H2 - Control of interaction in robot manipulators

Outline

Introduction to interaction control methods

Task Space impedance control

Admittance control

Visual servoing

Interaction control

- So far we have assumed that the robot is controlled in a free environment
- However, the robot has to interact with the environment either to manipulate it, to avoid collisions with it, or to interact with other devices or humans
- **Difficulty**: we need to know how the object is behaving (and this is difficult to model).
- **Objective**: regulate contact forces

Applications

- A robot commonly interacts with the working environment, manipulating objects and performing operations on surfaces:

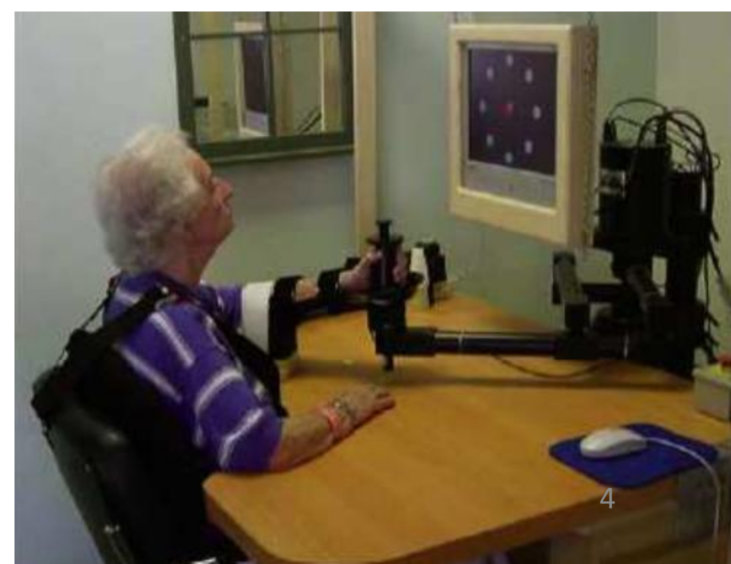
Drilling, grinding, deburring

Surface finishing, polishing

Assembly

- Human robot interaction:

In modern robotics, situations are common where the robot physically interacts with the operator (think about tele-manipulation or rehabilitation, assistive robotics).

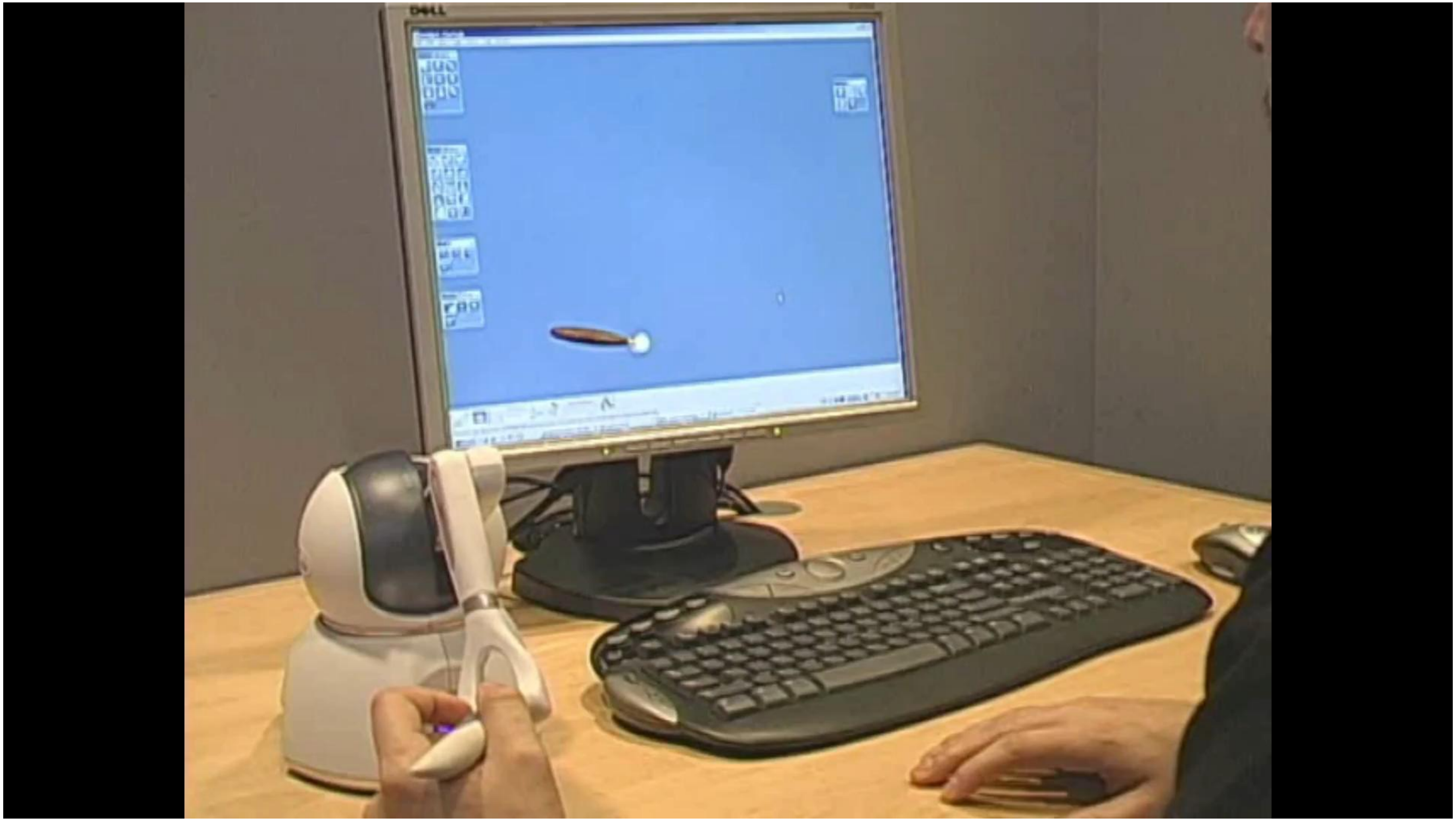


Applications

Robot milling

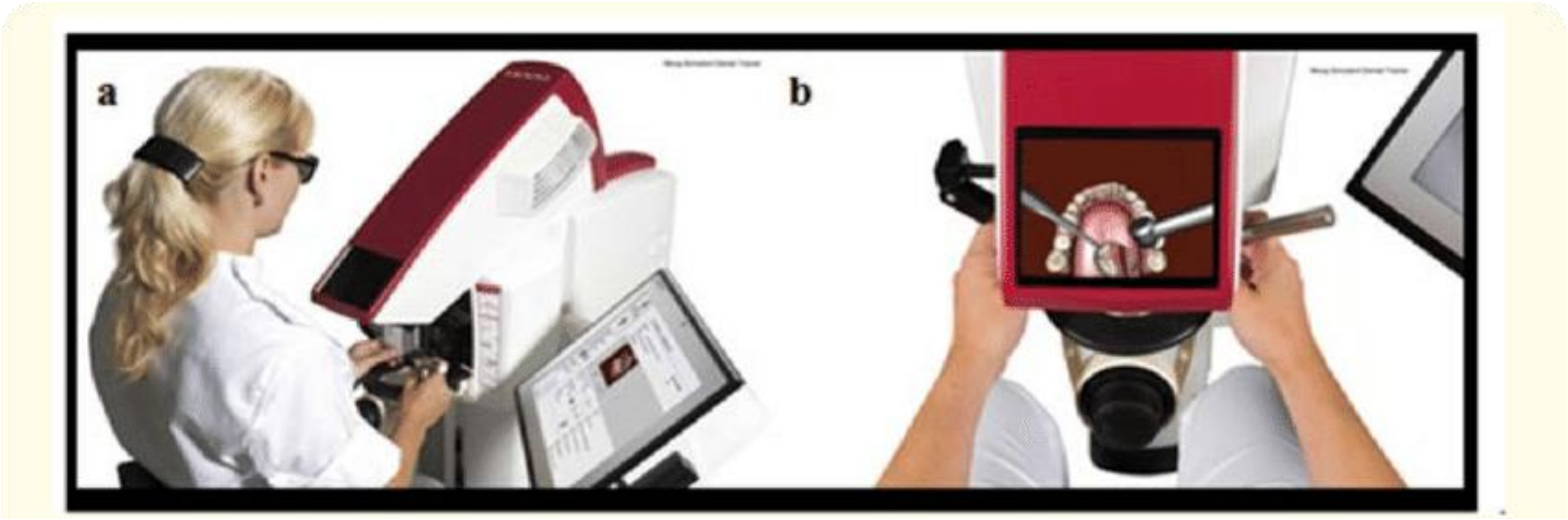
Applications

Haptic devices



Applications

Haptic devices



Applications

Mobile/legged robots

ANYmal, ETH
(2016)

Atlas, Boston Dynamics (2019)

HyQ, IIT (2010)

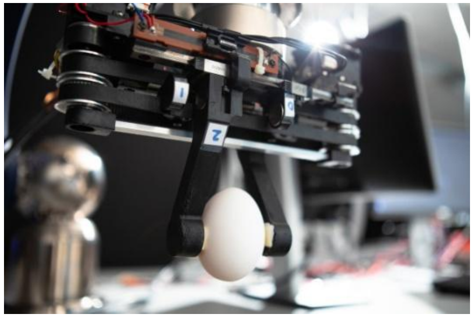
HyQReal, IIT (2019)

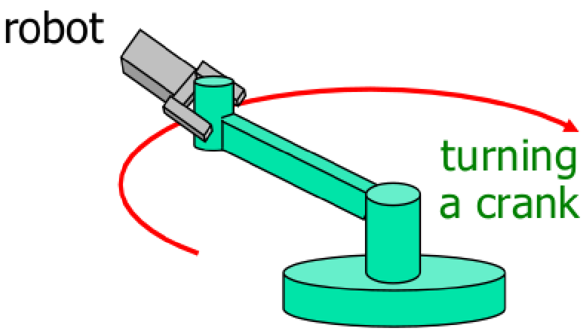
Wearable robots (exoskeletons)

Interaction tasks of interest / objectives

The interaction tasks with the environment of interest, usually require:

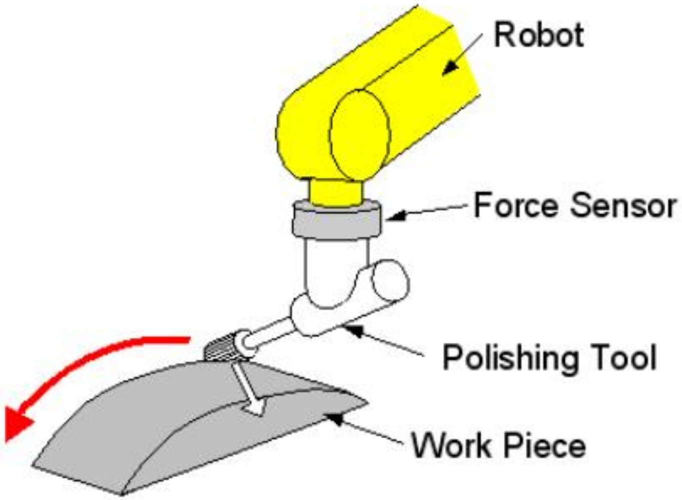
- accurate following/reproduction by the robot end-effector of desired trajectories (even at high speed) defined on the surface of objects
- control of forces/torques applied at the contact with environments having low (soft) or high (rigid) stiffness. Examples:
  - safety: avoid to apply too large forces, to do not damage the environment or himself
  - Apply specific force in some directions and motion in others
  - balancing





e.g., opening a door

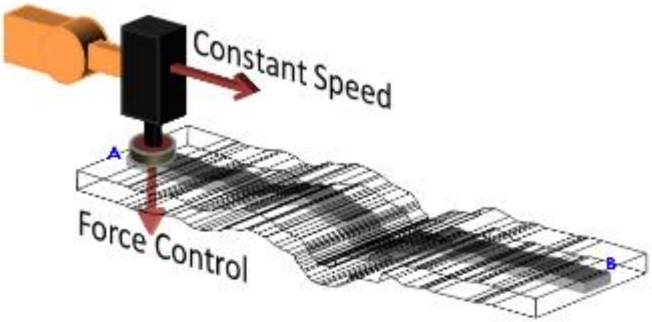
Contour following



Following with constant pushing force

Washstand

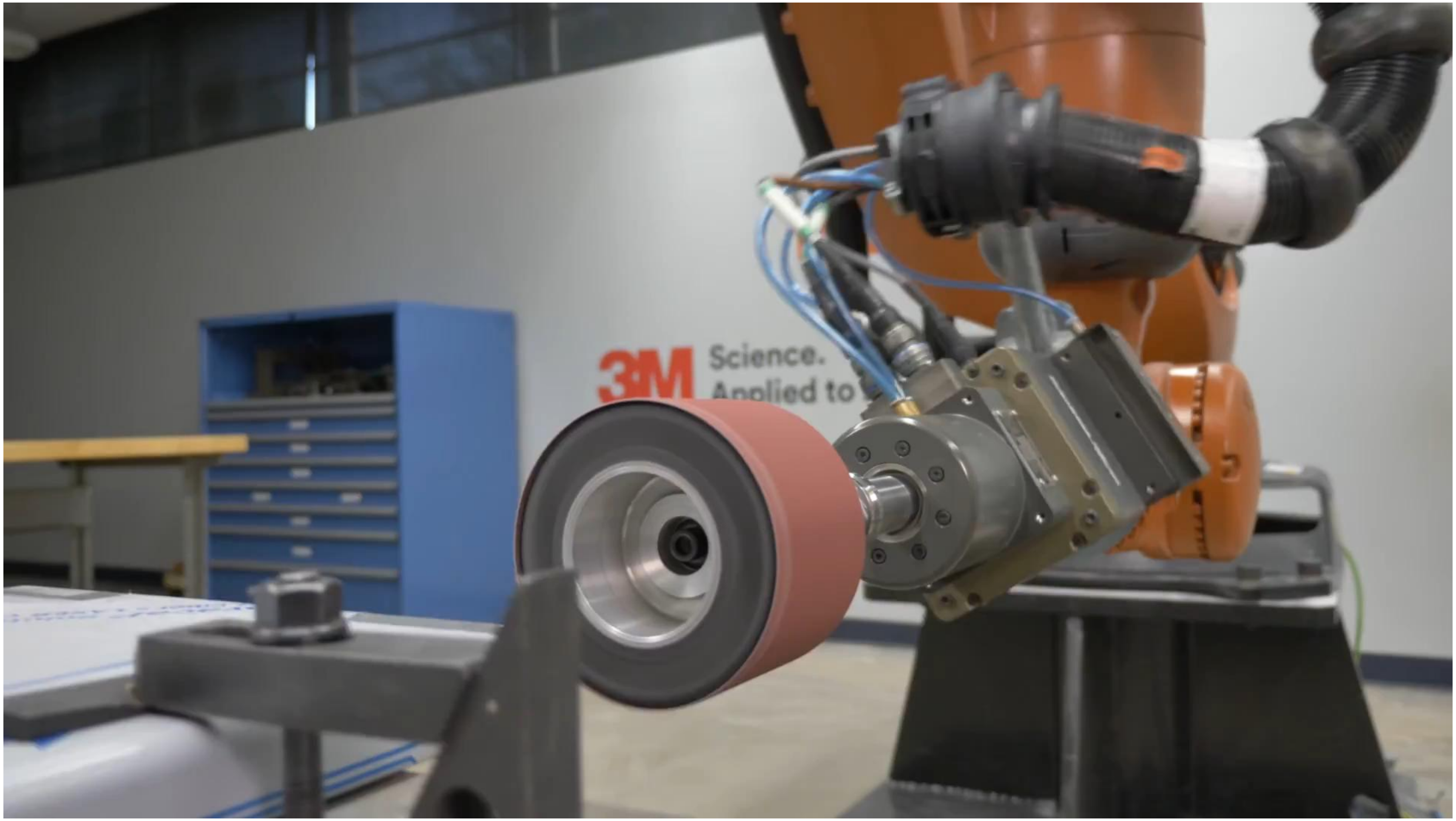
Metal Cabinet



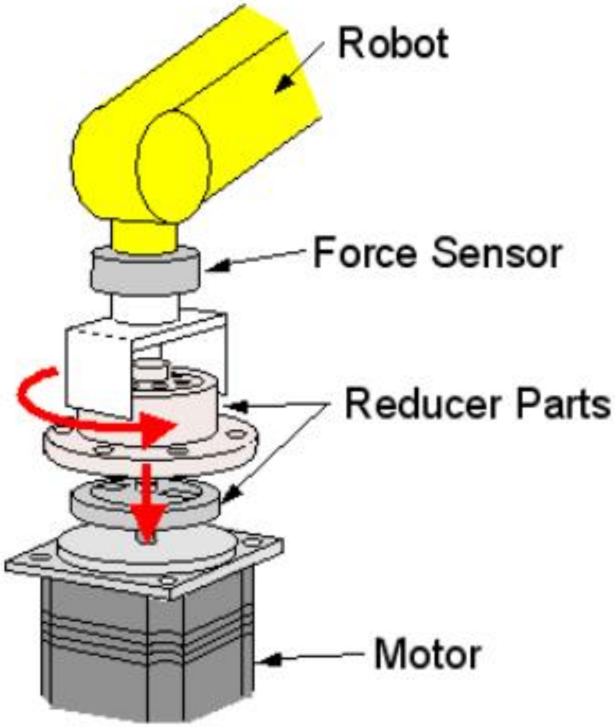
The use of a purely positional control strategy (the same adopted in free motion) may lead to problems due to positioning errors and uncertainties in task planning related to an incomplete knowledge of the environment

Contour following

Sanding/polishing



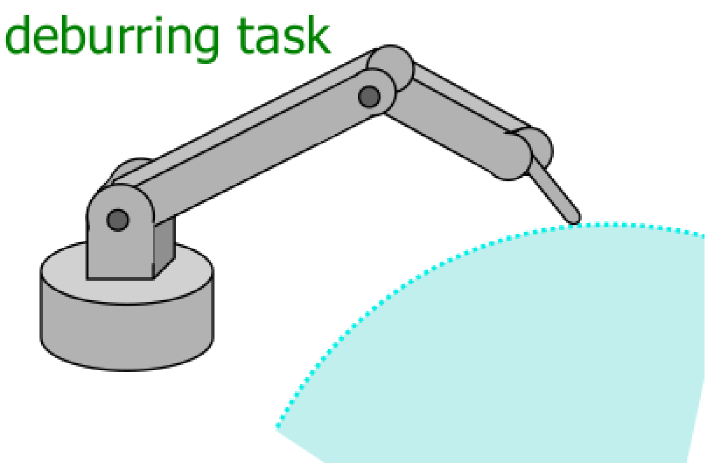
Assembly task

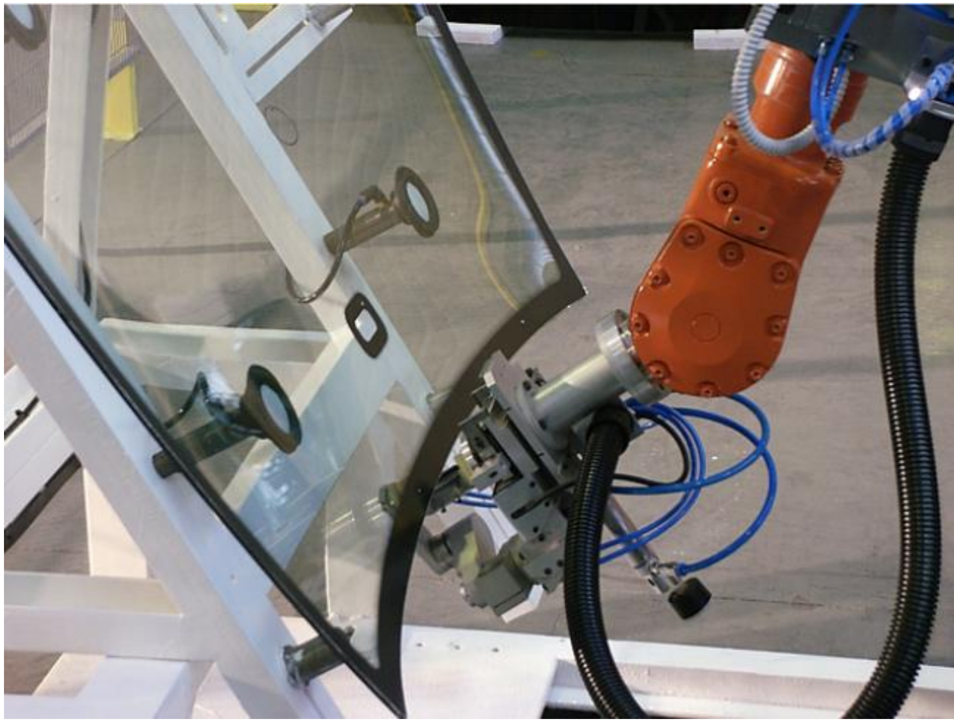


Phase matching by force sensing

Gear Parts

Robotized deburring of windshields





c/o ABB Excellence Center in Cecchina (Roma), 2002

Passive VS active methods

Passive methods

Physical springs are introduces between the robot and the environment, to reduce interaction force

(+) Higher control stability

(+) **infinite** force bandwidth

(-) low flexibility: fixed stiffness

(+) more flexible: is possible to change stiffness **online** via software

(-) controller **delay** affects the maximum bandwidth at which we can control the force

Active methods

Use feedback control techniques

A) **Direct** force control: employs explicit force feedback

(-) require force sensor at the E-E

(-) stability issues

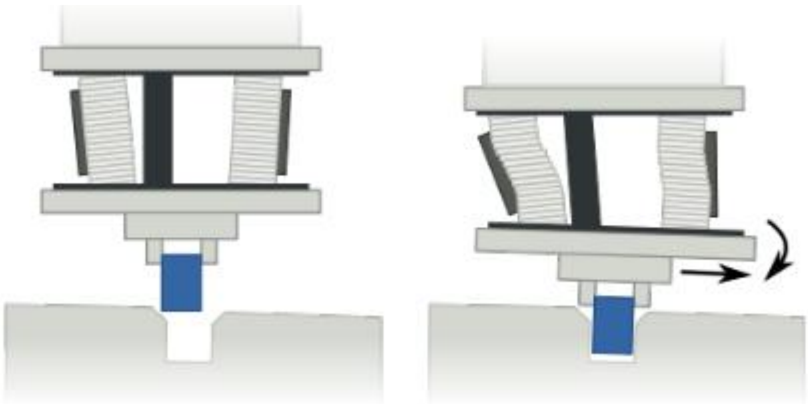
B) **Indirect** force control: control force and position at the same time

- Compliance control
- Impedance control
- Admittance control

C) **Hybrid** position and force control: control force in some direction and position in others

Passive control of compliance with RCC

To endow the manipulator with devices that facilitate the execution of the task in a passive way

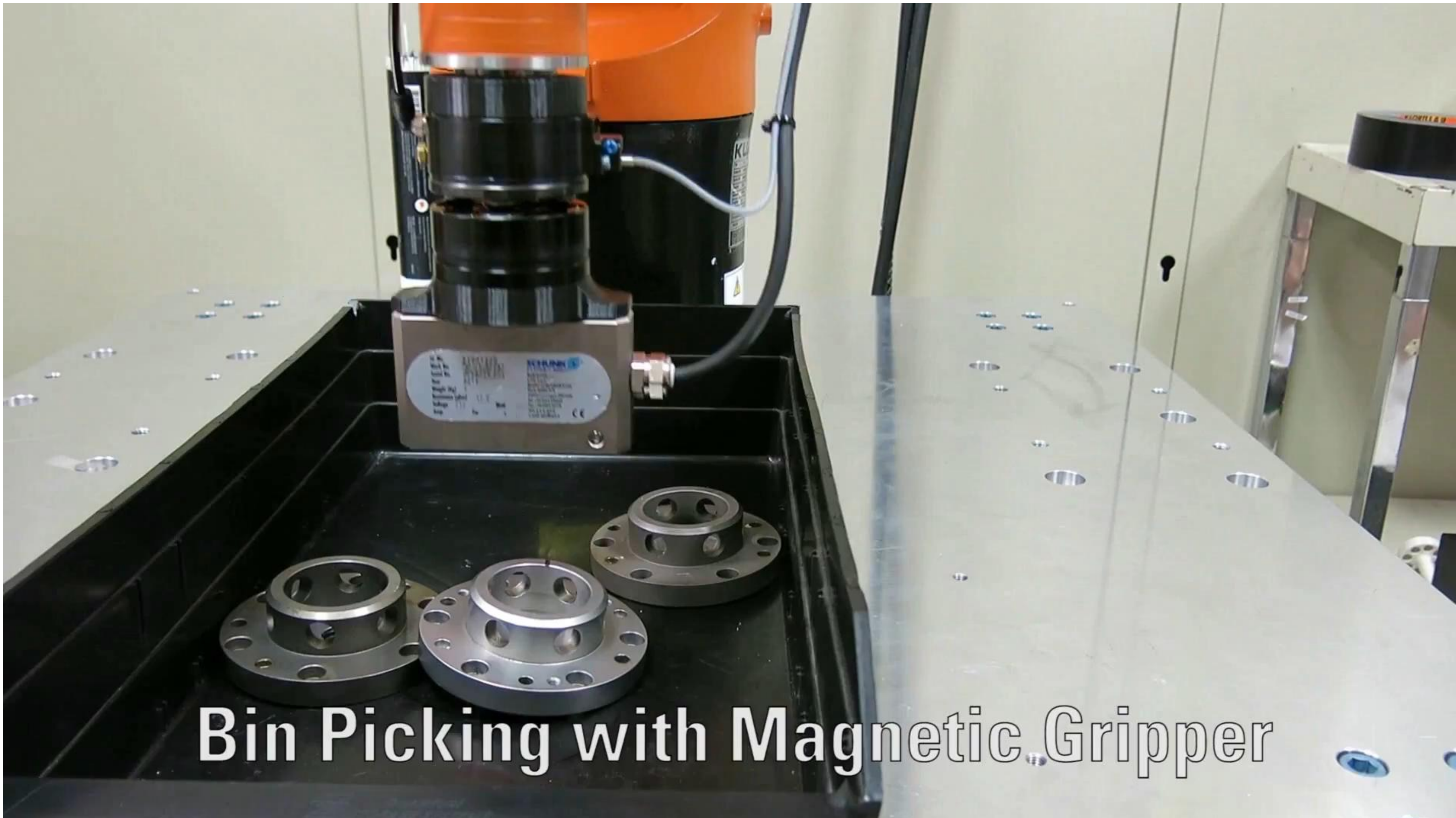


RCC
Remote Center of Compliance

- The RCC is used in assembly tasks (peg-in-a-hole)
- It is typically placed between the robot’s wrist and the gripper
- The RCC lets the gripper assembly move in the plane perpendicular to the peg’s axis. This allows the peg to rotate.
- The forces generated by any misalignment can be compensated in a **passive** way

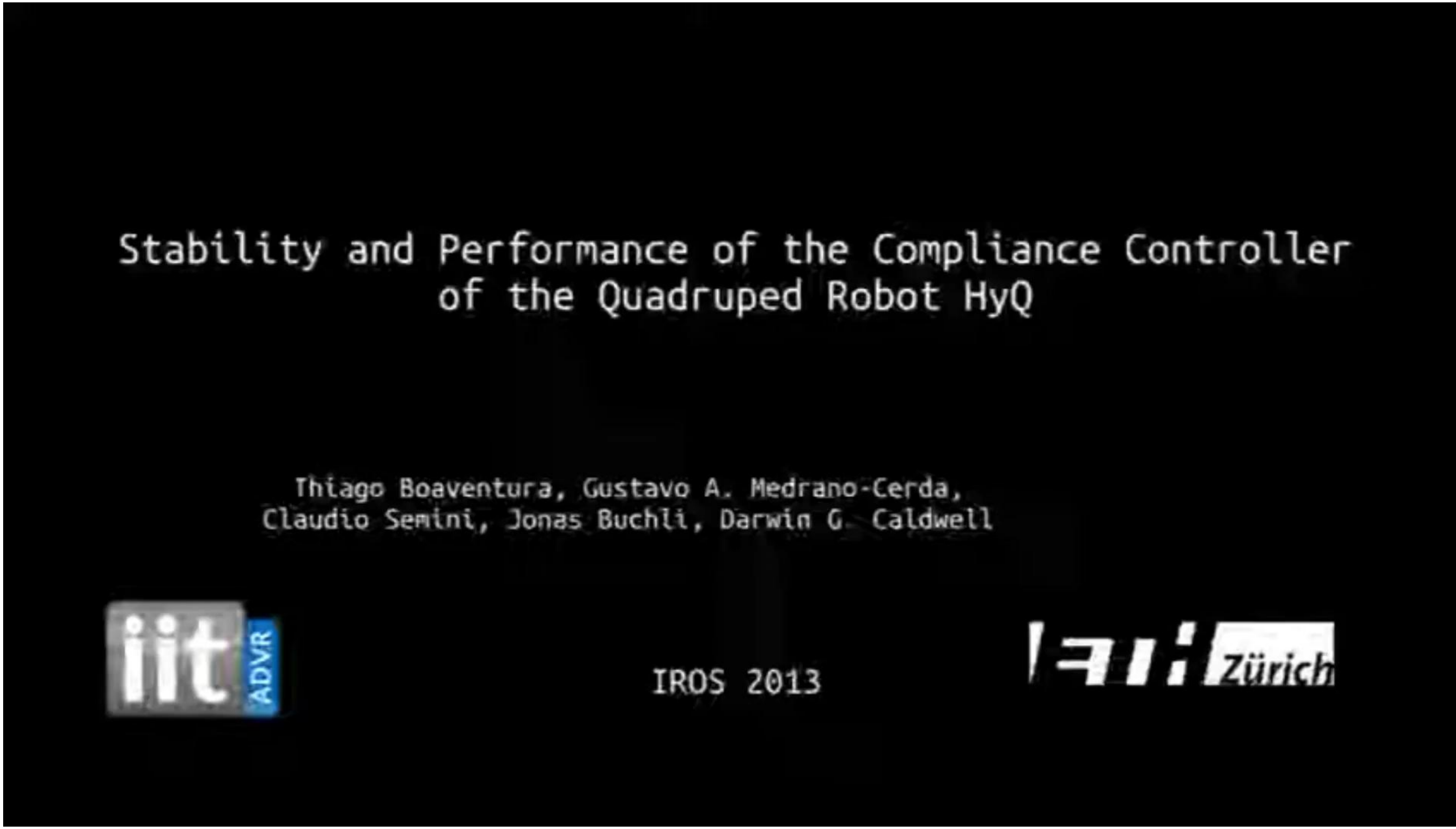
Passive control of compliance with RCC

Universal Compliance Compensator



Active compliance

Control of leg of HyQ



DIRECT FORCE CONTROL

Goal: we have a reference force f^d that we want to track

IDEA:

1. measure contact force f
2. if $f < f^d \Rightarrow$ apply more force
3. if $f > f^d \Rightarrow$ apply less force

$$\boxed{f^* = f^d + K_f \underbrace{(f^d - f)}_{e_f} + \dots \text{integral}}$$

$$\tau = -J^T f^* + h$$

DYNAMICS:

$$M\ddot{q} + h = \tau + J^T f$$

at steady state:

$$\cancel{g} - J^T f = -J^T f^* + \cancel{g} \Rightarrow f = f^d + K_f e_f$$

$$(1 + K_f) e_f = 0 \Rightarrow e_f = 0$$

Active method: Impedance control

Position control

Control position no matter what force is applied

(+) high accuracy

(-) high interaction forces

- Actuator saturation
- Break mechanical parts

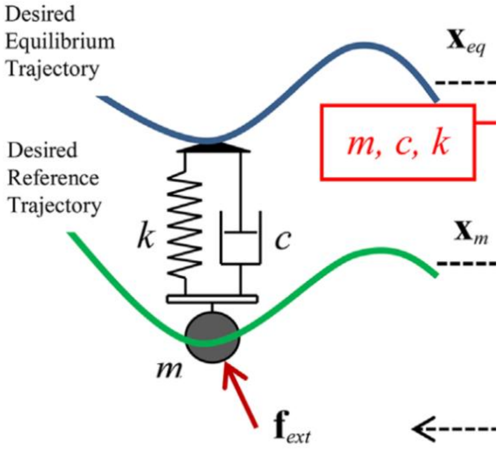
Force control

Control force no matter which position is achieved

(-) instability

Impecance control is something in the middle…

Idea: indirectly regulate contact forces by generating a motion that satisfies a dynamic relationship (mechanical impedance) between force and position



Make the manipulator, in interaction with the environment, assume a desired mechanical impedance, like a virtual mass-spring-damper system

Mechanical impedance

- Impedance control aims to achieve a desired behavior at the interaction between end-effector and environment
- This behavior has the form of a **mechanical impedance** and it is defined as dynamical relation between force and velocity (or position) for a mechanical system. The **admittance** is just the reciprocal of the impedance

- This impedance that is typically use has the form of a mechanical system with mass matrix M_d, damping D_d, and stiffness K_d.

$$M_x \ddot{p} + D_x \dot{p} + K_x p = F$$

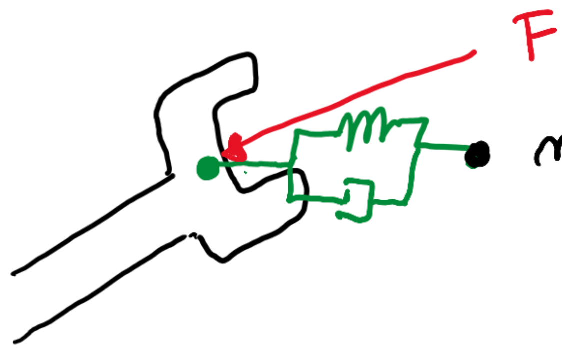
impedance in cartesian space

$$\boxed{M_q \ddot{q} + D_q \dot{q} + K_q q = \tau}$$

→ not used in practice

impedance in joint space

- **Intuitively**: a mechanical impedance gives an idea on how a point of a system moves if you apply a force to it.



neutral state

⇓

it can be a reference point

- is a 2° order system, stable if K, D > 0

- it will restore back to zero

- No need of environment model describing how reaction forces are generated by the environment as a consequence of a deformation

- Since force error loop is missing (at the end-effector), we cannot control forces but we just try to keep them small, the contact forces are **indirectly** assigned by controlling the position

CARTESIAN SPACE IMPEDANCE CONTROL

Typically the desired impedance is defined w.r.t. a reference trajectory

$$\boxed{M_x^d(\ddot{p} - \ddot{p}^d) + D_x^d(\dot{p} - \dot{p}^d) + K_x^d(p - p^d) = F_{ext}} \quad (1)$$

desired apparent inertia $M_x > 0$

desired damping $D_x \geq 0$

desired stiffness $K_x > 0$

external force from environment

$M_x^d, D_x^d, K_x^d \in \mathbb{R}^{m \times m}$ in general are diagonal matrices (decoupled)

Real dynamics (in contact):

$$\boxed{M(q)\ddot{q} + R(q, \dot{q}) = u + J^T F_{ext}} \quad (2)$$

note this is the geometric Jacobian

Knowing that $\ddot{q} = J^{-1}(\ddot{p} - \dot{J}\dot{q})$

we can plug it in (2) to get the torque commands doing feed-back linearization in cartesian space (with force measure)

$$u = M J^{-1}(\ddot{p} - \dot{J}\dot{q}) + h - J^T F_{ext}$$

$$\boxed{\ddot{p} = \ddot{p}^d + {M_x^d}^{-1}\left[D_x^d(\dot{p}^d - \dot{p}) + K_x^d(p^d - p) + F_{ext}\right]} \quad (3)$$

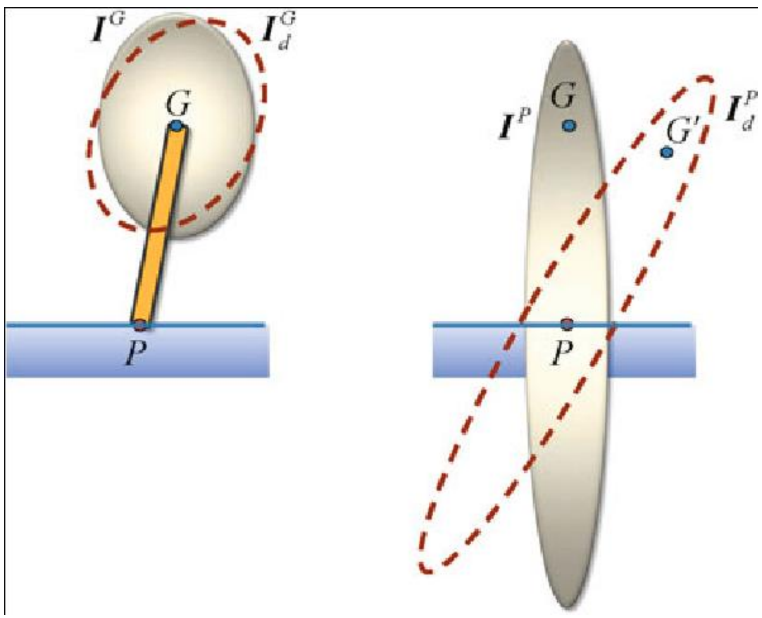
$$u = M J^{-1}\left\{\ddot{p}^d - \dot{J}\dot{q} + {M_x^d}^{-1}\left[K_x^d e_x + D_x^d \dot{e}_x + F_{ext}\right]\right\} + h - J^T F_{ext}$$

$$\boxed{\begin{aligned} u = {} & M J^{-1}\left\{\ddot{p}^d - \dot{J}\dot{q} + {M_x^d}^{-1}\left[K_x^d e_x + D_x^d \dot{e}_x\right]\right\} + h \\ & + \left[M J^{-1} {M_x^d}^{-1} - J^T\right] F_{ext} \end{aligned}}$$

Problem:
- requires measure of Fext
- an exact cancellation is hard

INERTIA SHAPING FEATURE

- Mask the true inertia of the manipulator and impose a desired one at the end-effector
- I cannot change manipulator inertia, but I can change the "apparent" one felt at the end-effector



example: I can make it configuration independent

SIMPLIFICATION

- if you chose the desired inertia M_x^d equal To The natural cartesian one $\Lambda(q)$

$$M_x^d = \Lambda(q) = \left(J(q)\, M^{-1}(q)\, J^T(q)\right)^{-1} \rightarrow \text{depends on } q$$

$$\boxed{u = M J^{-1} \left\{ \ddot{p}^d - \dot{J}\dot{q} \right\} + J^T \left[D_x^d (\dot{p}^d - \dot{p}) + K_x^d (p^d - p) \right] + h}$$

↳ ≈ PD + FFWD in Cartesian space

⊕ no contact force feedback needed!
control law all expressed in joint coordinates

⊖ non-constant apparent inertia

⊖ non-linear impedance

$$M_x^d(q)(\ddot{p} - \ddot{p}^d) + D_x^d(\dot{p} - \dot{p}^d) + K_x^d(p - p^d) = F_{ext}$$

- zero tracking error when $F_{ext} = 0$

in case of $p^d = \text{const}$, $\dot{p}^d = 0$, $\ddot{p}^d = 0$ This simplifies to a cartesian PD + gravity compensation

$$\boxed{u = J^T \left[K_x^d (p^d - p) - D_x^d \dot{p} \right] + g(q)}$$

Note: for small displacements (gravity compensated) a diagonal cartesian stiffness corresponds to a variable joint stiffness

$$(p^d - p) \approx J(q^d - q)$$

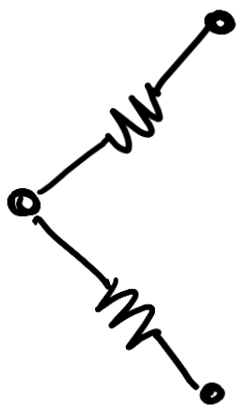
$$u = \underbrace{J^T K_x J}_{K_q} (q^d - q) \quad \Rightarrow \text{compliance control}$$

$$\begin{tikzcd}
\Delta p \arrow[r] & K_x \arrow[r] & F_x \arrow[d, "J^T"] \\
\Delta q \arrow[u, "J"] \arrow[r] & K_q \arrow[r] & u
\end{tikzcd}$$

$$\boxed{K_q(q) = J(q)^T K_x J(q)}$$

SUPERIMPOSITION OF IMPEDANCES

Because the desired imperances are linear we can superimpose their effects



- each impedance can represent one task
- The behaviour will be a compromise between the tasks (if they are conflicting)

SELECTION OF IMPEDANCE PARAMETERS

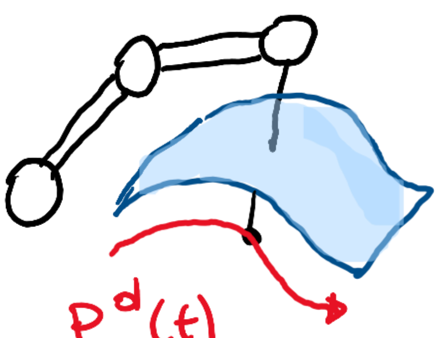
The impedance parameters are chosen according to the admissible contact force and the desired transient:

1. select K_x (stiffness) according to how much force we expect for a certain deflexion

   $K \uparrow\uparrow \Rightarrow$ high force

Thumb rule: adapt to dynamic characteristics of the environment:

- be stiff with compliant environment
- be compliant if environment is stiff



desired motion $p^d(t)$ should be planned slightly insid the environment (e.g cleaning task)

② Select M_x (inertia) according to how "light" we want to "feel" the robot at the end-effector

- directions where we expect contact : $M^d_{x,i} \uparrow$ $K^d_{x,i} \downarrow$

  reduced acceleration low force

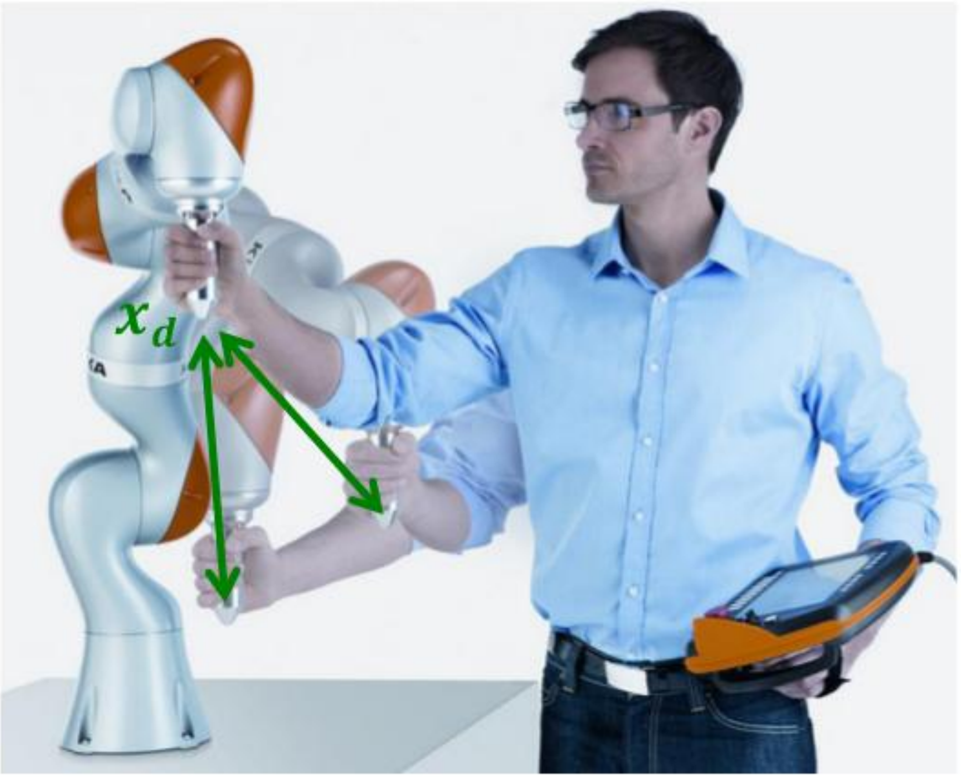
- directions where we expect free motion : $M^d_{x,i} \downarrow$ $K^d_{x,i} \uparrow$

  fast acceleration good tracking

③ Select D_x (damping) to regulate the transient (e.g. no overshoot). K_x, D_x could also be non linear.

Examples of desired reference in impedance control

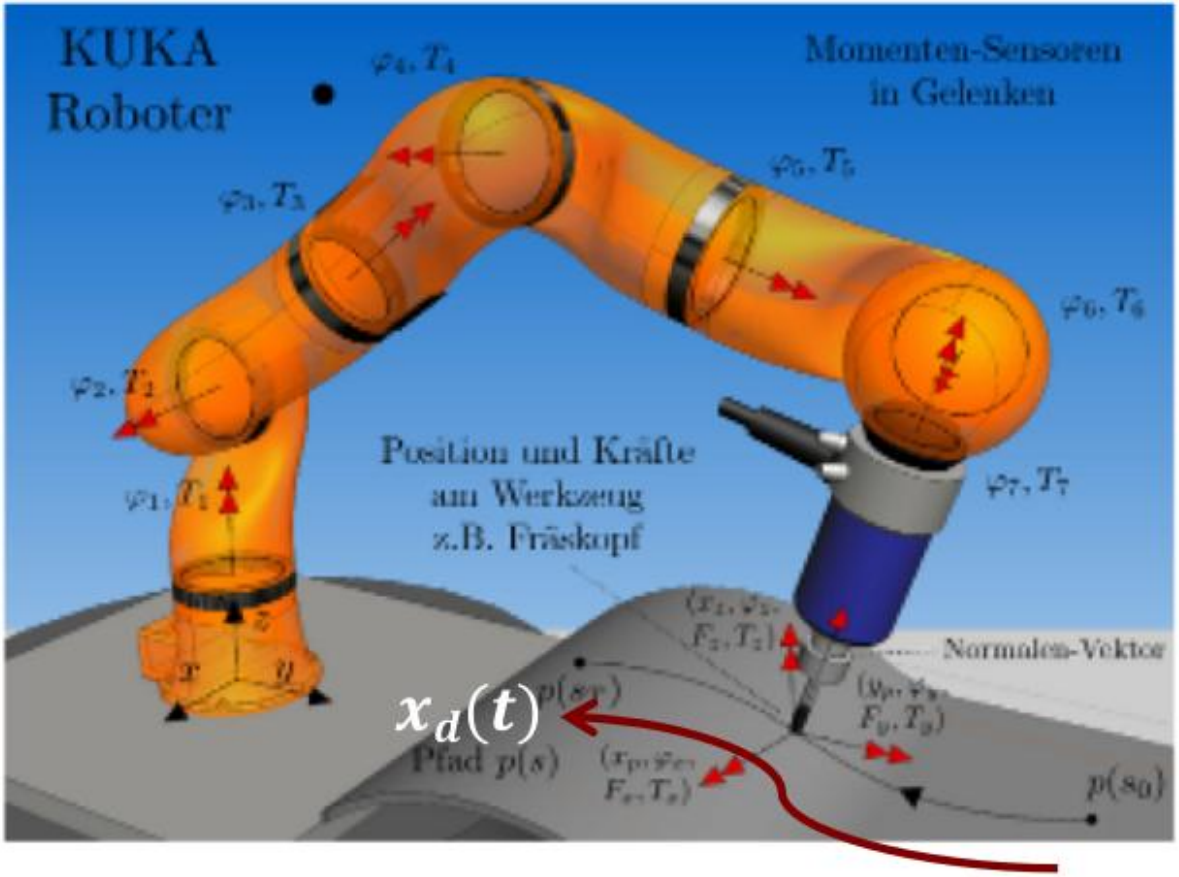
- constant desired pose $x^d(t)$ is the rest position in a human-robot interaction task



KUKA iiwa robot with human operator

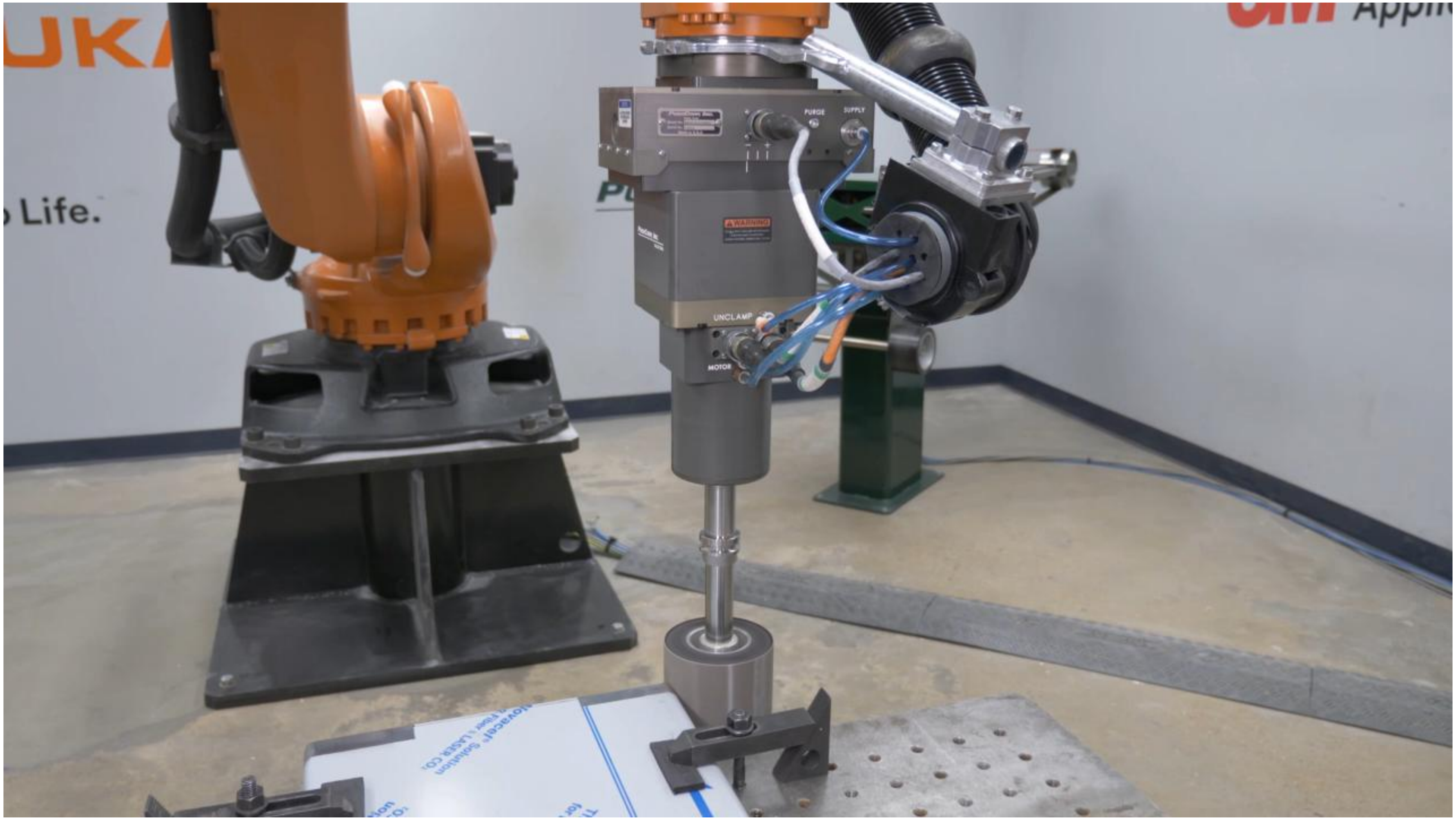
Examples of desired reference in impedance control

- the desired motion x^d is slightly inside the environment (keeping thus the contact)

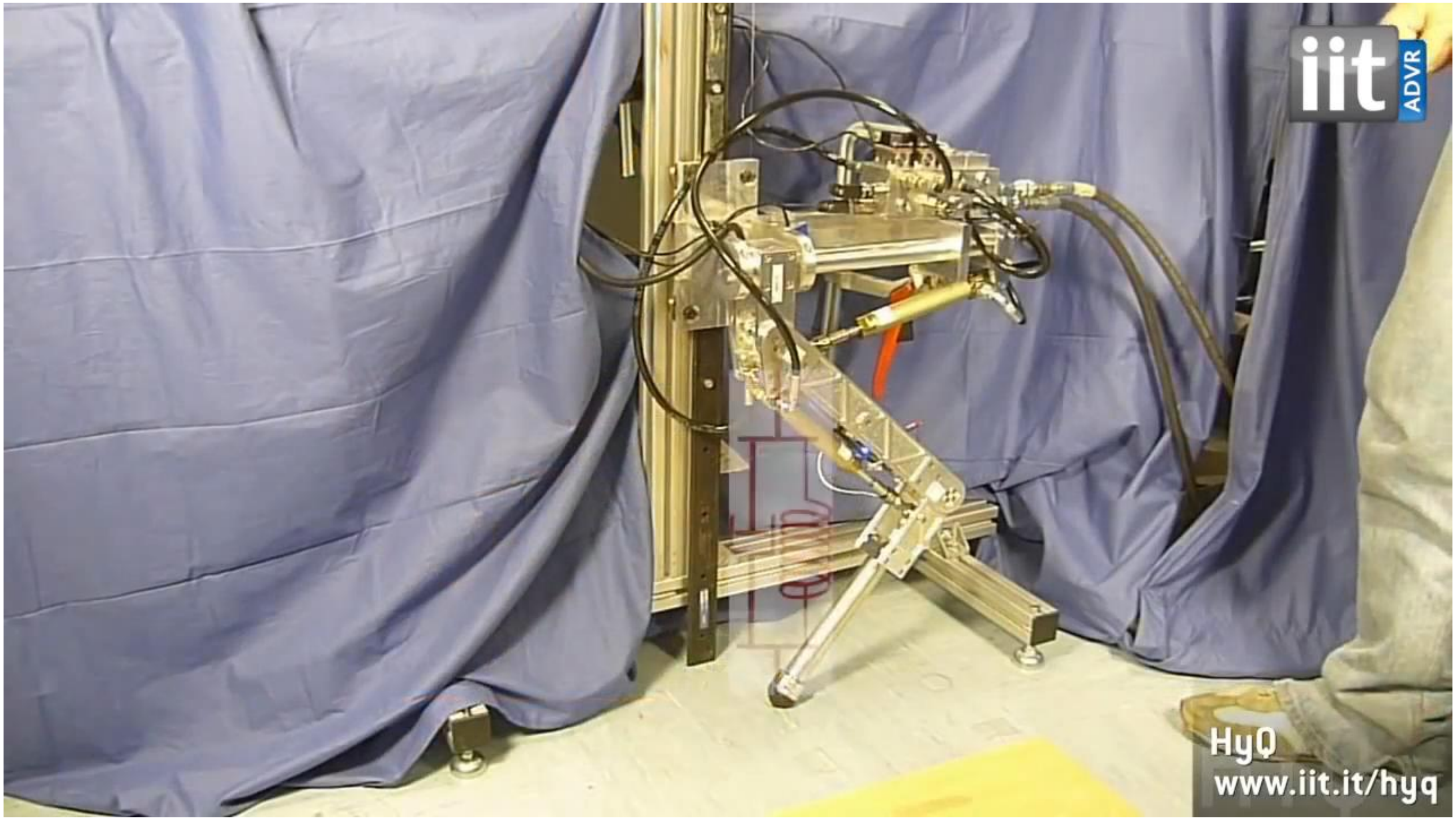


robot writing on a surface

Sanding and polishing



Impedance control on HyQ leg



Rotational impedance

$$M_x \Delta\ddot{P} + D_x \Delta\dot{P} + K_x \Delta P = F_{ext}$$ linear impedance

As we did in the linear case we can set "Torsional" impedance to control orientation

ϕ^d: desired orientation

ϕ : actual orientation

$\Delta\phi = \phi - \phi^d$

$$\boxed{M_\theta \Delta\ddot{\phi} + D_\theta \Delta\dot{\phi} + K_\theta \Delta\phi = T(\phi)^T m_{ext}}$$ Torsional impedance

m_{ext}: contact moment

$\Rightarrow$ due to the presence of T this relation is subject to representation singularities

Impedance control video

ADMITTANCE CONTROL

- for robots that are only position controlled
- maps contact force into displacements w.r.t. the reference position
- need a force sensor to measure the contact force
- admittance control modifies the setpoints of position control

EXAMPLE: ONLY COMPLIANCE

CARTESIAN SPACE

$$\Delta p \simeq K_x^{-1} F_{ext}$$

$$\boxed{\Delta q \simeq J^{-1}(q)\, K_x^{-1}\, F_{ext}}$$

$\hookrightarrow > 0$

$J^{\#}(q)$ for redundancy

JOINT SPACE

$$\Delta q \simeq K_q^{-1} \tau_{ext}$$

$\uparrow$

$J^T F_{ext}$

$$\boxed{\Delta q \simeq K_q^{-1} J^T F_{ext}}$$

$\hookrightarrow K_q > 0$

- Δq to be added to the position reference q^d

$$q^d(k+1) = q^d(k) + \Delta q(k)$$

- more complex admittance:

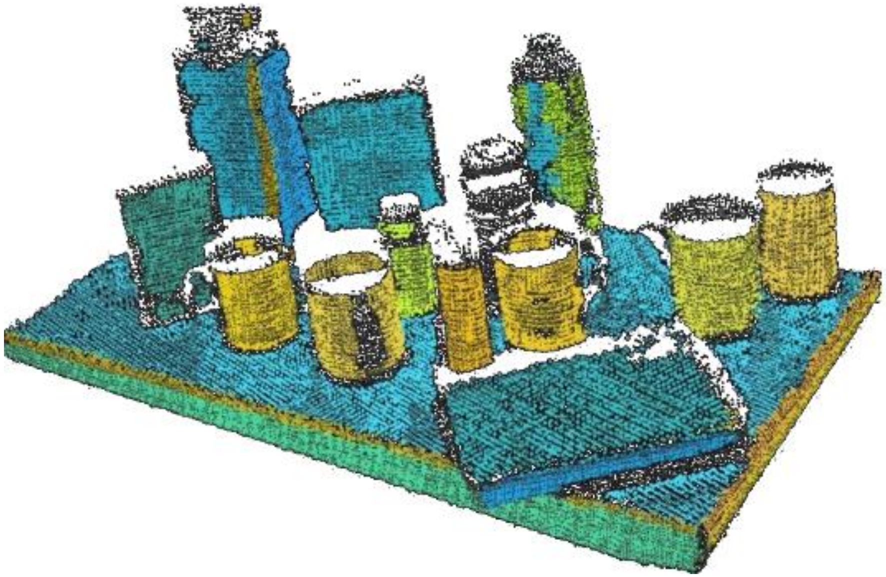
$$\Delta P = G(s) F_{ext} \qquad G(s) = \frac{1}{M_x^d s^2 + D_x^d s + K_x^d}$$

	ADMITTANCE	IMPEDANCE
Good for	render high impedances in low imp. env.	render low impedances in a high imp. env.
inner loop	position / velocity control	Torque control

Visual servoing

- Artificial vision devices are useful sensors for robotics because they mimic the human sense of sight and allow to gather information from the environment **without** contact.
- Vision in industrial robotics is to detect an object in the robot’s scene, whose position (and orientation) is then used for online path planning in order to drive the robot to the identified object.
- Concept of visual servoing: visual measurements can be used in **a real time feedback loop** in order to control the position control of the end effector

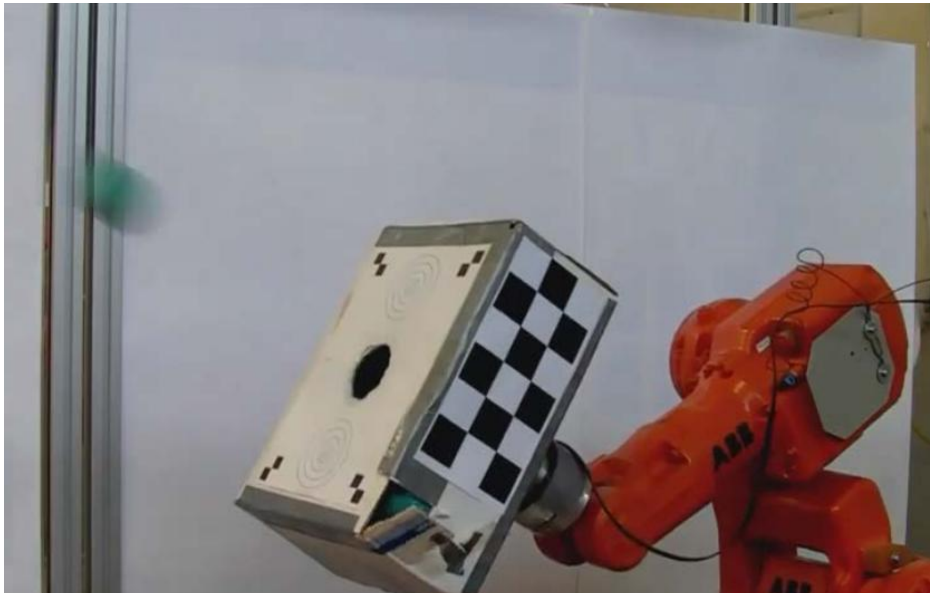
Depth map

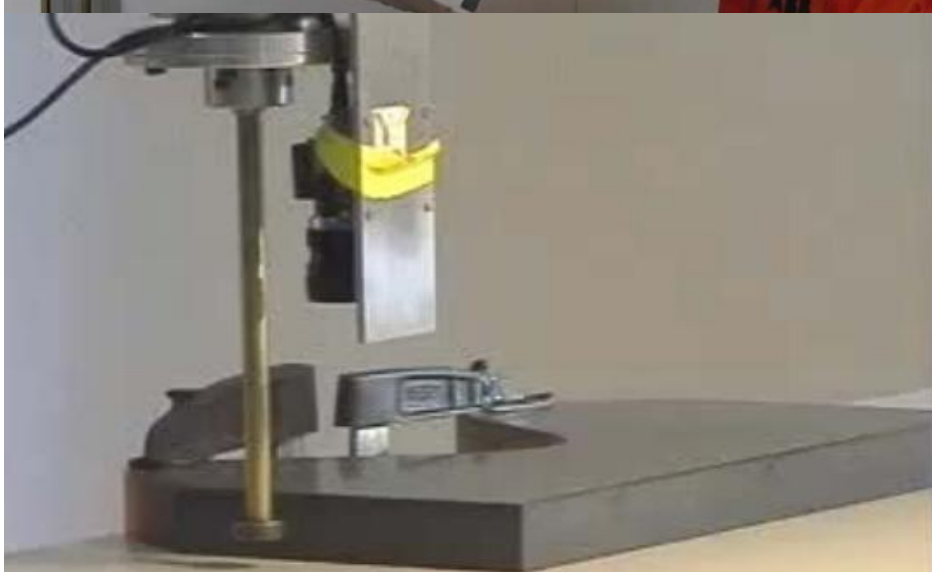


Visual servoing examples

A ball catching robot

A binpicking problem

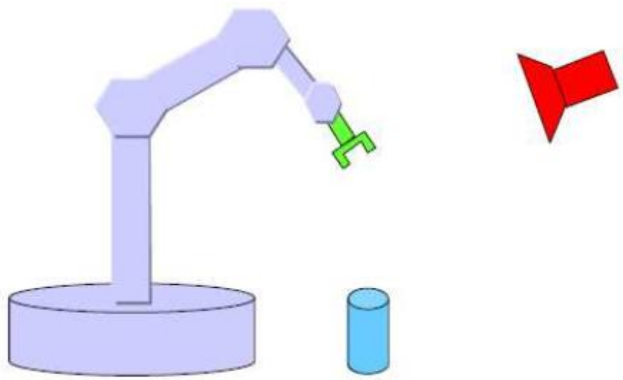




Following a corner during a contouring task

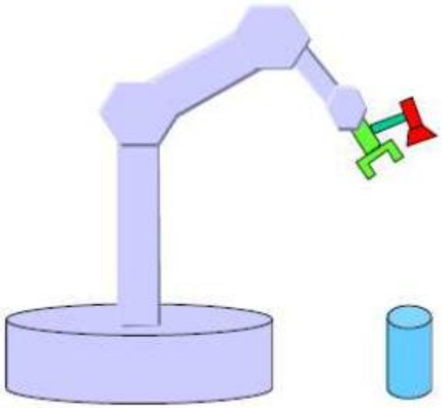
Visual servoing

- The first decision to be made when setting up a vision-based control system is where to place the camera.



Eye-To-Hand

- (+) Field of view does not change
- (+) Fixed geometric relationship between the camera and the workspace
- (-) As the manipulator moves through the workspace it can occlude the camera's field of view

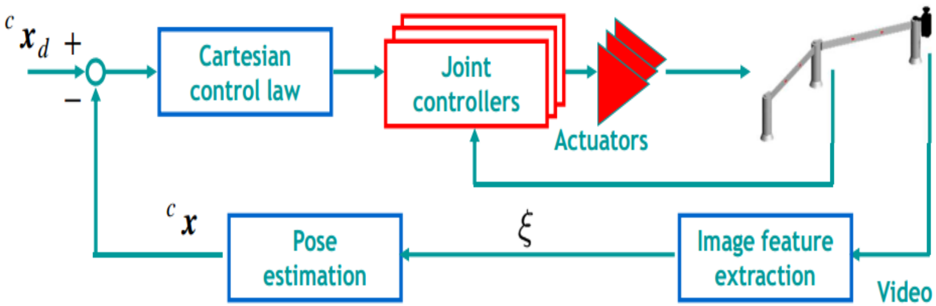


Eye-In-Hand

- (+) No occlusion
- (-) Geometric relationship between the camera and the workspace changes as the manipulator moves
- (-) Field of view changes even for small movements

Control architectures for visual servoing

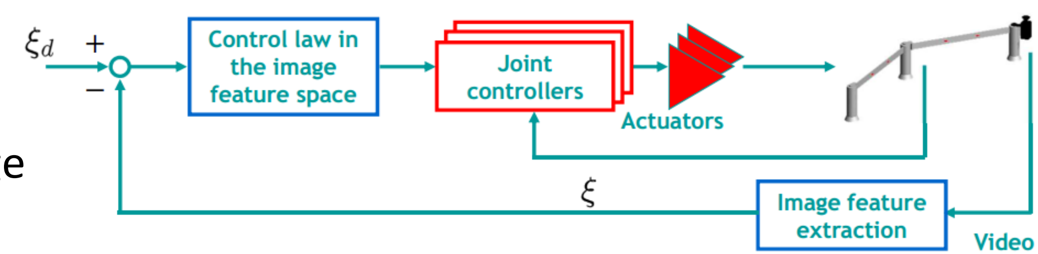
Position-based - look and move



- Vision system providing set-points as input to robot's joint-level controller
- Sampling rate of the visual signal does not compromise the overall performance of the position control system

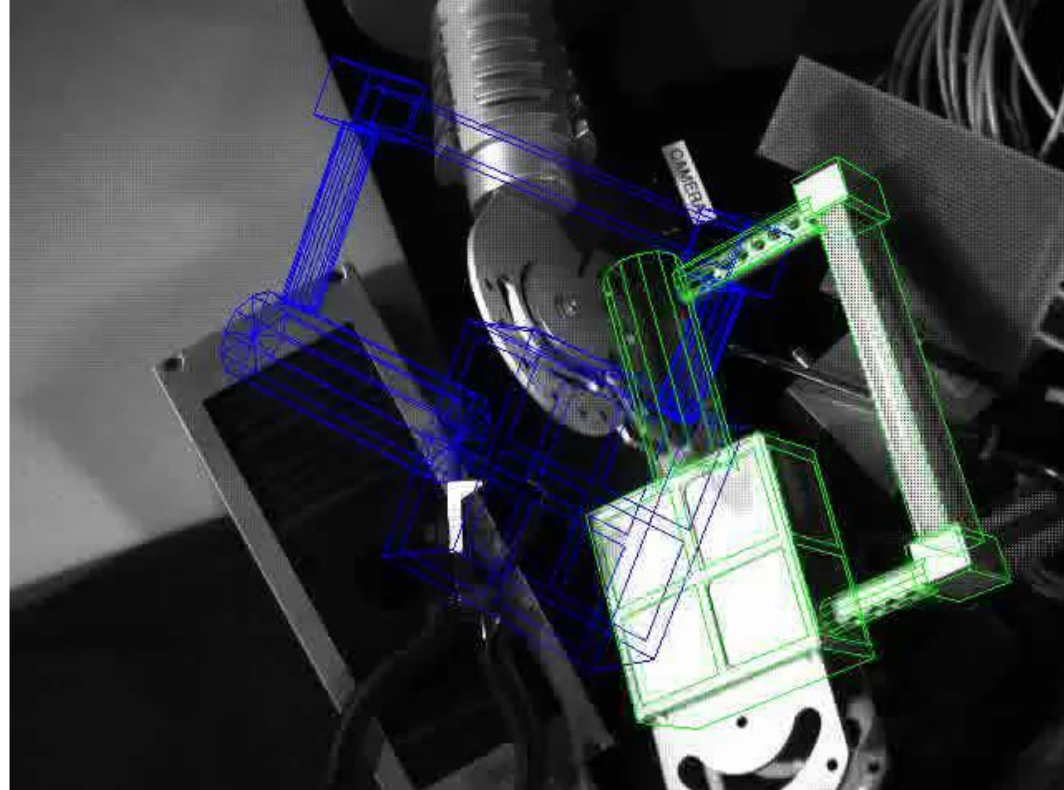
Image-based - visual servoing

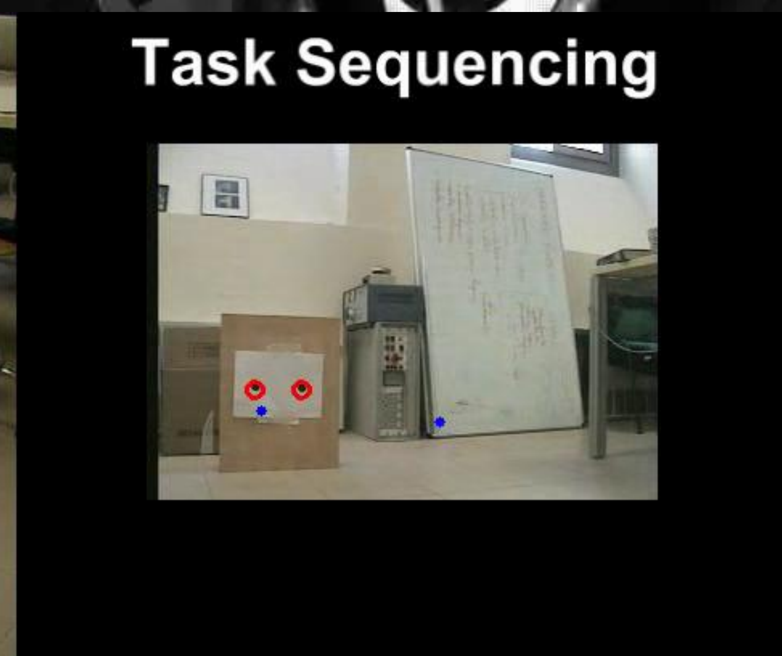
- uses the image data directly to control the robot motion
- an error function is defined in terms of quantities in the image plane



- a control law is constructed that maps this error directly to robot motion

Videos





References

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- N. Hogan, “Impedance Control: An Approach to Manipulation: PartI,II,III,”, 1985.