Robotics 2

Impedance Control

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Impedance control

- imposes a desired dynamic behavior to the interaction between robot end-effector and environment
- the desired performance is specified through a generalized dynamic impedance, namely a complete set of mass-spring-damper equations (typically chosen as linear and decoupled, but also nonlinear)
- a model describing how reaction forces are generated in association with environment deformation is not explicitly required
- suited for tasks in which contact forces should be “kept small”, while their accurate regulation is not mandatory
- since a control loop based on force error is missing, forces are only indirectly assigned by controlling position
- the choice of a specific stiffness in the impedance model along a Cartesian direction results in a trade-off between contact forces and position accuracy in that direction

Dynamic model of a robot in contact

$N = M$

$$B(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) = u + J^T(q)F$$

generalized Cartesian force

(linear) forces

$$F = \begin{pmatrix} \gamma \\ \mu \end{pmatrix} \in \mathbb{R}^M \quad \text{performing work on} \quad v = \begin{pmatrix} \dot{p} \\ \omega \end{pmatrix} = J(q)\dot{q} \neq \dot{x} = \begin{pmatrix} \dot{p} \\ \dot{\phi} \end{pmatrix} = J_a(q)\dot{q}$$

(angular) torques

"geometric" Jacobian

"analytic" Jacobian

angular velocity

derivative of Euler angles

direct kinematics

$$J_a(q) = \frac{df(q)}{dq} = T_a(\phi)J(q) \Rightarrow \dot{x} = T_a(\phi)v$$

$$B(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) = u + J_a^T(q)F_a \quad \text{with } F_a = T_a^{-T}(\phi)F$$

generalized forces performing work on $\dot{x}$

Dynamic model in Cartesian coordinates

$$B_x(q)\ddot{x} + S_x(q,\dot{q})\dot{x} + g_x(q) = J_a^{-T}(q)u + F_a$$

with

$$B_x(q) = J_a^{-T}(q)B(q)J_a^{-1}(q)$$

$$S_x(q,\dot{q}) = J_a^{-T}(q)\,S(q,\dot{q})\,J_a^{-1}(q) - B_x(q)\,\dot{J}_a(q,\dot{q})\,J_a^{-1}(q)$$

$$g_x(q) = J_a^{-T}(q)\,g(q)$$

...and the usual structural properties

- $B_x(q) > 0$, if $J_a(q)$ is non-singular
- $\dot{B}_x - 2S_x$ is skew-symmetric, if $\dot{B} - 2S$ satisfies the same property
- the Cartesian dynamic model of the robot is linearly parameterized in terms of a set of dynamic coefficients

Design of the control law

designed in two steps:

1. feedback linearization in the Cartesian space

$$\boxed{u = J_a^T(q)\left[B_x(q)a + S_x(q,\dot{q})\dot{x} + g_x(q) - F_a\right]}$$

$$\Rightarrow \quad \boxed{\ddot{x} = a}$$ closed-loop system

2. imposition of a dynamic impedance model

most of the times it is "decoupled" (diagonal matrices)

$$\boxed{B_m\left(\ddot{x} - \ddot{x}_d\right) + D_m\left(\dot{x} - \dot{x}_d\right) + K_m\left(x - x_d\right) = F_a}$$

desired (apparent) inertia (> 0) — desired damping (≥ 0) — desired stiffness (> 0) — external forces from the environment

is realized by choosing

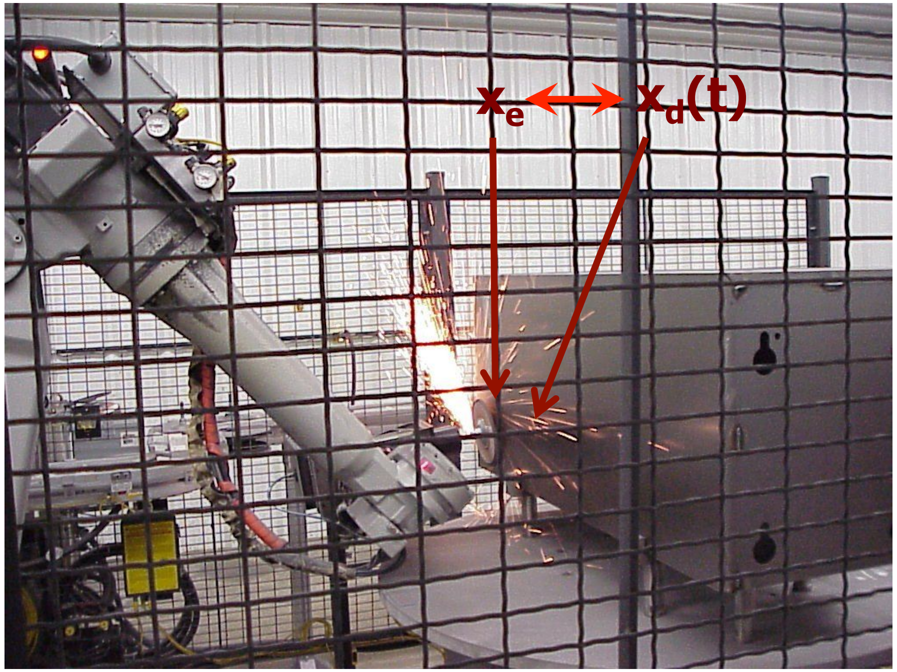
$$\boxed{a = \ddot{x}_d + B_m^{-1}\left[D_m\left(\dot{x}_d - \dot{x}\right) + K_m\left(x_d - x\right) + F_a\right]}$$

Note: $x_d(t)$ is the desired motion, which typically "slightly penetrates" inside the compliant environment (keeping thus contact)...

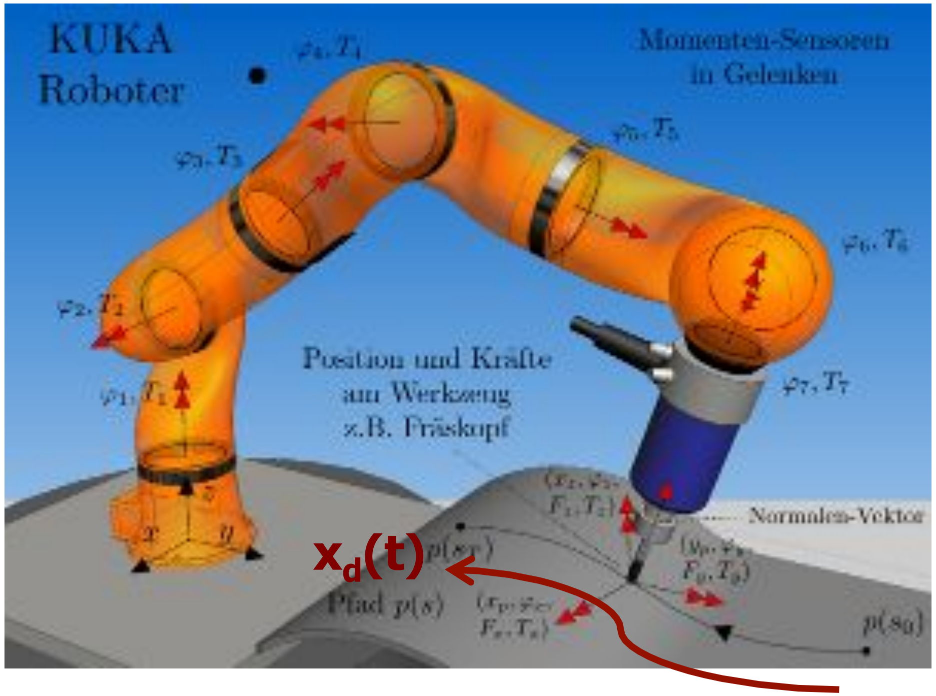
Examples of desired reference x_d in impedance/compliance control

$$\boxed{B_m(\ddot{x}-\ddot{x}_d)+D_m(\dot{x}-\dot{x}_d)+K_m(x-x_d)=F_a}$$

the desired motion **$x_d(t)$ is lightly inside** the environment (keeping thus contact)



robot in grinding task

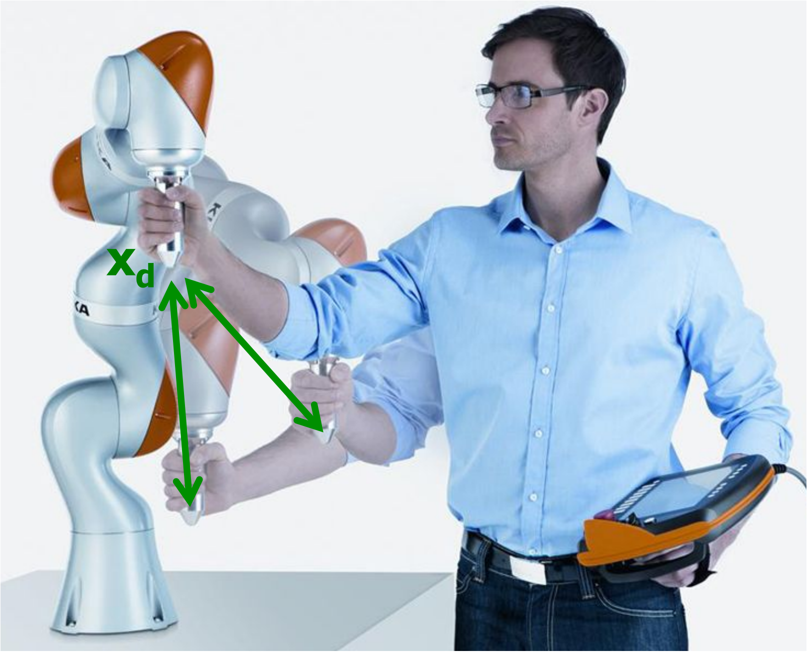


robot writing on a surface

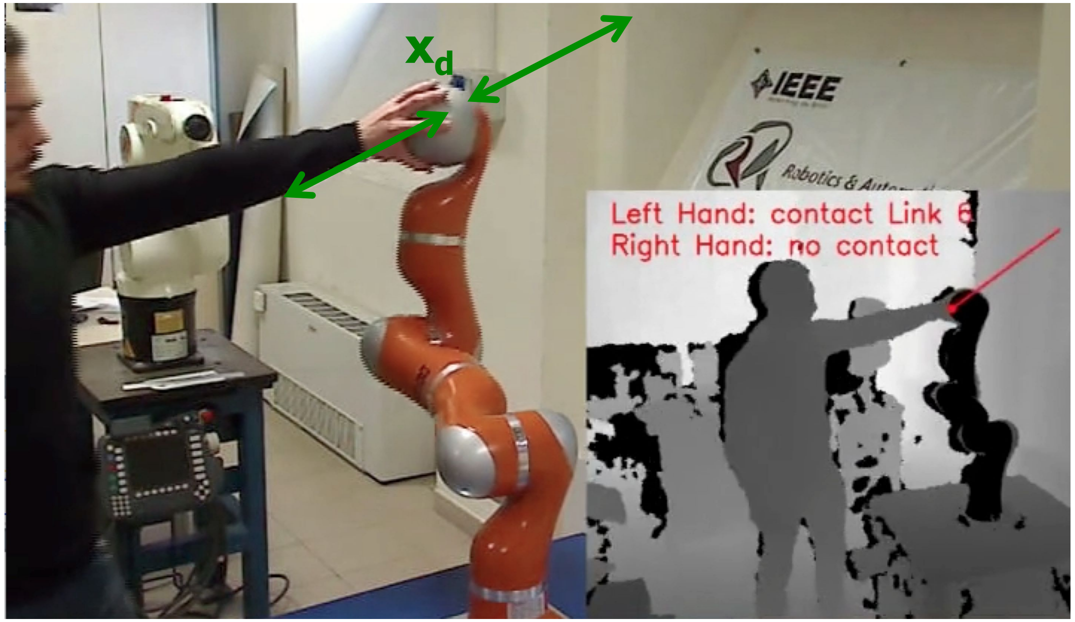
Examples of desired reference x_d in impedance/compliance control

$$\boxed{B_m(\ddot{x}-\ddot{x}_d)+D_m(\dot{x}-\dot{x}_d)+K_m(x-x_d)=F_a}$$

constant desired pose $\mathbf{x_d}$ is the free Cartesian **rest position** in a human-robot interaction task



KUKA iiwa robot with human operator



KUKA LWR robot in pHRI (collaboration)

Control law in joint coordinates

substituting and simplifying…

$$\boxed{\begin{aligned} u = {} & B(q)J_a^{-1}(q)\left\{\ddot{x}_d - \dot{J}_a(q)\dot{q} + B_m^{-1}\left[D_m\left(\dot{x}_d - \dot{x}\right) + K_m\left(x_d - x\right)\right]\right\} \\ & + S(q,\dot{q})\dot{q} + g(q) + J_a^T(q)\underbrace{\left[B_x(q)B_m^{-1} - I\right]}_{\text{matrix weighting the measured contact forces}}F_a \end{aligned}}$$

- the following identity holds for the term involving contact forces

$$J_a^T(q)\left[B_x(q)B_m^{-1} - I\right]F_a = \left[B(q)J_a^{-1}(q)B_m^{-1} - J_a^T(q)\right]F_a$$

  which eliminates from the control law also the appearance of the last remaining Cartesian quantity (the Cartesian inertia matrix)

- while the principle of control design is based on dynamic analysis and desired (impedance) behavior as described in the Cartesian space, the final control implementation is always made at robot joint level

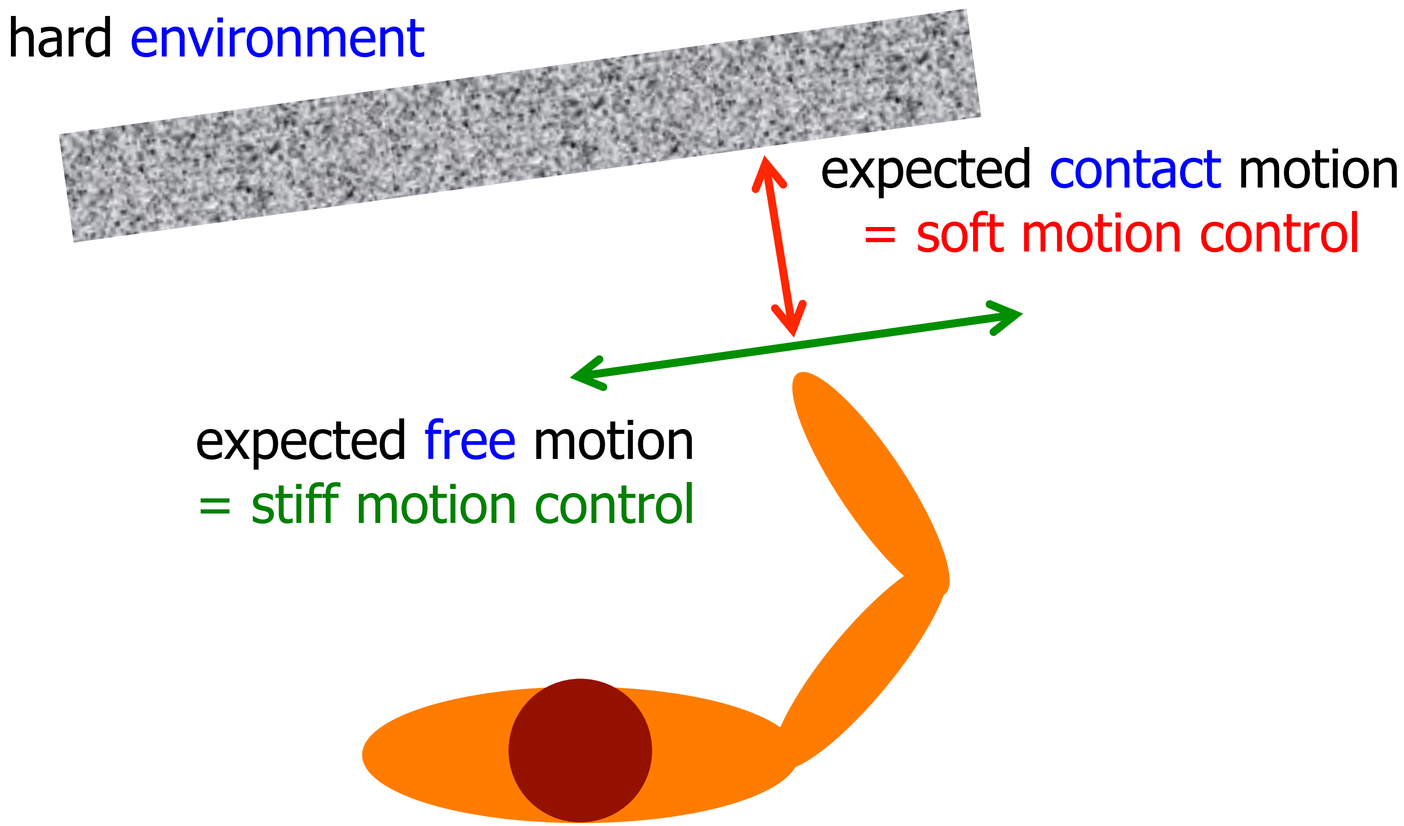
Choice of the impedance model

rationale ...

- avoid large impact forces due to uncertain geometric characteristics (position, orientation) of the environment
- adapt/match to the dynamic characteristics (in particular, stiffness) of the environment, in a complementary way
- mimic the behavior of a human arm
  - ➔ fast and stiff in free motion, slow and compliant in "safeguarded" motion

- large $B_{m,i}$ and small $K_{m,i}$ in Cartesian directions where contact is foreseen (➔ low contact forces)
- large $K_{m,i}$ and small $B_{m,i}$ in Cartesian directions that are supposed to be free (➔ good tracking of desired motion trajectory)
- damping coefficients $D_{m,i}$ are used to shape transient behaviors

Human arm behavior



in selected directions:
the stiffer is the environment, the softer is the chosen model stiffness $K_{m,i}$

A notable simplification - 1

choose the apparent inertia equal to the natural Cartesian inertia of the robot

$$B_m = B_x(q) = J_a^{-T}(q)B(q)J_a^{-1}(q)$$

then, the control law becomes

$$\boxed{\begin{aligned} u &= B(q)J_a^{-1}(q)\left[\ddot{x}_d - \dot{J}_a(q)\dot{q}\right] + S(q,\dot{q})\dot{q} + g(q) \\ &\quad + J_a^T(q)\left[D_m(\dot{x}_d - \dot{x}) + K_m(x_d - x)\right] \end{aligned}}$$

WITHOUT contact force feedback! (a F/T sensor is no longer needed…)

actually, this is a pure motion control during interaction,
designed so as to keep limited contact forces at the end-effector level
(as before, K_m is chosen as a function of the expected environment stiffness)

A notable simplification - 2

technical issue: if the impedance model (now, nonlinear) is still supposed to represent a real mechanical system, then in correspondence to a desired non-constant inertia ($B_x(q)$) there should be Coriolis and centrifugal terms...

$$B_x(q)\left(\ddot{x}-\ddot{x}_d\right)+\left(S_x(q,\dot{q})+D_m\right)\left(\dot{x}-\dot{x}_d\right)+K_m\left(x-x_d\right)=F_a$$

nonlinear impedance model ("only" gravity terms disappear)

redoing computations, the control law becomes

$$\begin{aligned} u = {} & B(q)J_a^{-1}(q)\left[\ddot{x}_d-\dot{J}_a(q)J_a^{-1}(q)\dot{x}_d\right]+S(q,\dot{q})J_a^{-1}(q)\dot{x}_d+g(q) \\ & +J_a^T(q)\left[D_m\left(\dot{x}_d-\dot{x}\right)+K_m\left(x_d-x\right)\right] \end{aligned}$$

which is indeed slightly more complex, but has the following advantages:

- guarantee of asymptotic convergence to zero tracking error (on $x_d(t)$) when $F_a = 0$ (no contact situation) ⇒ Lyapunov + skew-symmetry of $\dot{B}_x-2S_x$
- further simplification when x_d is constant

Cartesian regulation revisited
(with no contact, $F_a = 0$)

if x_d is constant $(\dot{x}_d = 0,\ \ddot{x}_d = 0)$, from the previous expression we obtain the control law

$$\boxed{u = g(q) + J_a^T(q)\left[K_m(x_d - x) - D_m\dot{x}\right]} \qquad (*)$$

Cartesian PD with gravity cancelation…

when $F_a = 0$ (absence of contact), we know already that this law ensures asymptotic stability of x_d, provided $J_a(q)$ has full rank

proof (alternative)

Lyapunov candidate $\quad V_1 = \frac{1}{2}\dot{x}^T B_x(q)\dot{x} + \frac{1}{2}(x_d - x)^T K_m(x_d - x)$

$$\Rightarrow \quad \dot{V}_1 = \dot{x}^T B_x(q)\ddot{x} + \frac{1}{2}\dot{x}^T \dot{B}_x(q)\dot{x} - \dot{x}^T K_m(x_d - x) = \ldots = -\dot{x}^T D_m \dot{x} \le 0$$

using skew-symmetry of $\dot{B}_x - 2S_x$ and $g_x = J_a^{-T} g$

Cartesian stiffness control
(in contact, $F_a \neq 0$)

when $F_a \neq 0$, convergence to x_d is not assured
(it may not even be a closed-loop equilibrium…)

- for analysis, assume an elastic contact model for the environment

$$\boxed{F_a = K_e(x_e - x)}$$ with stiffness $K_e \geq 0$ and rest position x_e

- closed-loop system behavior

Lyapunov candidate

$$V_2 = \tfrac{1}{2}\dot{x}^T B_x(q)\dot{x} + \tfrac{1}{2}(x_d - x)^T K_m (x_d - x) + \tfrac{1}{2}(x_e - x)^T K_e (x_e - x)$$

$$= V_1 + \tfrac{1}{2}(x_e - x)^T K_e (x_e - x)$$

$$\dot{V}_2 = \dot{x}^T B_x(q)\ddot{x} + \tfrac{1}{2}\dot{x}^T \dot{B}_x(q)\dot{x} - \dot{x}^T K_m (x_d - x) - \dot{x}^T K_e (x_e - x)$$

$$= \ldots = -\dot{x}^T D_m \dot{x} + \dot{x}^T\left(F_a - K_e(x_e - x)\right) = -\dot{x}^T D_m \dot{x} \leq 0$$

Stability analysis (with $F_a \neq 0$)

when $\dot{x} = \ddot{x} = 0$, at the closed-loop system equilibrium it is

$K_m(x_d - x) + K_e(x_e - x) = 0$, which has the unique solution

$$x = (K_m + K_e)^{-1} (K_m x_d + K_e x_e) =: x_E$$

(check that the Lyapunov candidate V_2 has in fact its minimum in x_E!!)

LaSalle $\Rightarrow$ x_E asymptotically stable equilibrium

$$x_E \approx \begin{cases} x_e \text{ for } K_e >> K_m \text{ (rigid environment)} \\ x_d \text{ for } K_m >> K_e \text{ (rigid controller)} \end{cases}$$

Note: the Cartesian stiffness control law (*) is often called also **compliance** control in the literature

"Active" equivalent of RCC device

IF

- displacement from the desired position x_d are small, namely

$$(x_d - x) \approx J_a(q_d - q)$$

- $g(q) = 0$ (gravity is compensated/canceled, e.g. mechanically)
- $D_m = 0$

THEN

$$\boxed{u = J_a^T(q) K_m J_a(q)(q_d - q) = K_x(q)(q_d - q)}$$

a variable joint level stiffness $K_x(q)$ corresponds to a constant Cartesian level stiffness K_m (and vice versa)

active counterpart of the Remote Center of Compliance (RCC) device