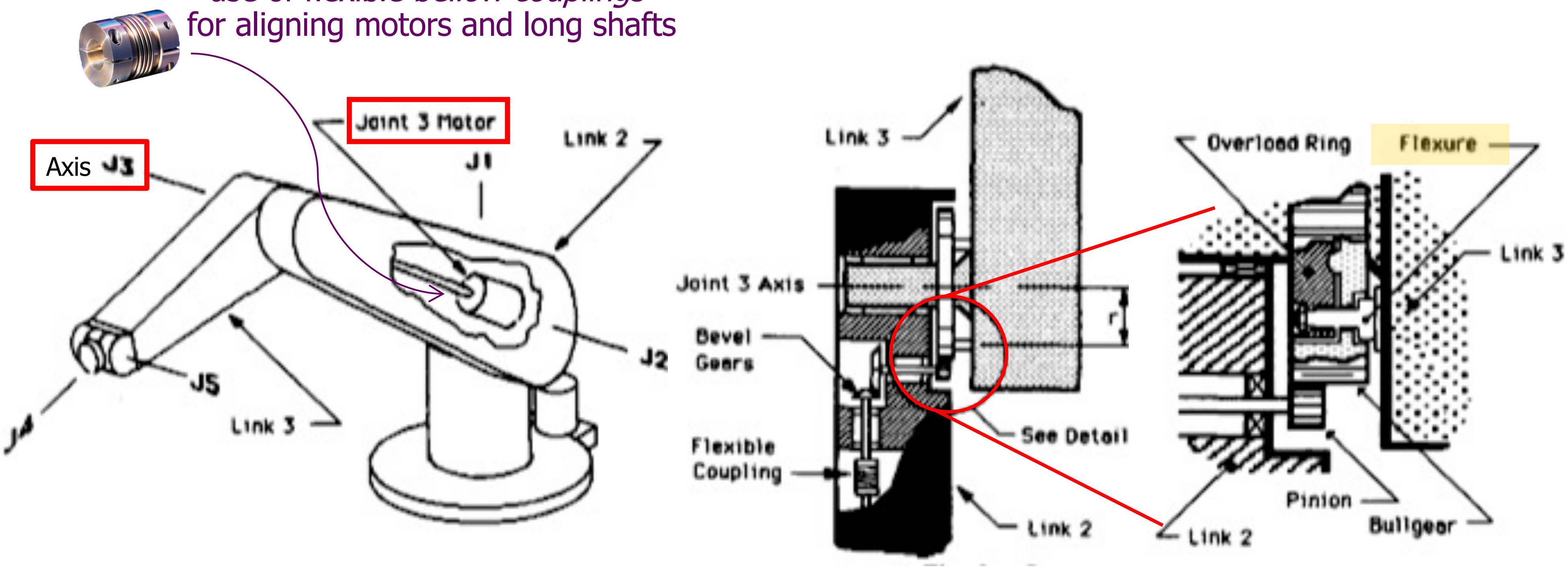


7 strain gauges glued[1] to a flexible aluminum beam (a robot "link") measuring its local "curvature" in dynamic bending during slew motions (a proprioceptive use of these sensors)

[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 elastic 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

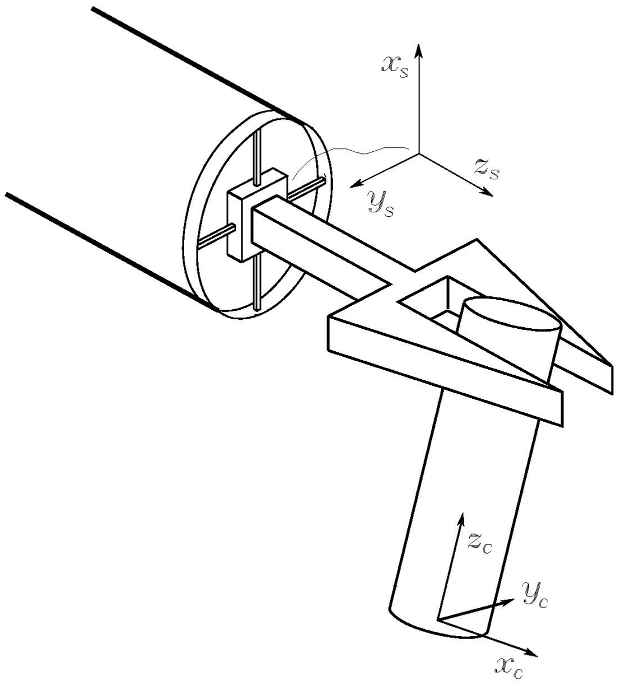
- a device (with the outer form of a cylinder), typically located between the last robot link and its end-effector
- top and bottom plates are mechanically connected by a number of deformable elements subject to strain under the action of forces and moments

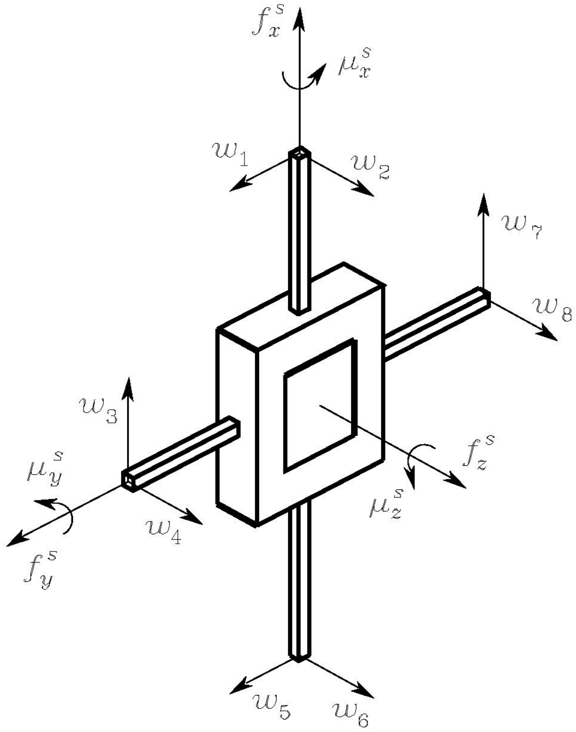
ATI
(USA)

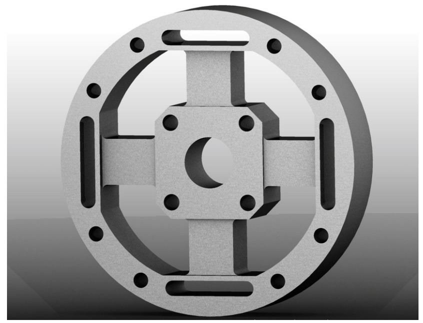
Schunk
(DEU)

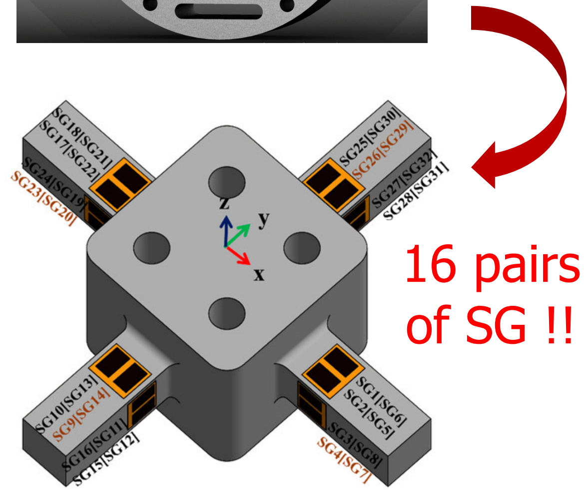
- there should be at least one such element in any direction along/around which a force or torque measure is needed
- since a complete "decoupling" of these measurements is hard to obtain, there are $N \geq 6$ such deformable elements
- on each element, a pair of strain gauges is glued so as to undergo opposite deformations (e.g., traction/compression) along or around 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

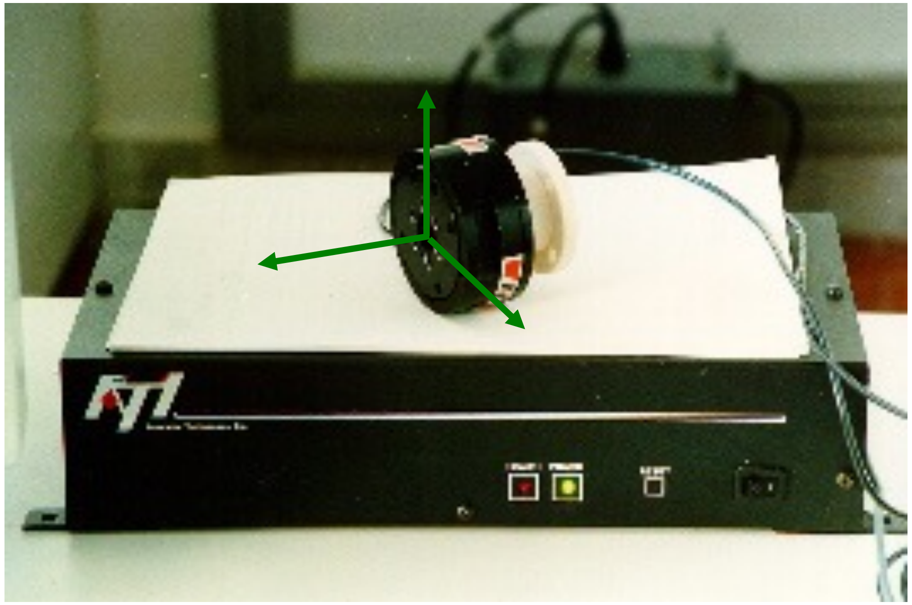
6D force/torque sensors

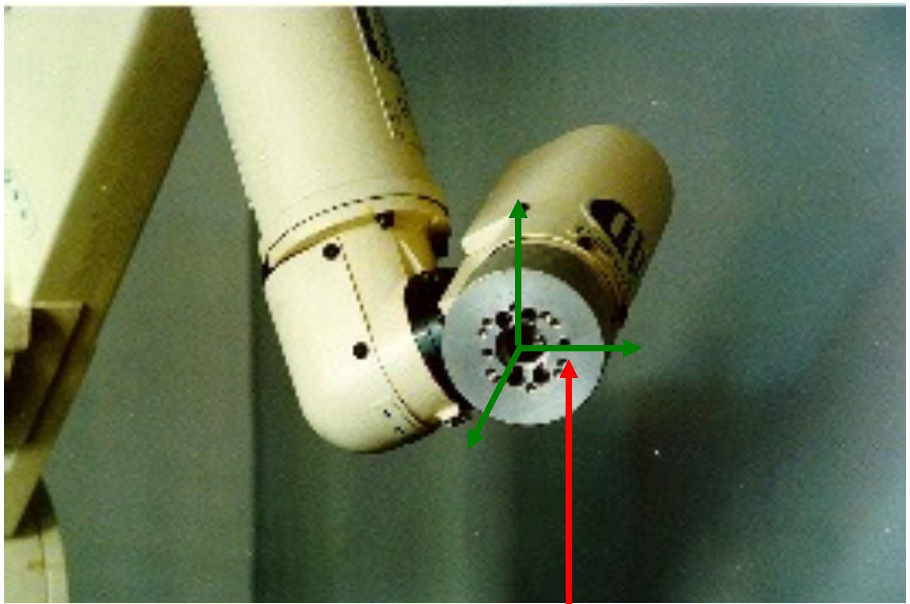
- ATI series
- cost (in 2016): about 6 K€ for Mini45 model + 700 € DAQ card

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)

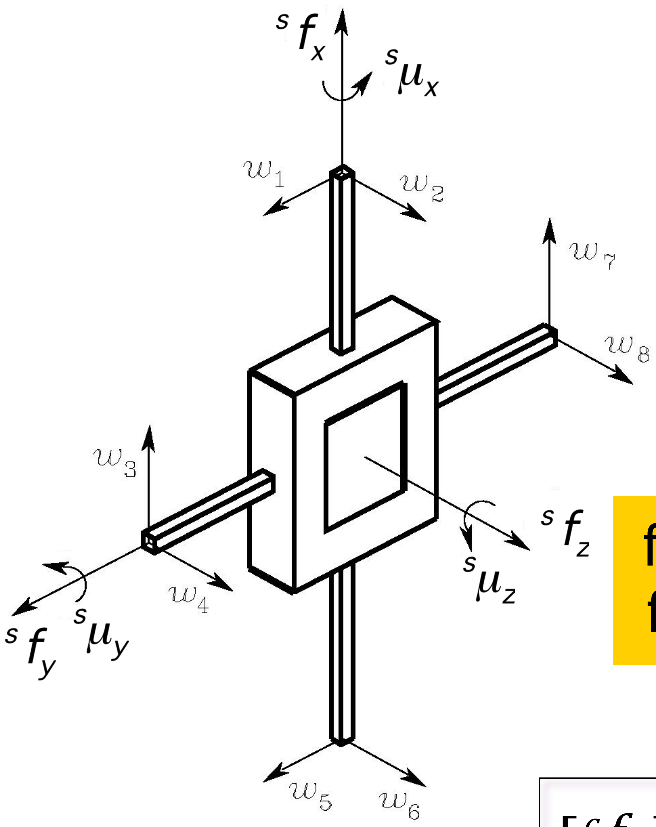




Net F/T interface (Net Box)
with EtherNet/IP and
CAN bus communication

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

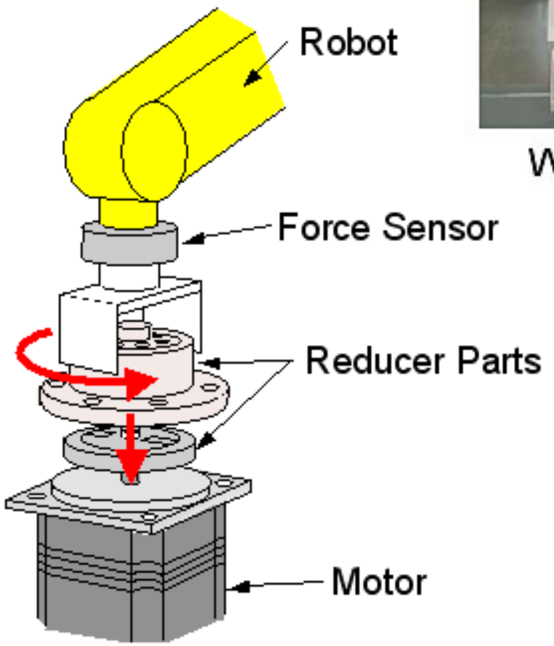
$$\begin{bmatrix} ^c f_c \\ ^c \mu_c \end{bmatrix} = \begin{bmatrix} ^c R_s & O \\ S(^c r_{cs})\, ^c R_s & ^c R_s \end{bmatrix} \begin{bmatrix} ^s f_s \\ ^s \mu_s \end{bmatrix}$$

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

Typical uses of a F/T sensor

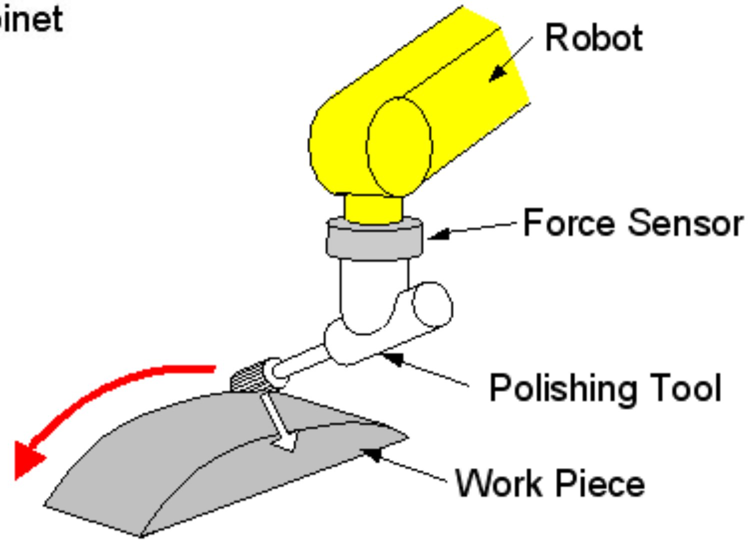
Washstand

Metal Cabinet



Phase matching by force sensing

Gear Parts



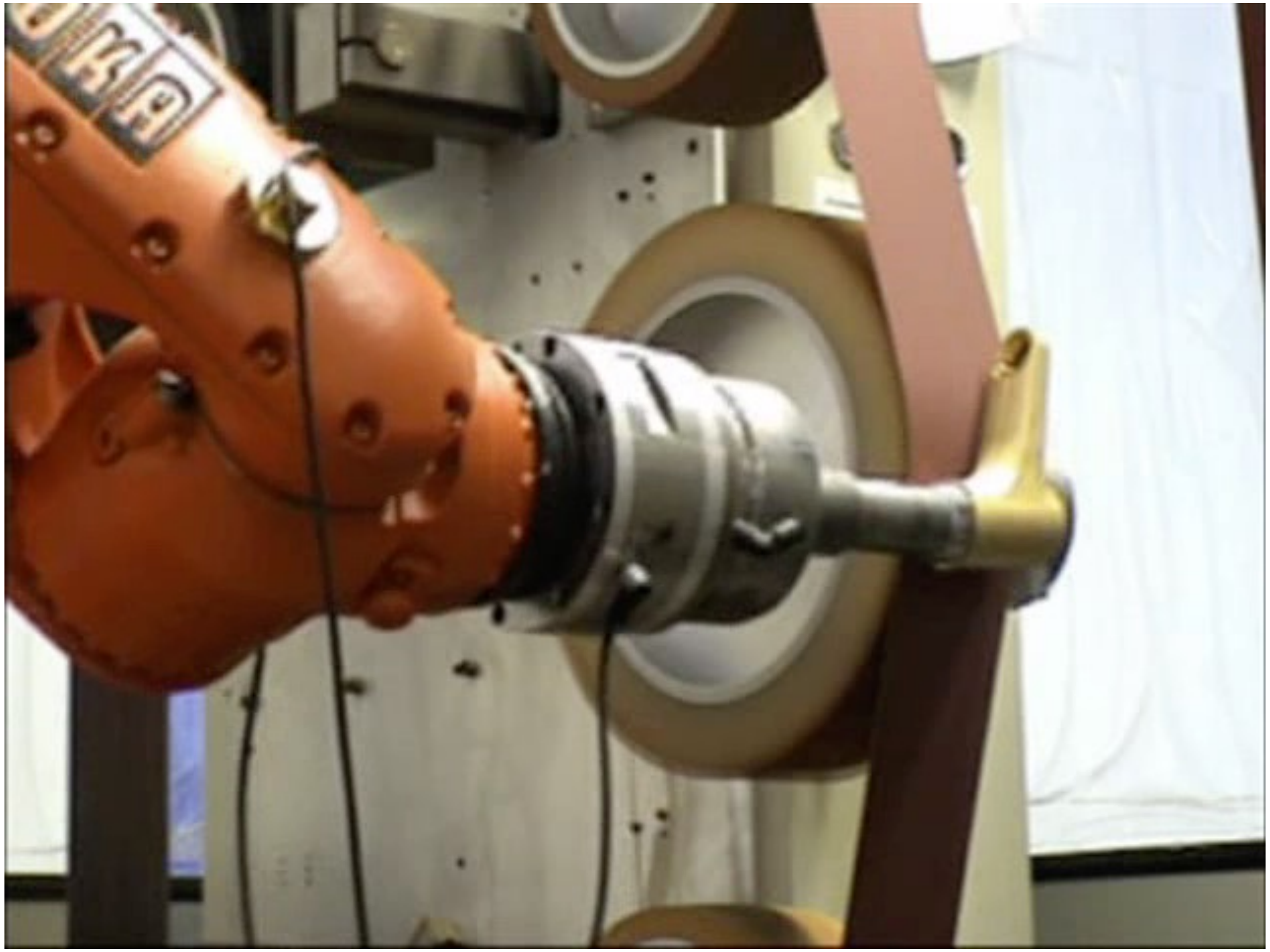
Following with constant pushing force

Active assembly with F/T sensor

video

ABB robot with ATI F/T sensor

Surface finishing with F/T sensor



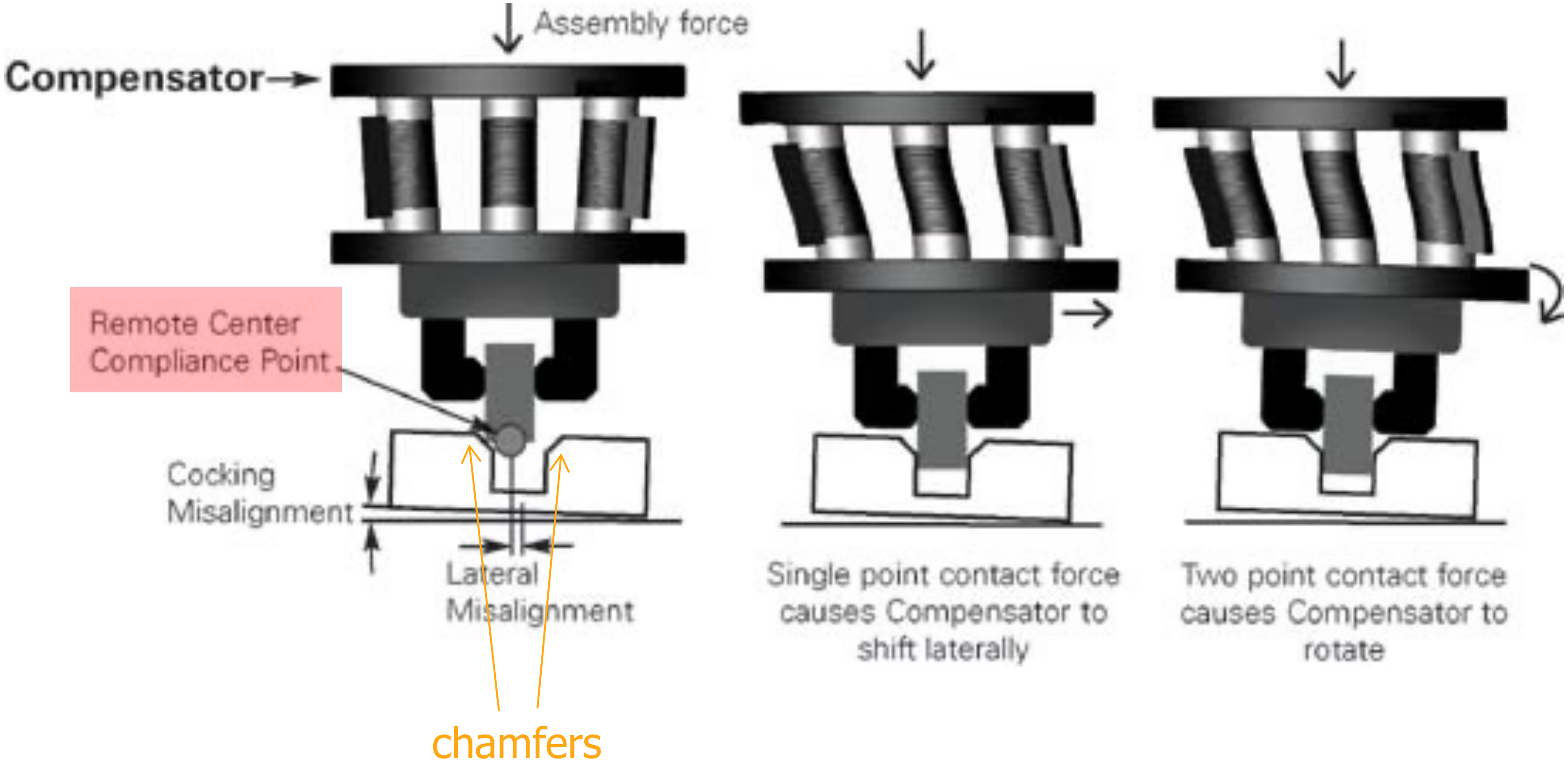
video

KUKA robot with F/T sensor

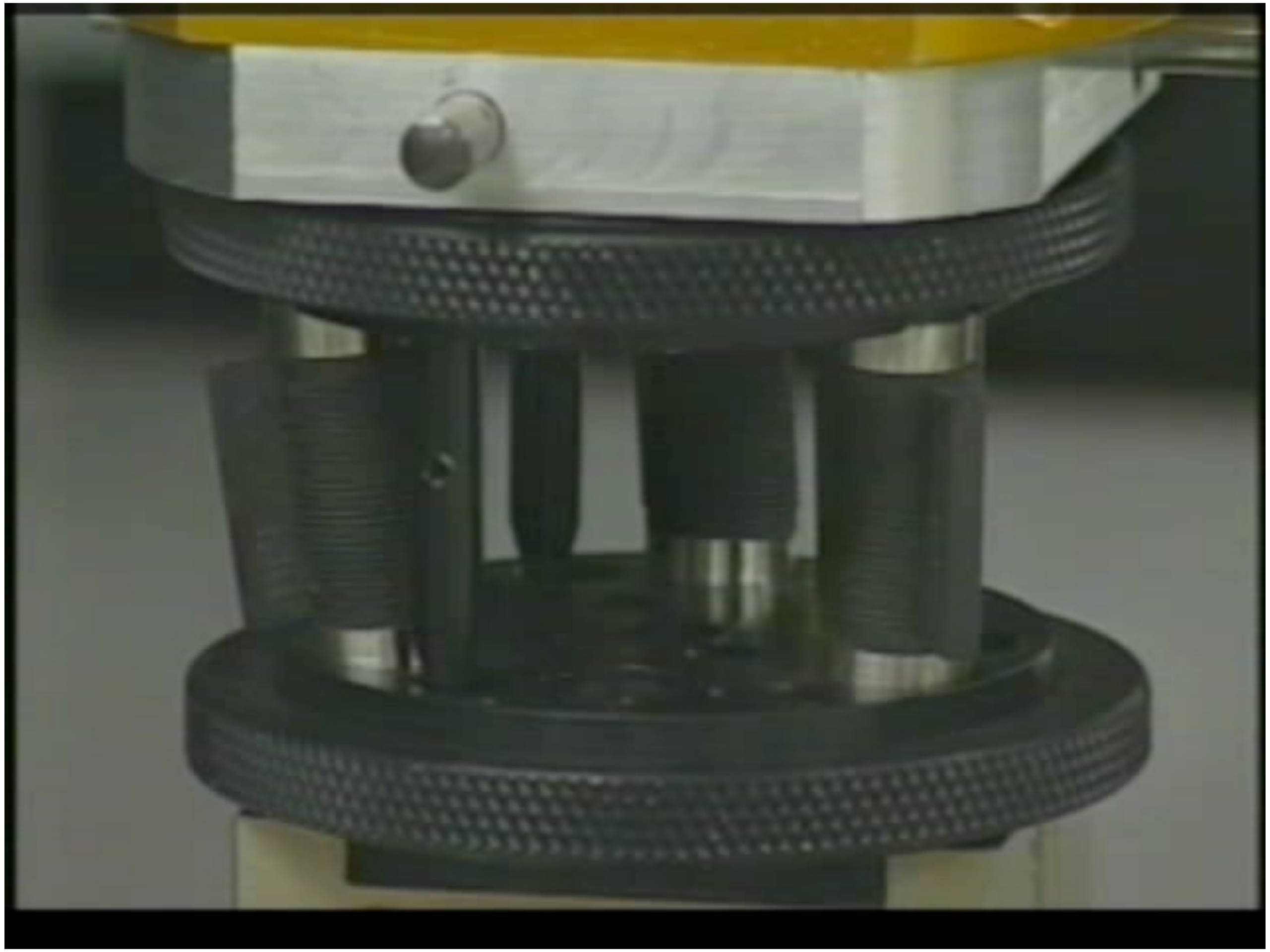
Passive RCC device

- 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

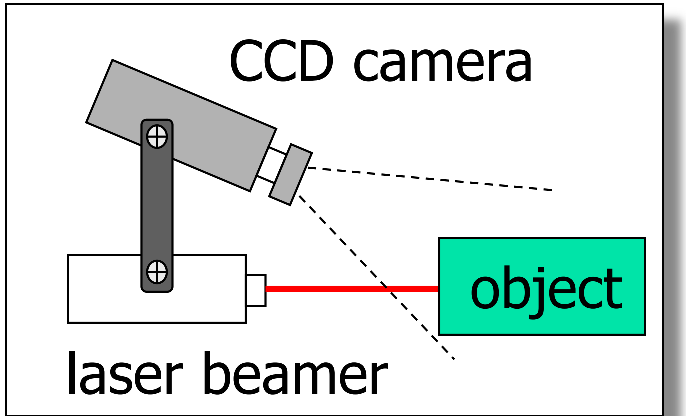


video

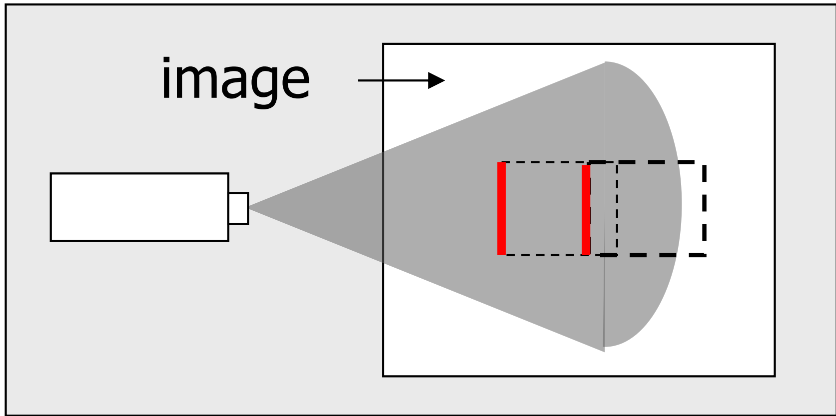
RCC by ATI Industrial Automation
http://www.ati-ia.com

Proximity/distance sensors

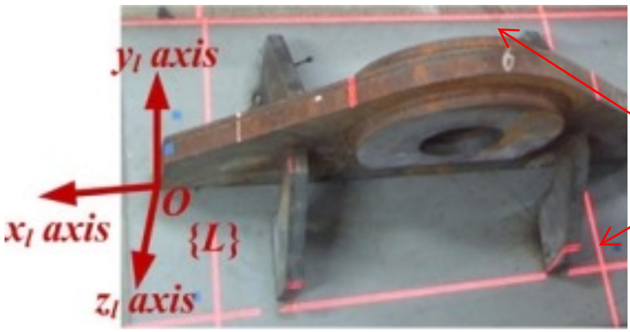
- structured light: a laser beam (coherent light source) is projected on the environment, and its planar intersection with surrounding objects is detected by a (tilted) camera
- the position of the "red pixels" on the camera image plane is in trigonometric relation with the object distance from the sensor



side view



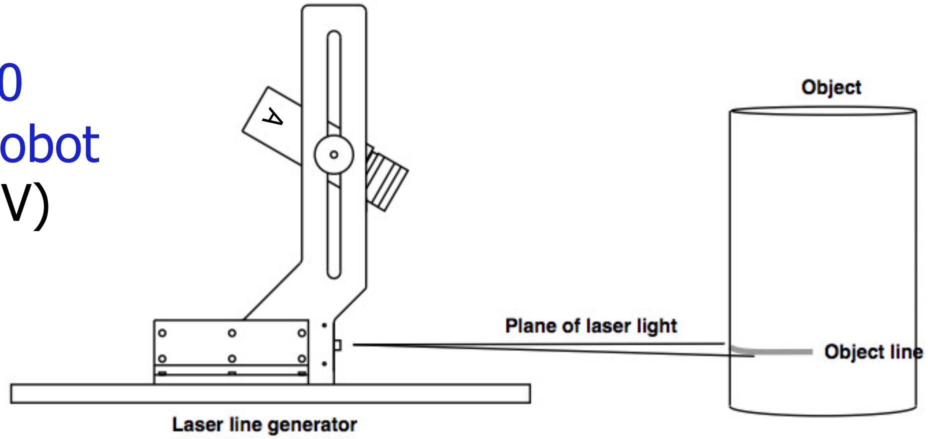
top view

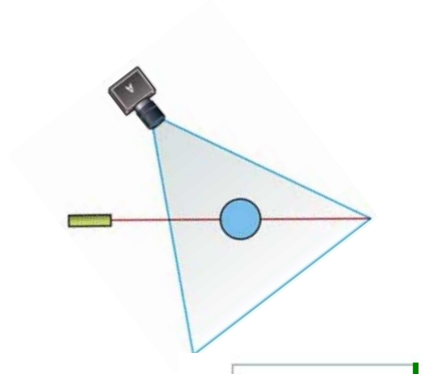


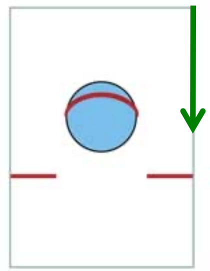
projected laser beams
(2D in this case)

Structured light sensor

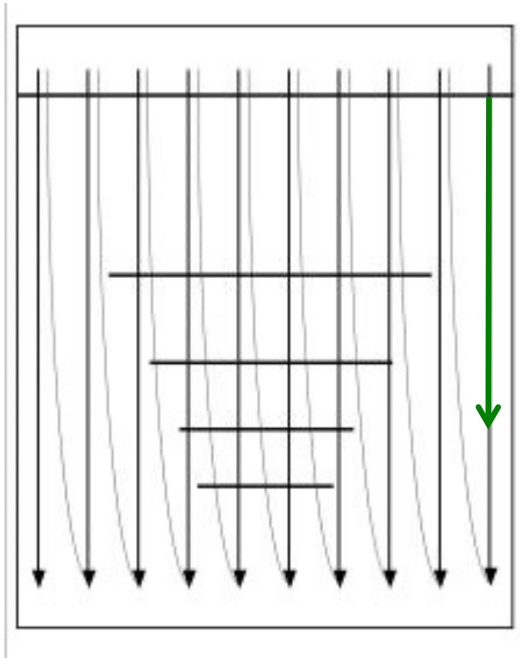
example: Sensus 500
on Nomad 200 mobile robot
(power data: 2A @12V)

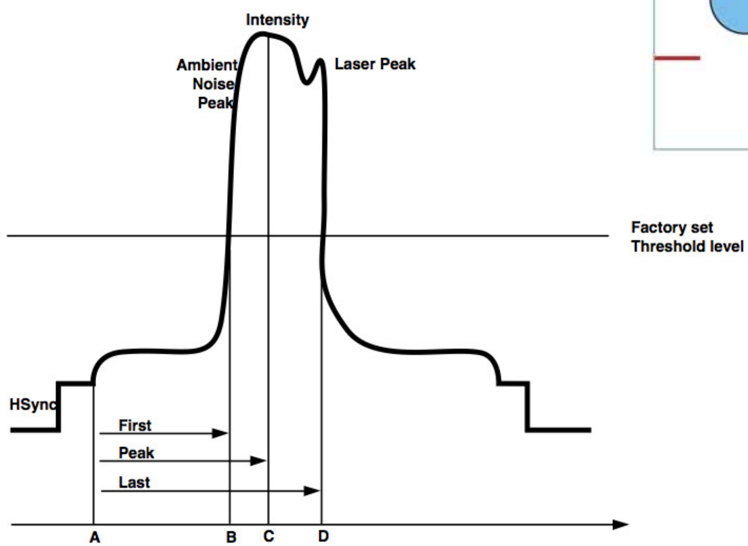






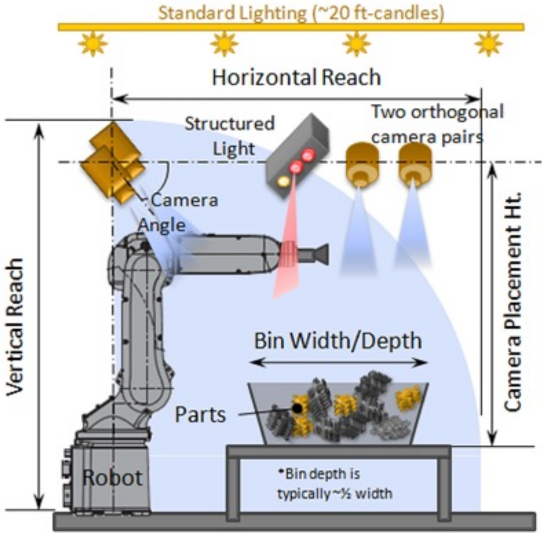
CCD camera with
510 × 490 pixels
(rotated by 90°
with respect to the
480 scan lines)



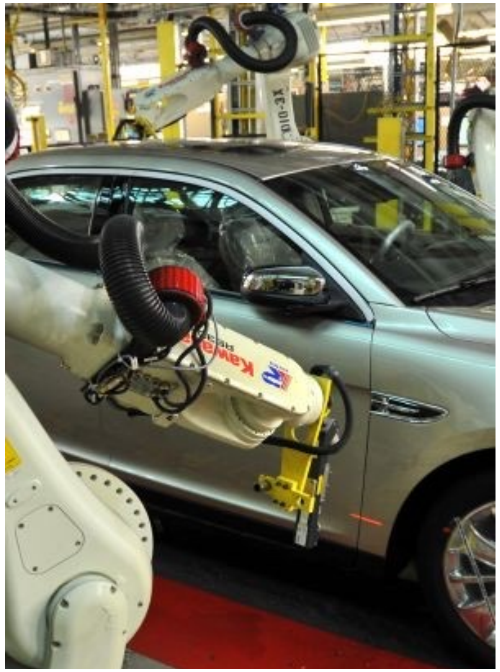


analog signal along a single scan line
with threshold level ⇒ 4 bytes of data:
pixels FIRST, LAST, PEAK; value INTENSITY

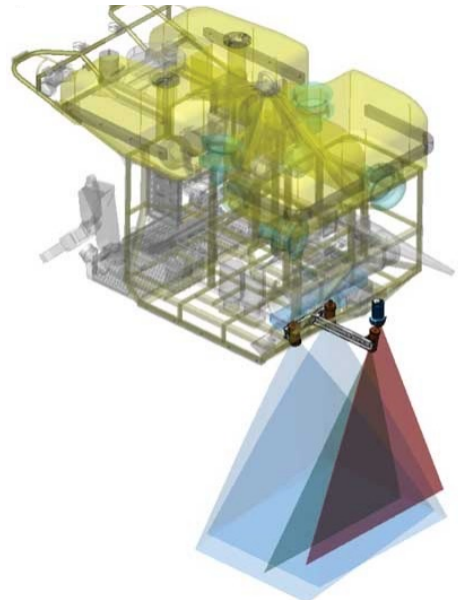
Use of structured light sensors



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.]



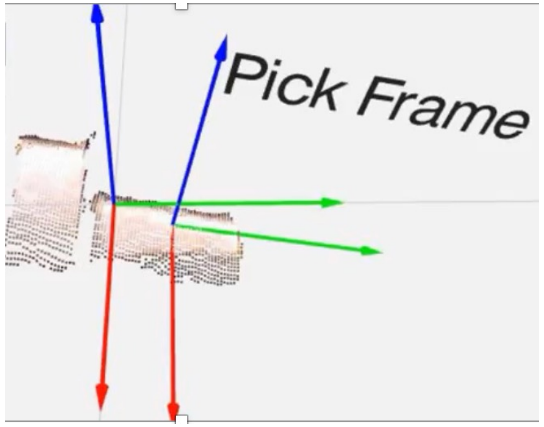
Hercules ROV + structured-laser-light imaging system for high-resolution bathymetric underwater maps [Univ. Rhode Island]

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

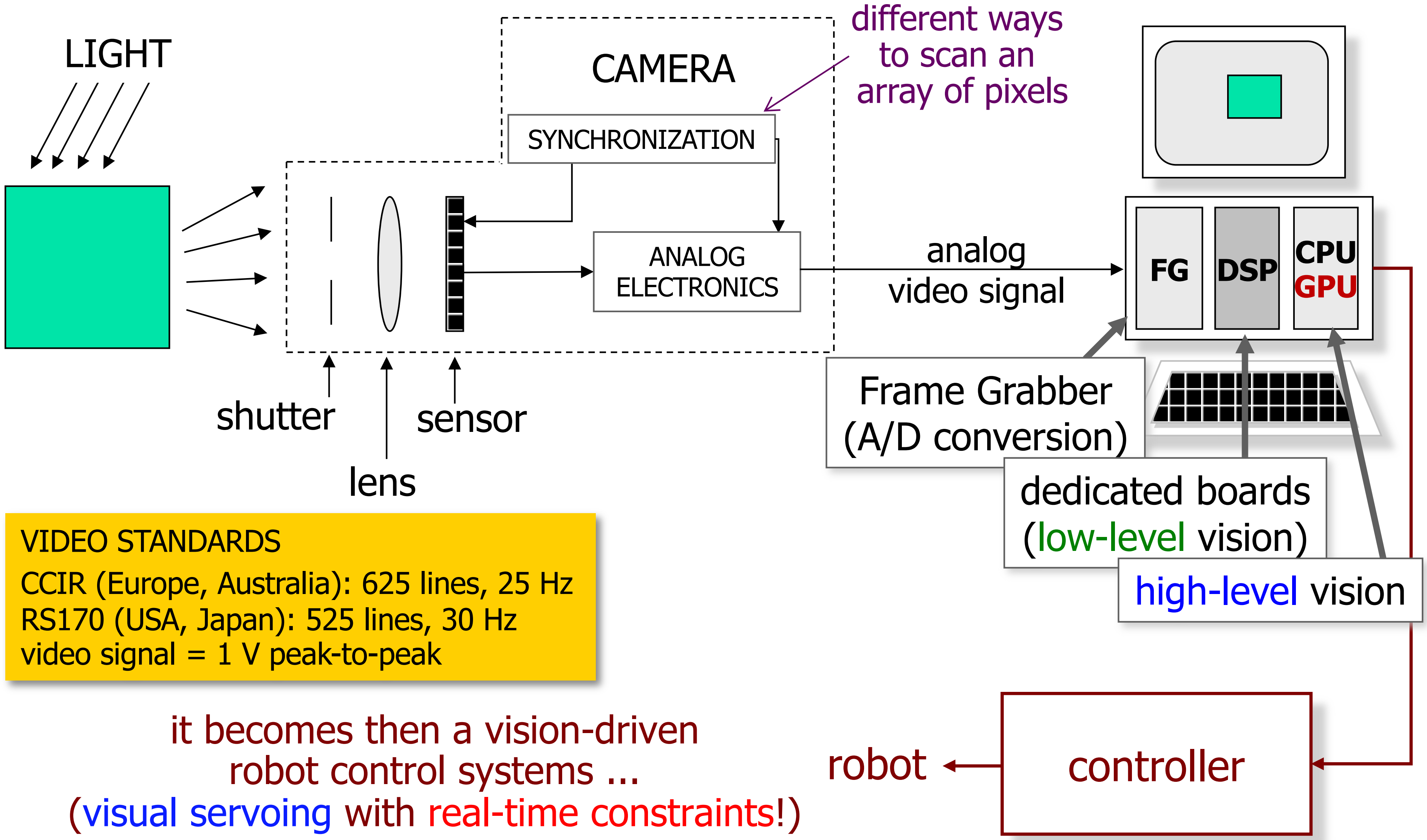
Robotic bin picking
using vision and structured light

video

video



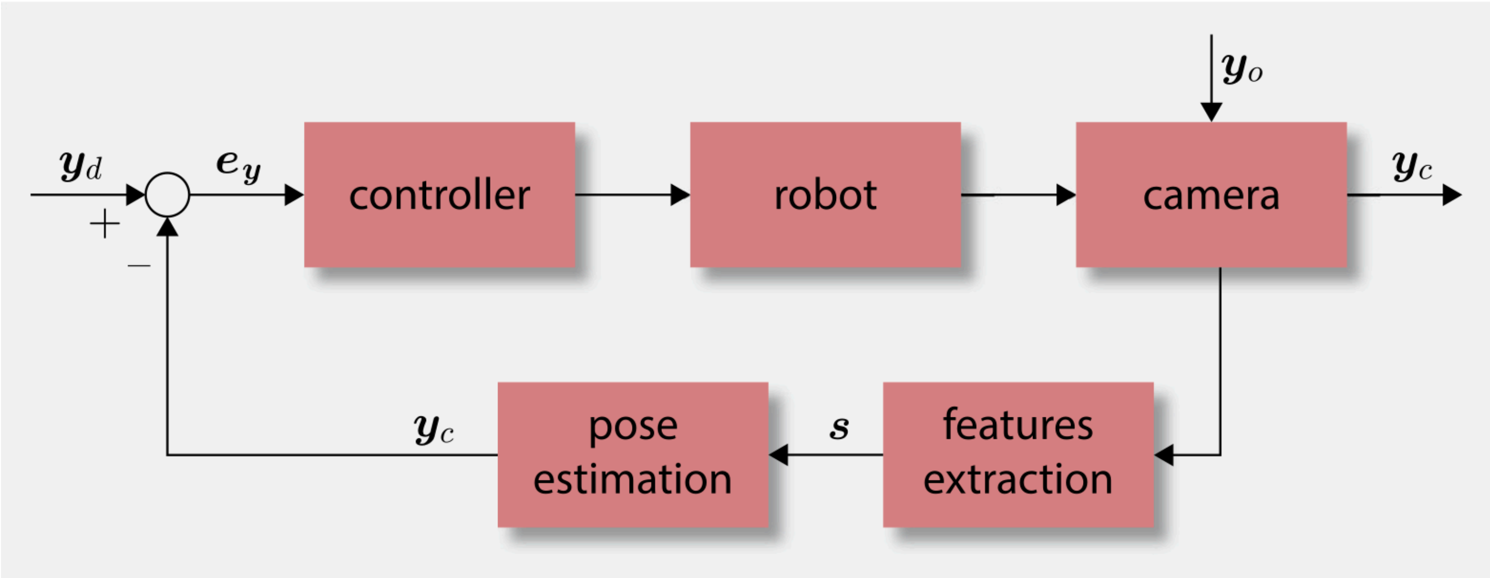
Traditional vision systems



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 ...
(visual servoing with real-time constraints!)

Visual servoing
two approaches



position-based visual servoing (PBVS)

in 3D Cartesian space

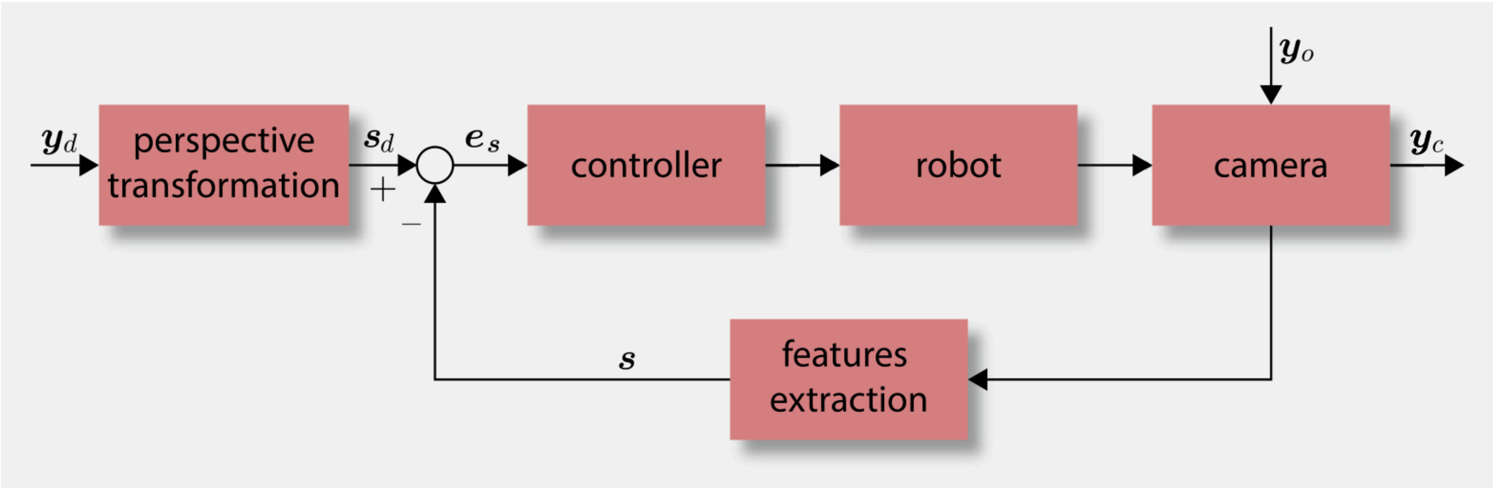


image-based visual servoing (IBVS)

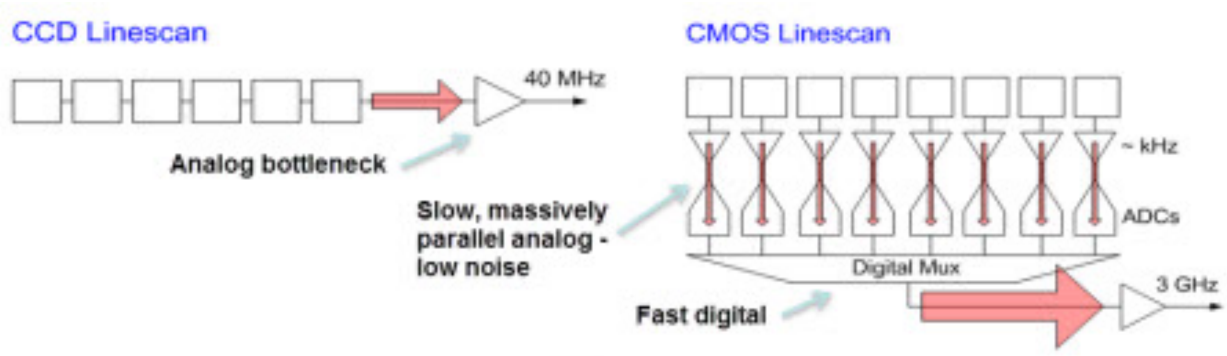
in 2D image space

block diagrams for the eye-in-hand case

... more in Robotics 2!

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

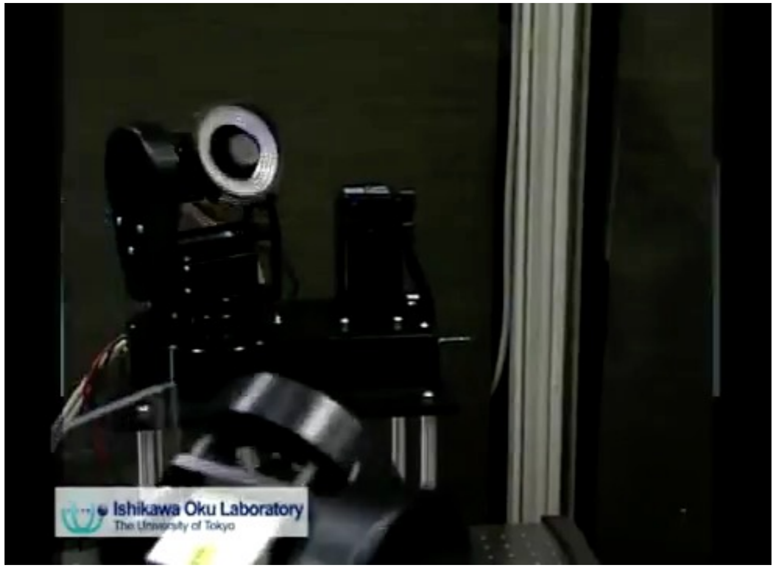


CMOS versus CCD

- reduction of fabrication costs of CMOS imagers
- better spatial resolution of elementary sensors
  - CMOS: 1M pixel, CCD: 768×576 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) ⟷ current "hot" alternative: event cameras https://en.wikipedia.org/wiki/Event_camera
- 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

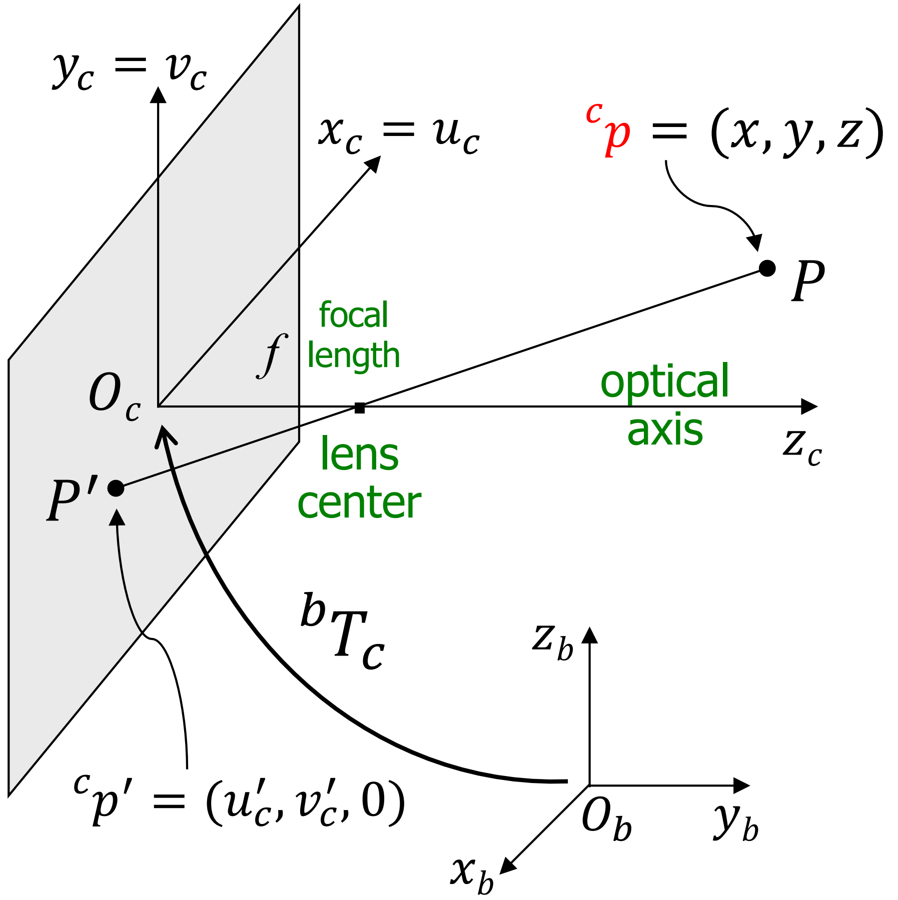
- 1 KHz vision frame rate
- 1 KHz robot control rate

  @ Ishikawa Lab – U Tokyo

  (2007-09)

Perspective transformation
with pinhole camera model

camera frame on image plane



1. in metric units

$$u'_c = \frac{fx}{f-z} \qquad v'_c = \frac{fy}{f-z}$$

2. in pixel

$$\bar{u}_c = \frac{u'_c}{\alpha_u} + u_{c0} = \frac{fx}{\alpha_u (f-z)} + u_{c0}$$

$$\bar{v}_c = \frac{v'_c}{\alpha_v} + v_{c0} = \frac{fy}{\alpha_v (f-z)} + v_{c0}$$

offsets of pixel coordinate system w.r.t. optical axis

metric/pixel scaling factor ($\approx \mu$m)

3. LINEAR MAP in homogeneous coordinates

$$(\bar{u}'_c, \bar{v}'_c) \Rightarrow (\lambda \bar{u}'_c, \overline{\lambda v}'_c, \lambda)$$

for $\lambda \neq 0$

$$\lambda \begin{pmatrix} \bar{u}_c \\ \bar{v}_c \\ 1 \end{pmatrix} = \Omega \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

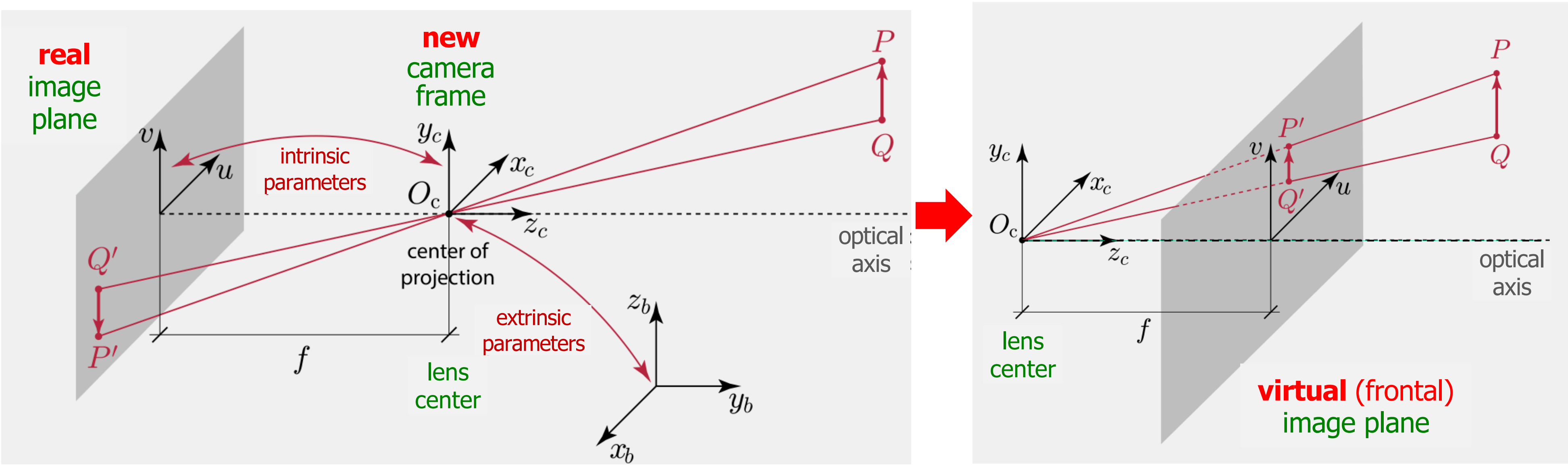
$$\Omega = \begin{bmatrix} 1/\alpha_u & 0 & u_{c0} & 0 \\ 0 & 1/\alpha_v & v_{c0} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/f & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

calibration matrix

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

intrinsic and extrinsic parameters

Perspective transformation
with camera frame at the lens center



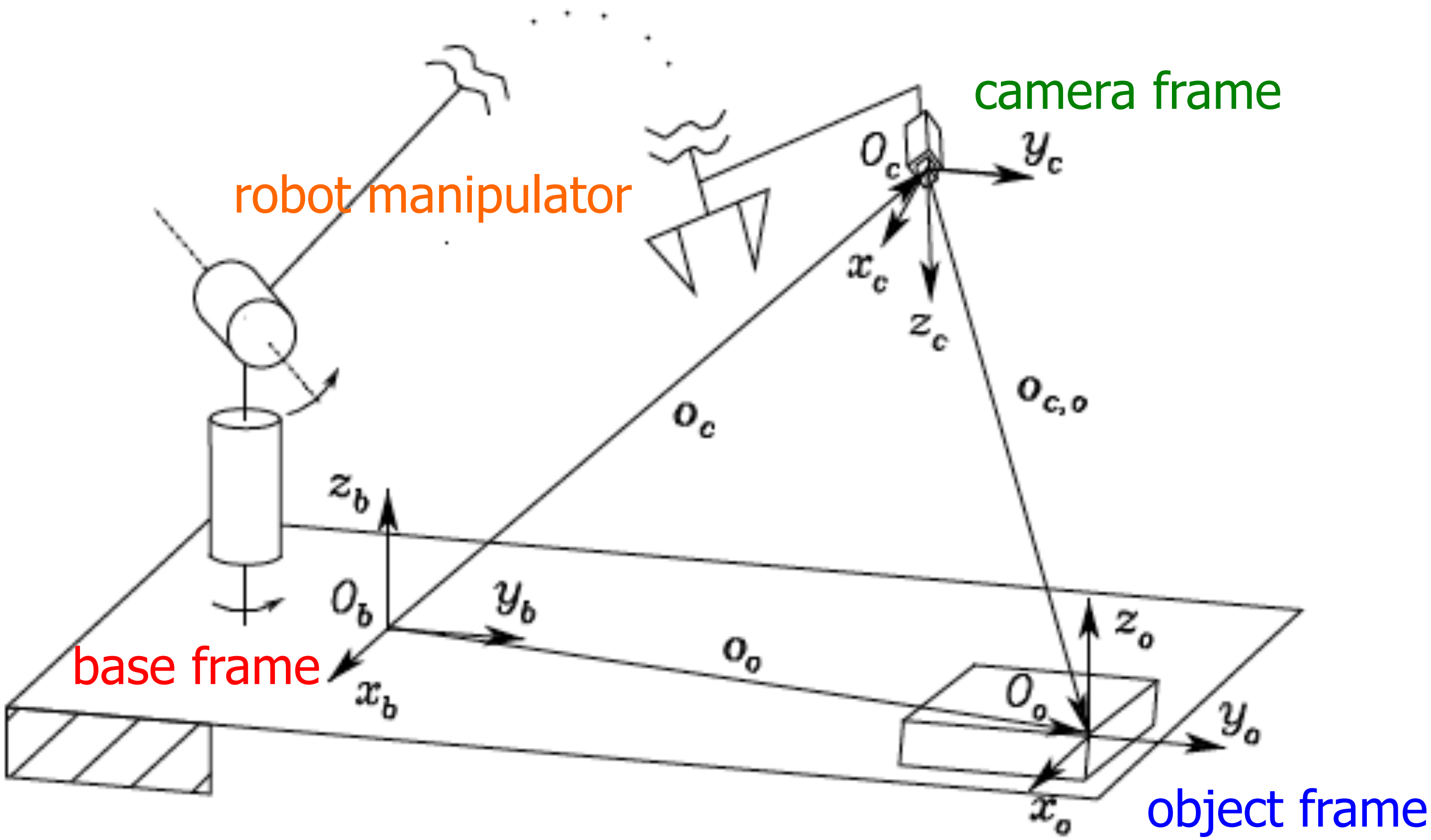
1. in metric units $u' = -\dfrac{fx}{z} \quad v' = -\dfrac{fy}{z}$ ➡ $u' = \dfrac{fx}{z} \quad v' = \dfrac{fy}{z}$

2. in pixel ... ➡ $\bar{u} = \dfrac{fx}{\alpha_u z} + u_0 \quad \bar{v} = \dfrac{fy}{\alpha_v z} + v_0$

3. LINEAR MAP in homogeneous coordinates ... ➡

$$\lambda \begin{bmatrix} \bar{u} \\ \bar{v} \\ 1 \end{bmatrix} = \Omega\ {}^{c}p_{hom} = \begin{pmatrix} f/\alpha_u & 0 & u_0 & 0 \\ 0 & f/\alpha_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

Eye-in-hand camera

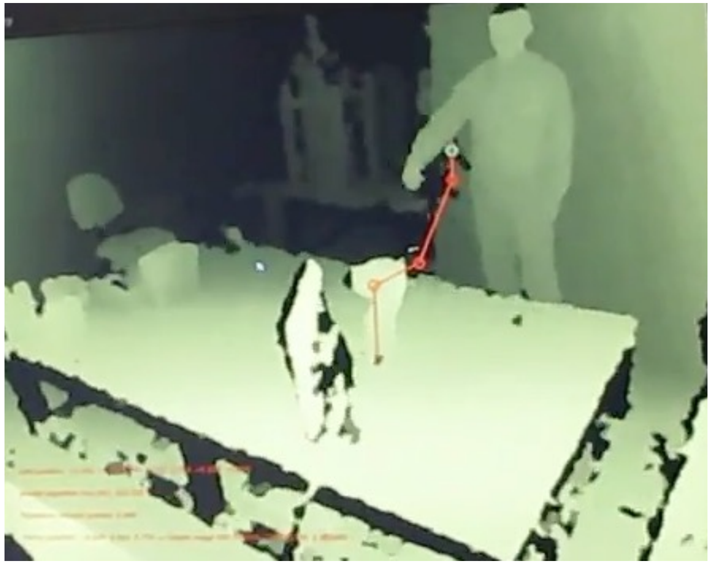


Relevant reference frames for visual-based tasks

Kinect

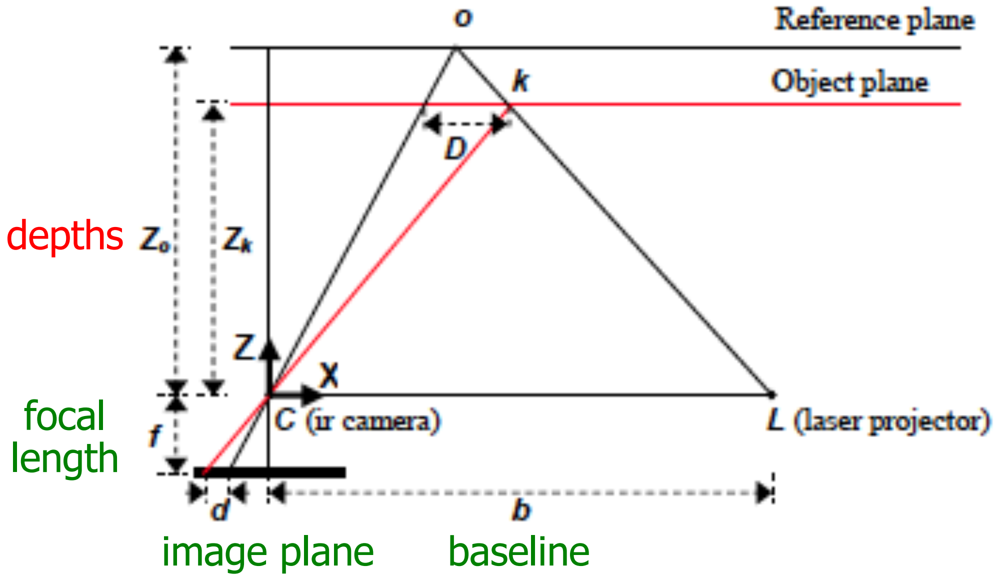
camera + structured light 3D sensor

- 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



- 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)

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

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

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

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)

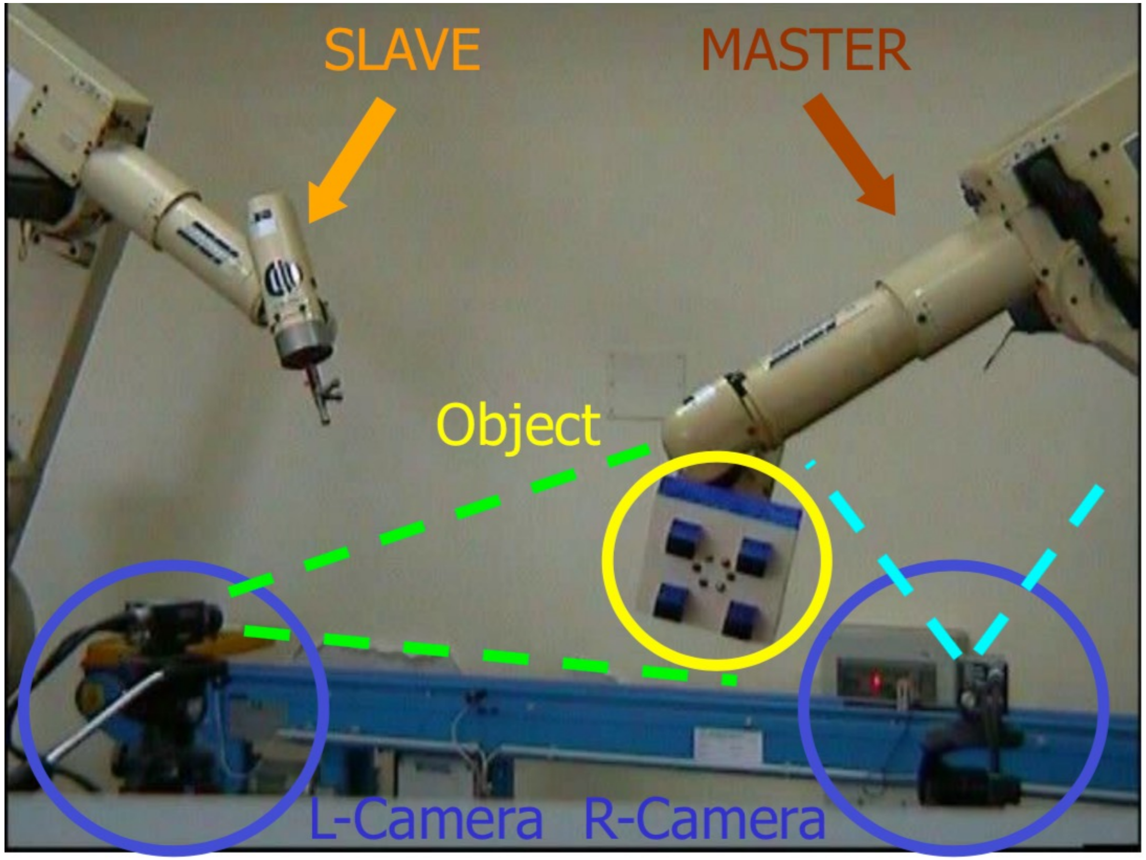
How Kinect works
(a 2-minute illustration...)

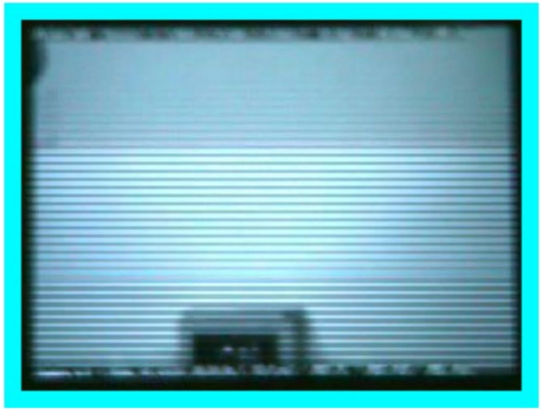
video

http://youtu.be/uq9SEJxZiUg

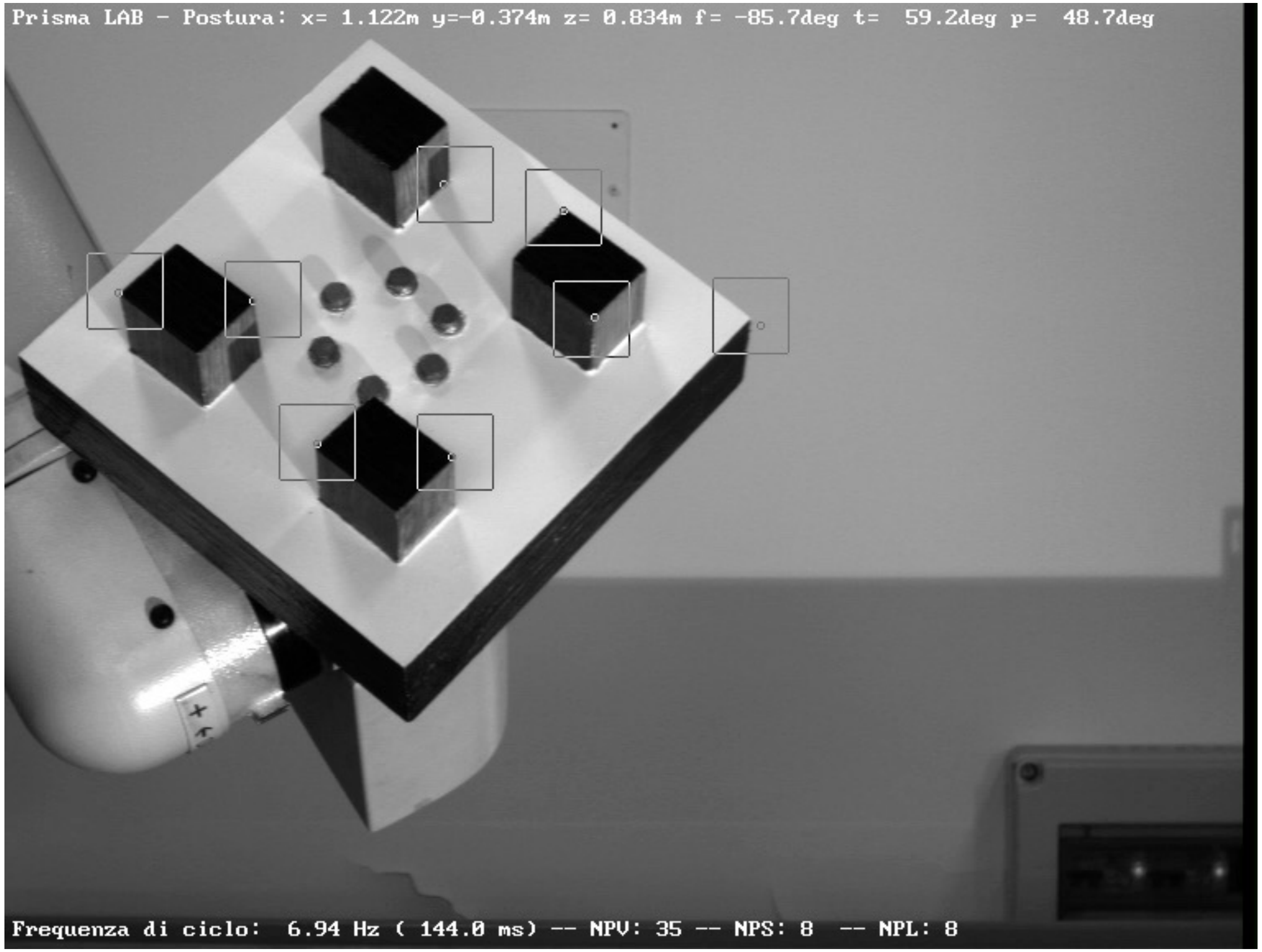
Manipulators and vision systems

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





Visual tracking eye-to-hand

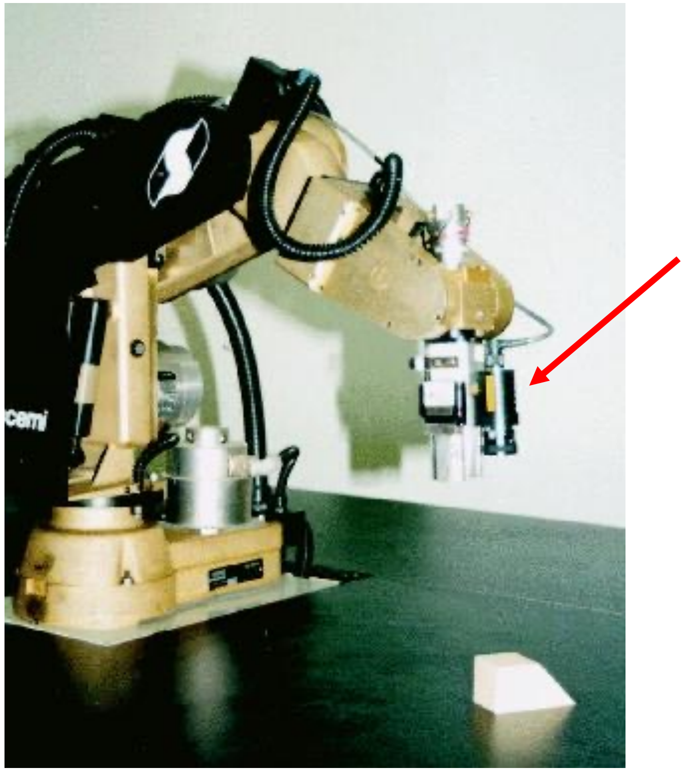


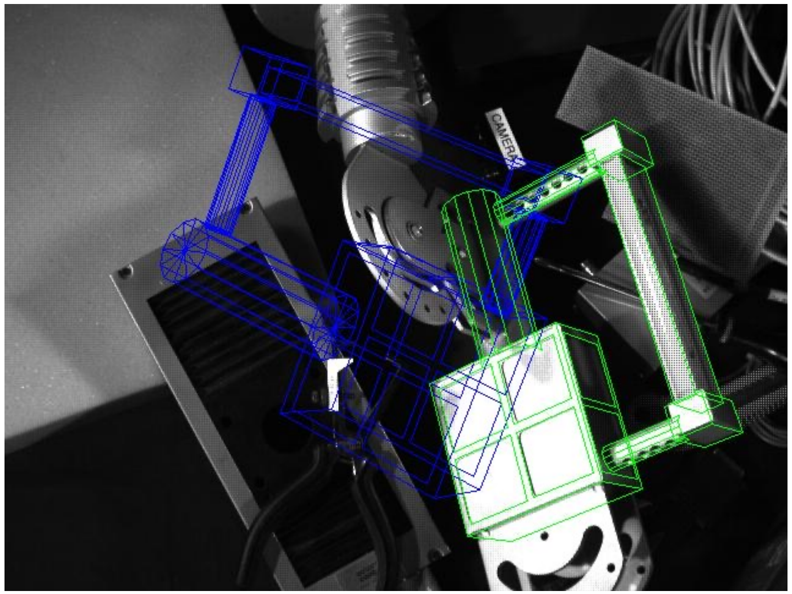
video

6R COMAU robot with PBVS for 6D tracking from external camera
(DIS, Università di Napoli Federico II)

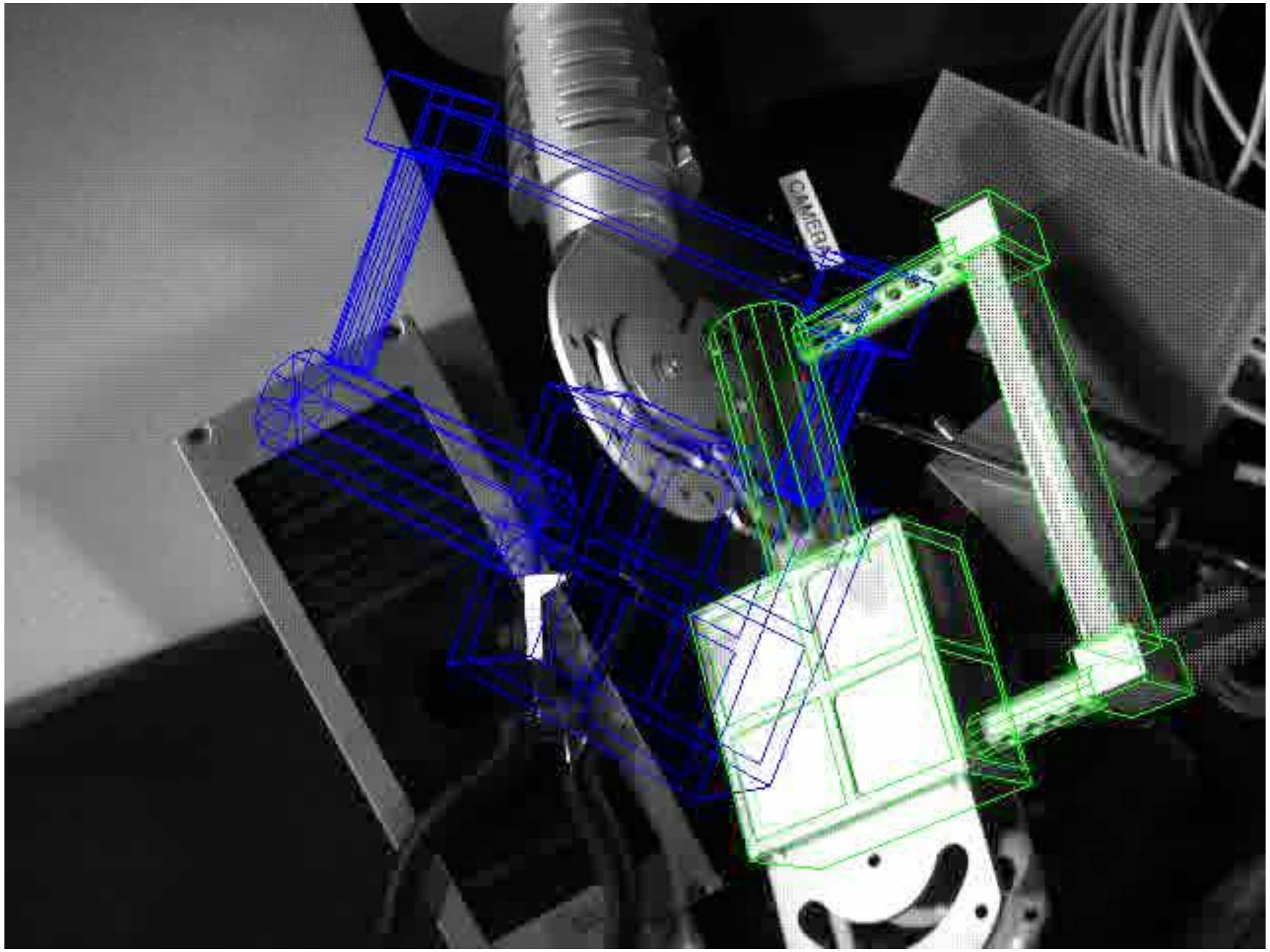
Manipulators and vision systems

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





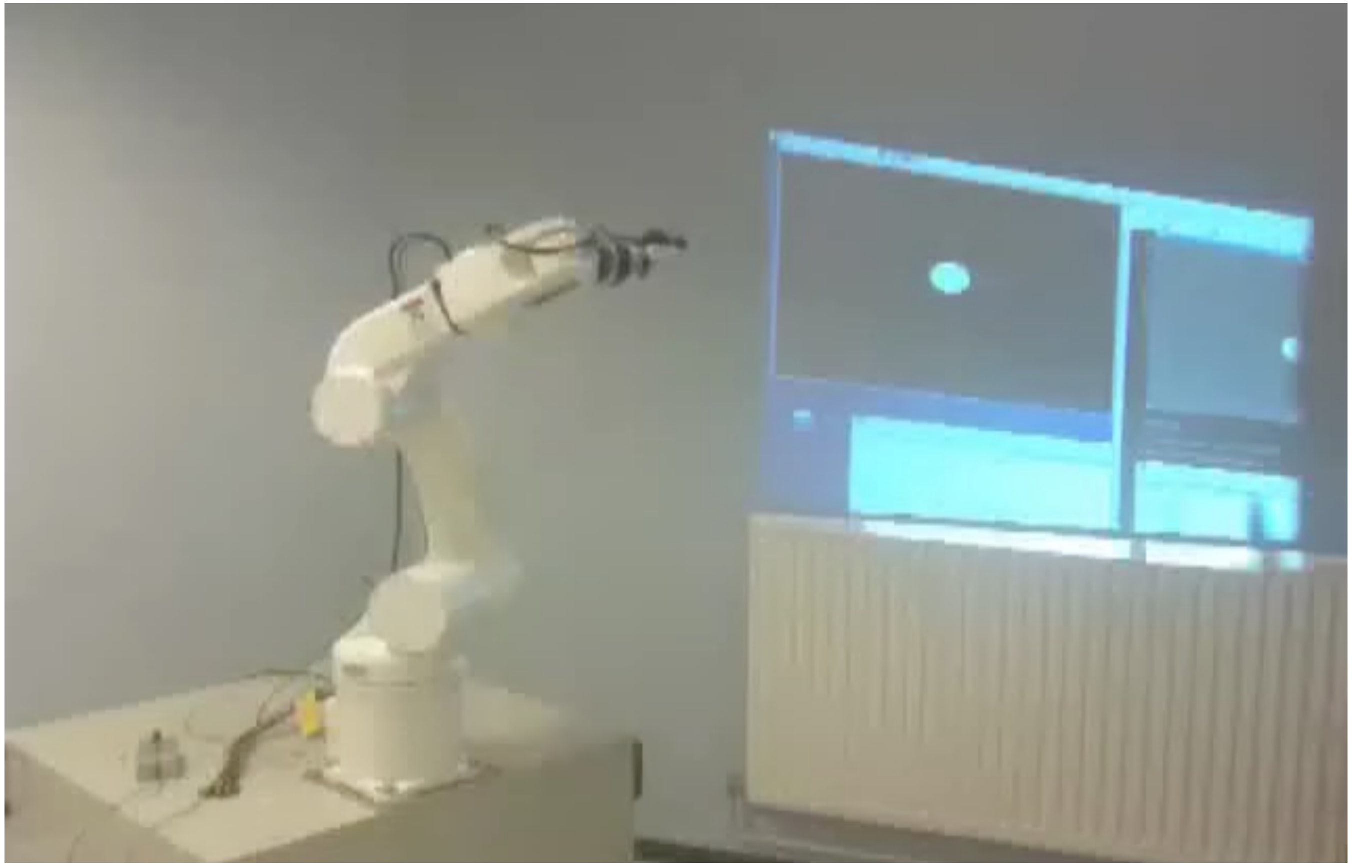
Visual servoing eye-in-hand



video

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

Visual servoing and redundancy



video

IBVS of circle features ($m = 3$: c_x, c_y, r) by Adept Viper robot ($n = 6$): redundancy is used for avoiding joint range limits (IRISA/INRIA, Rennes)

Combined visual/force assembly

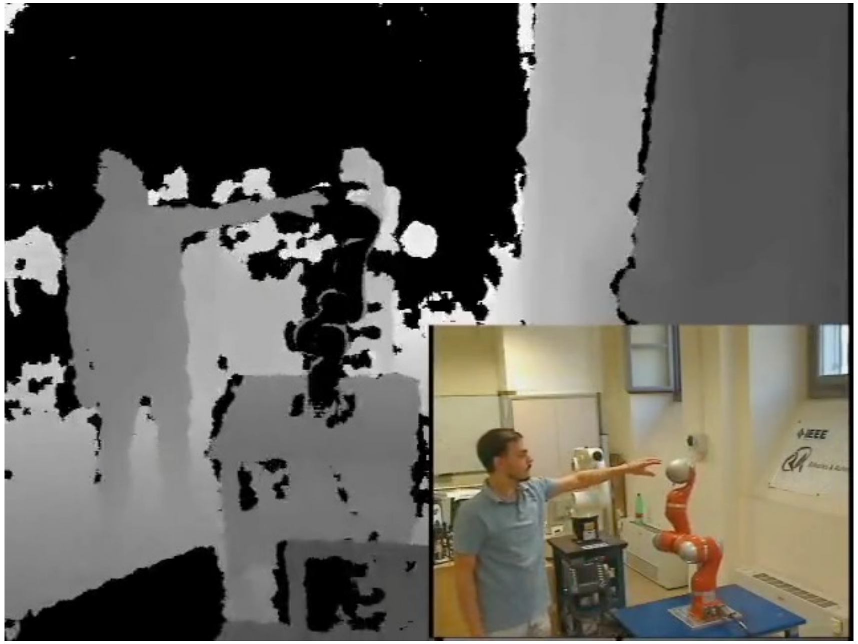
video

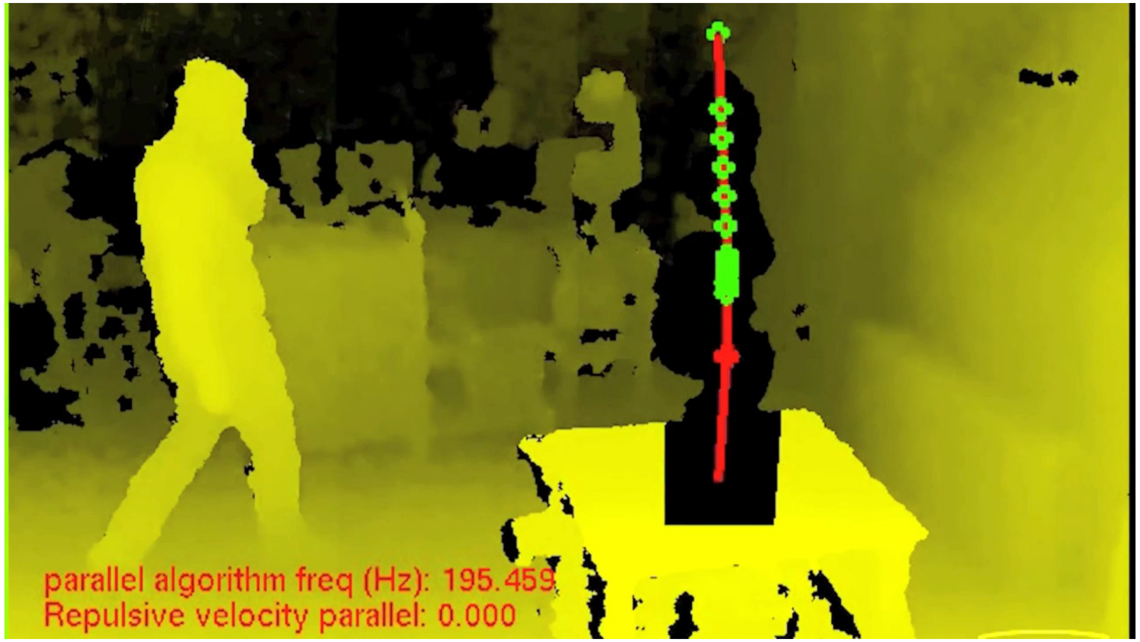
KUKA LWR with eye-in-hand camera and F/T sensor
(DLR, IEEE ICRA'07 demo in Roma)

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)