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Flexible joint robots: Model-based control revisited

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Summary

- A world of soft robots
  - flexible joints, serial elastic actuation (SEA), variable stiffness actuation (VSA), distributed link flexibility
  - lightweight robots with flexible joints in physical Human-Robot Interaction (pHRI)
- Dynamic modeling of flexible joint manipulators
  - … with few comments on its properties
- Classical control tasks and their solution
  - full-state feedback linearization design for trajectory tracking
  - regulation with partial state feedback and gravity compensation
- Model-based design based on feedback equivalence
  - exact gravity cancellation
  - damping injection on the link side
  - environment interaction via generalized impedance control
- Outlook

Classes of soft robots

Robots with elastic joints

- design of lightweight robots with stiff links for end-effector accuracy
- compliant elements absorb impact energy
  - soft coverage of links (safe bags)
  - elastic transmissions (HD, cable-driven, ...)


- elastic joints decouple instantaneously the *larger* inertia of the driving motors from *smaller* inertia of the links (involved in contacts/collisions!)
- *relatively* soft joints need more sensing (e.g., joint torque) and better control to compensate for static deflections and dynamic vibrations

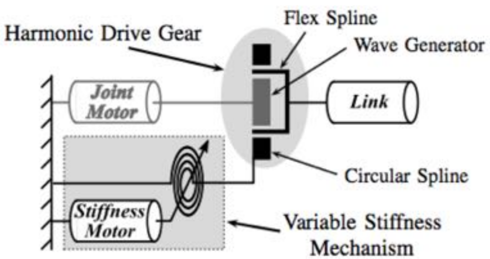



➡ torque-controlled robots (DLR LWR-III, KUKA LWR-IV & iiwa, Franka, ...)

Classes of soft robots

Robots with **Variable Stiffness Actuation** (VSA)

- uncertain interaction with dynamic environments (say, *humans*) requires to adjust online the compliant behavior and/or to control contact forces
  - passive joint elasticity & active impedance control used in parallel
- nonlinear flexible joints with variable (controlled) stiffness work at best
  - can be made *stiff when moving slow* (performance), *soft when fast* (safety)
  - enlarge the set of achievable robot compliance in a task-oriented way
  - feature also **robustness**, optimal **energy use**, **explosive motion** tasks, ...



Classes of soft robots

Robots with flexible links

- distributed link deformations
  - design of very long and slender arms needed in the application
  - use of lightweight materials to save weight/costs
  - due to large payloads (viz. large contact forces) and/or high motion speed
- as for joint elasticity, neglecting link flexibility will limit static (steady-state error) or dynamic (vibrations, poor tracking) performance
- extra control issue due to non-minimum phase nature of the outputs of interest w.r.t. the command inputs … "move in the opposite direction!"




A matter of terminology ...

Different sources of elasticity, though similar robotic systems

- elastic joints vs. SEA (Serial Elastic Actuators)
  - based on the same physical phenomenon: compliance in actuation
  - compliance added on purpose in SEA, mostly a disturbance in elastic joints
  - different range of stiffness: 5-10K Nm/rad down to 0.2-1K Nm/rad in SEA
- joint deformation is often considered in the linear domain
  - modeled as a concentrated torsional spring with constant stiffness at the joint
  - nonlinear flexible joints share similar control properties
  - nonlinear stiffness characteristics are needed instead in VSA
  - a (serial or antagonistic) VSA working at constant stiffness is an elastic joint
- flexible joint robots are classified as underactuated mechanical systems
  - have less commands than generalized coordinates
  - non-collocation of command inputs and dynamic effects to be controlled
  - however, they are controllable in the first approximation (the *easy* case!)

Exploiting joint elasticity in pHRI

Detection and selective reaction in torque control mode, based on residuals

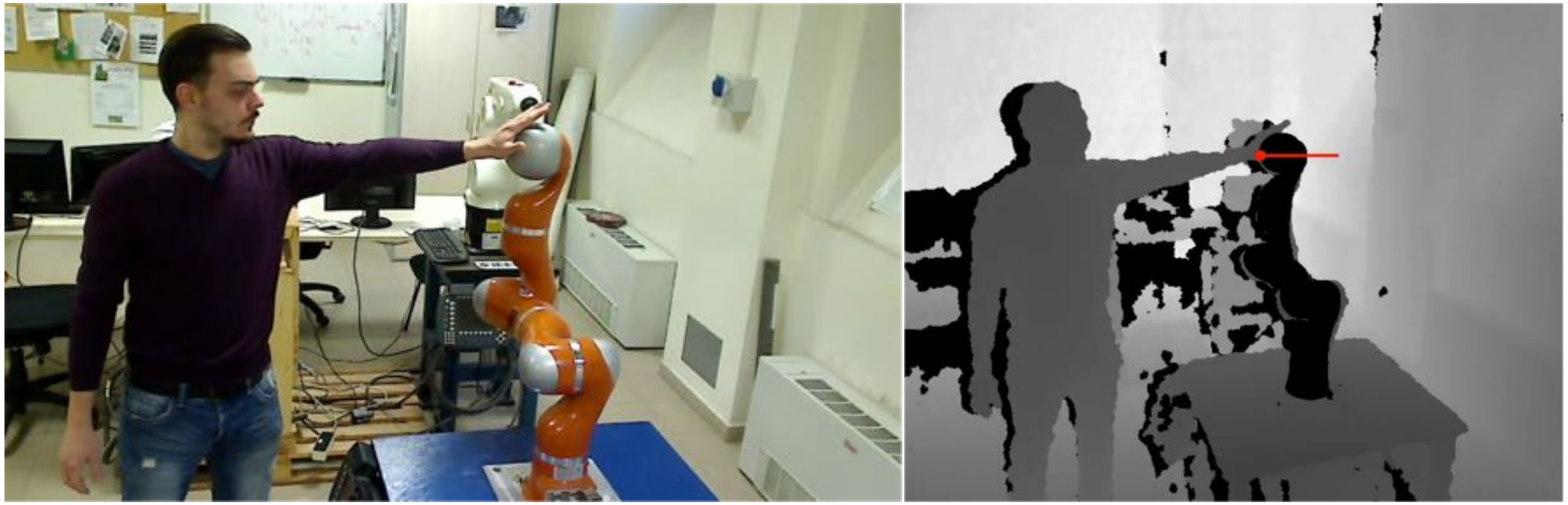
- collision detection & reaction for safety (model-based + joint torque sensing)

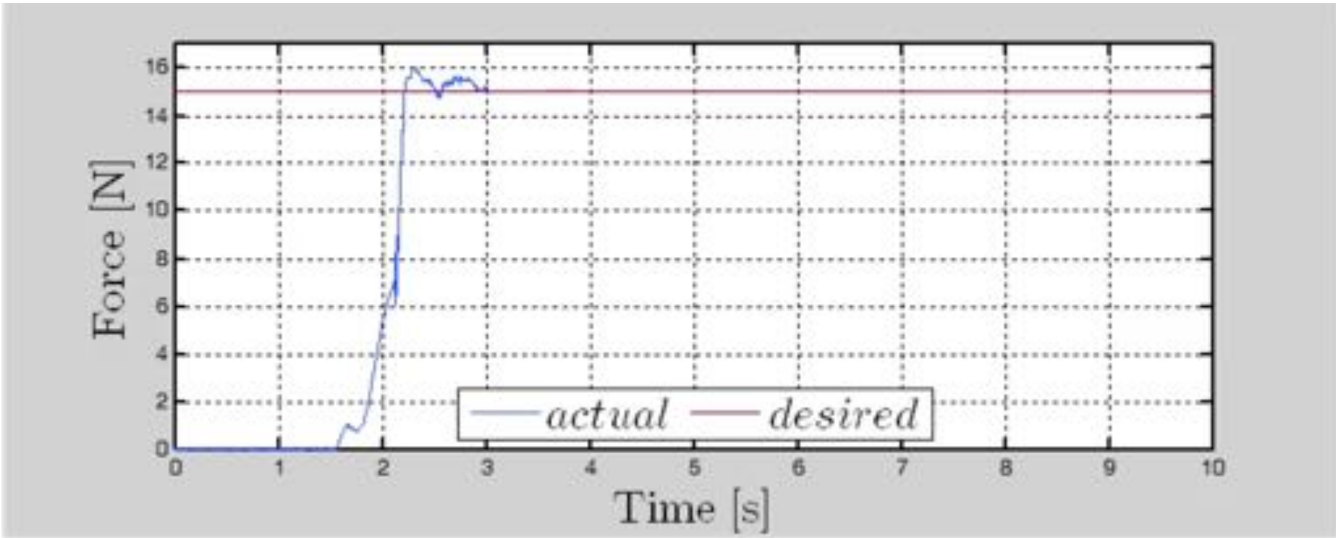
[De Luca *et al,* 2006; Haddadin *et al,* 2017]

Exploiting joint elasticity in pHRI

Human-robot collaboration in torque control mode

- contact force estimation & control (virtual force sensor, anywhere/anytime)





[Magrini *et al*, 2015]

Dynamic modeling

Lagrangian formulation (so-called reduced model of Spong)

- open chain robot with N elastic joints and N rigid links, driven by electrical actuators
- use N motor variables θ (as reflected through the gear ratios) and N link variables q
- assumptions

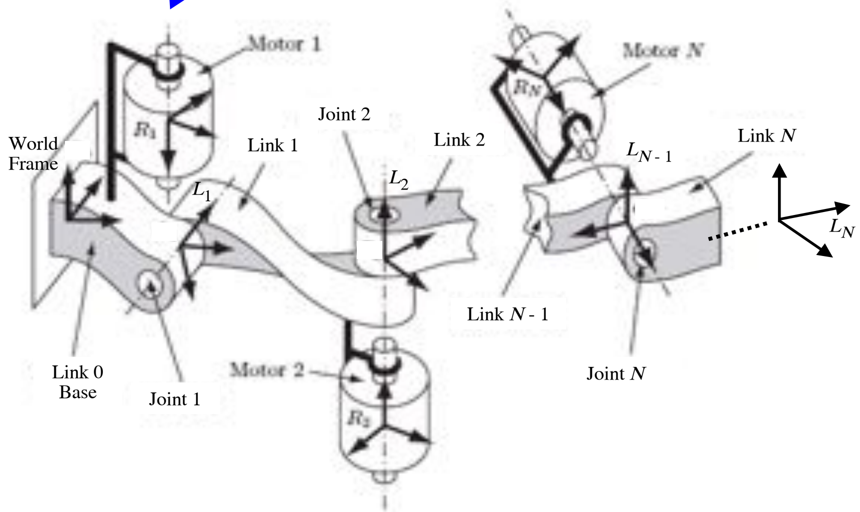
  A1) small displacements at joints

  A2) axis-balanced motors

  A3) each motor is mounted on the robot in a position preceding the driven link

  A4) no inertial couplings between motors and links

center of mass of rotors on rotation axes



A4) ⇒ 2N × 2N inertia matrix Is block diagonal

A2) ⇒ inertia matrix and gravity vector are independent from θ

$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta-q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau \end{pmatrix}$$

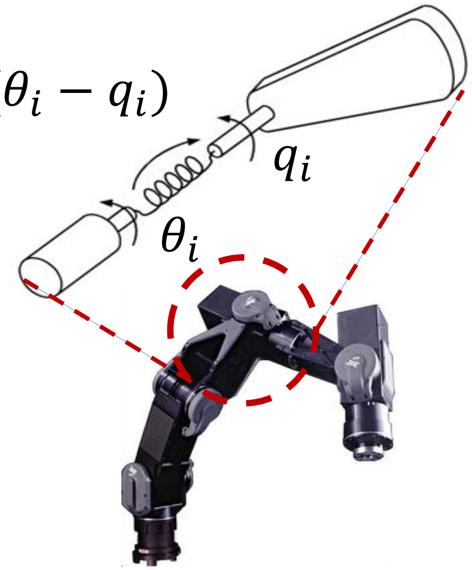
link equation

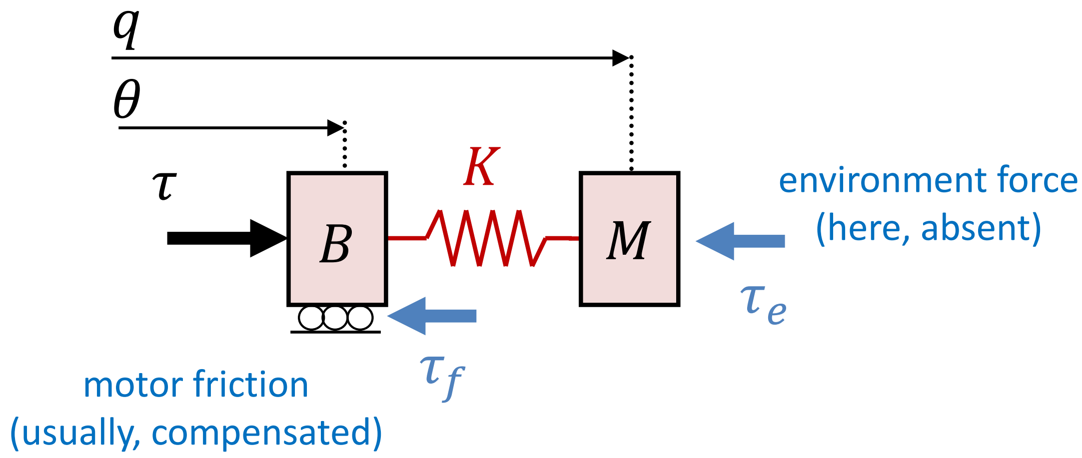
motor equation

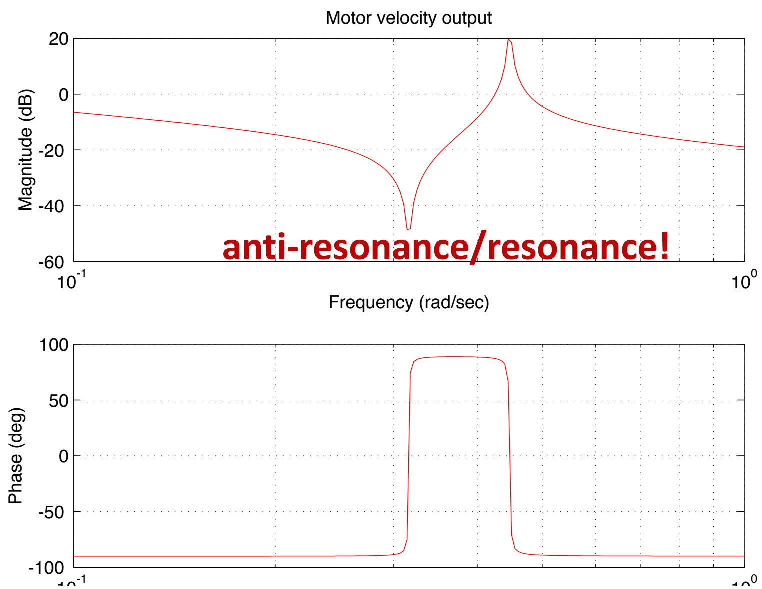
Single elastic joint

Transfer functions of interest

$$\tau_{ei} = K_i(\theta_i - q_i)$$







$$P_{\text{motor}}(s) = \frac{\theta(s)}{\tau(s)} = \frac{Ms^2 + K}{MBs^2 + (M+B)K}\,\frac{1}{s^2}$$

- system with zeros and relative degree = 2
- passive (zeros always *precede* poles on the imaginary axis)
- stabilization can be achieved via output θ feedback

$$P_{\text{link}}(s) = \frac{q(s)}{\tau(s)} = \frac{K}{MBs^2 + (M+B)K}\,\frac{1}{s^2}$$

- NO zeros!!
- maximum relative degree = 4

Feedback linearization

For accurate trajectory tracking tasks

- the link position q is a linearizing (flat) output

$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta-q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau \end{pmatrix} \quad \Longleftrightarrow \quad \boxed{q^{(4)} = u}$$

- differentiating twice the link equation and using the motor acceleration yields

$$\tau = BK^{-1}M(q)u + K(\theta - q) + B\ddot{q} + BK^{-1}\left(2\dot{M}q^{(3)} + \ddot{M}\ddot{q} + \frac{d^2}{dt^2}\left(C\dot{q} + g(q)\right)\right)$$

- an exactly linear and I/O decoupled closed-loop system is obtained
  - to be stabilized with standard techniques for linear dynamics (pole placement, LQ, …)
- requires higher derivatives of q —— $q, \dot{q}, \ddot{q}, q^{(3)}$
- however, these can be computed from the model using the state measurements
- requires higher derivatives of the dynamics components —— $\ddot{M}, \ddot{C}, \ddot{g}$
- A $O(N^3)$ Newton-Euler recursive numerical algorithm is available for this problem

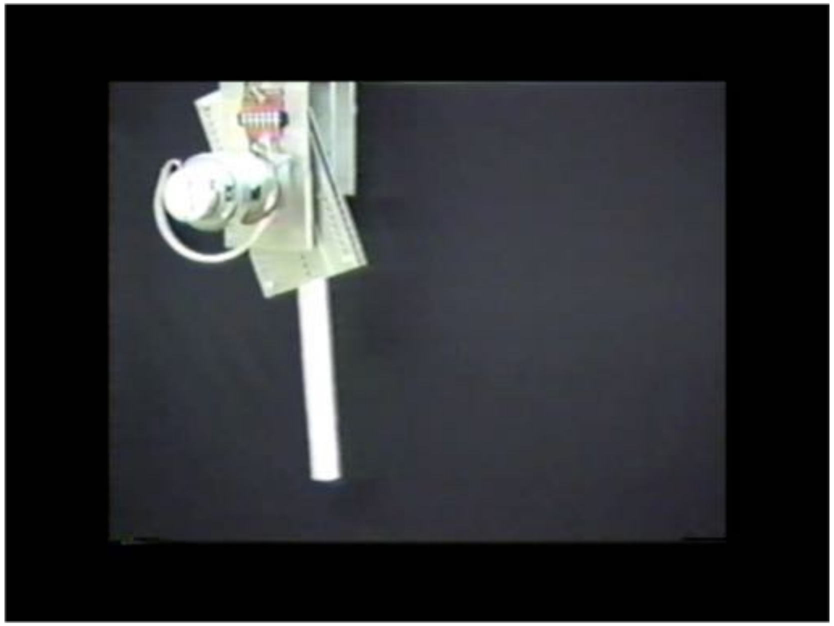
Feedback linearization

Based on the rigid model only vs. when including joint elasticity

$$\tau = M(q)\left(\ddot{q}_d + K_D(\dot{q}_d - \dot{q}) + K_P\,(q_d - q)\right) + C(q,\dot{q})\dot{q} + g(q)$$

$$\tau = BK^{-1}M(q)u + K(\theta - q) + B\ddot{q} + BK^{-1}\left(2\dot{M}q^{(3)} + \ddot{M}\ddot{q} + \frac{d^2}{dt^2}\left(C\dot{q} + g(q)\right)\right)$$

$$u = \left(q_d^{[4]} + K_J(\dddot{q}_d - \dddot{q}) + K_A(\ddot{q}_d - \ddot{q}) + K_D(\dot{q}_d - \dot{q}) + K_P\,(q_d - q)\right)$$



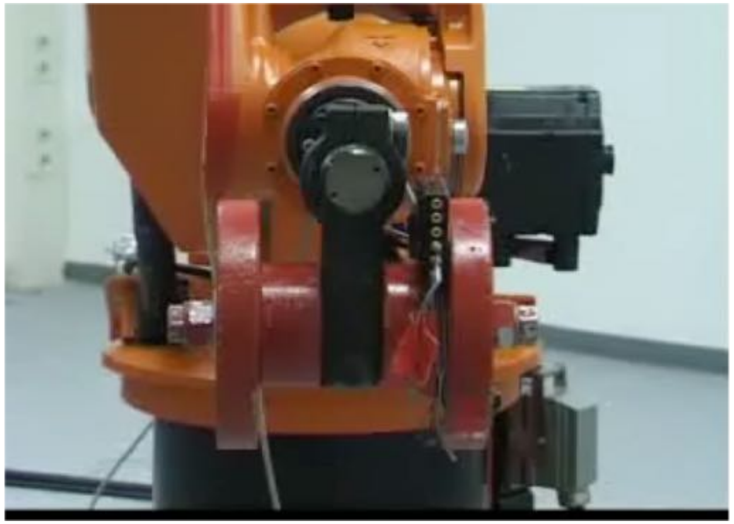
rigid computed torque [Spong, 1986] elastic joint feedback linearization

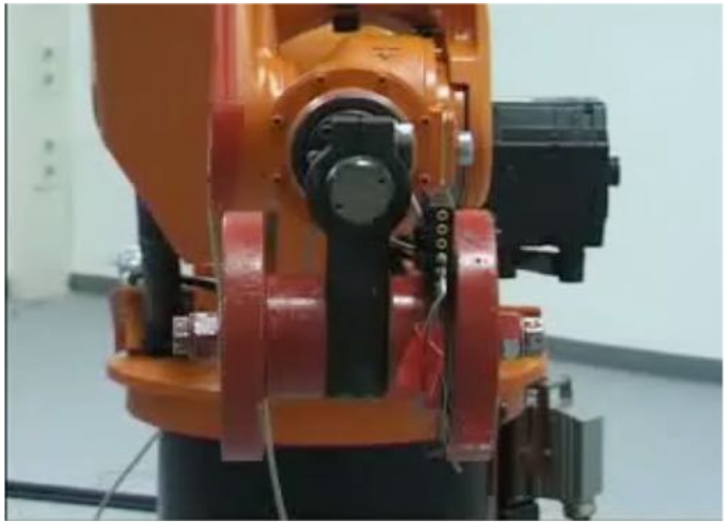
Feedback linearization

Benefits on an industrial KUKA KR-15/2 robot (235 kg) with joint elasticity

conventional industrial robot control

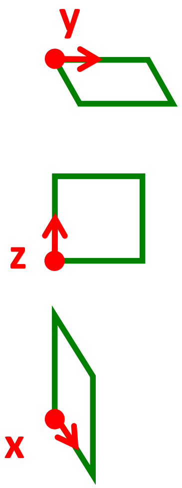
feedback linearization + high-damping





trajectory tracking with model-based control

three squares in:



horizontal plane

vertical front plane

vertical sagittal plane

[Thümmel, 2007]

Regulation tasks

Using a minimal PD+ action on the motor side

for a desired constant link position q_d

- evaluate the associated desired motor position θ_d at steady state
- collocated (partial state) feedback preserves passivity, with stiff K_P gain dominating gravity
- focus on the term for **gravity compensation** (acting on link side) from motor measurements

$$\theta_d = q_d + K^{-1} g(q_d) \qquad \tau = \tau_g + K_P(\theta_d - \theta) - K_D\dot{\theta} \qquad K_D > 0$$

τ_g	gain criteria for stability	
$g(q_d)$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K+K_P \end{bmatrix} > \alpha$	[Tomei, 1991]
$g(\theta - K^{-1}g(q_d))$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K+K_P \end{bmatrix} > \alpha$	[De Luca, Siciliano, Zollo, 2004]
$g(\bar{q}(\theta))$, $\bar{q}(\theta)$: $g(\bar{q}) = K(\theta - \bar{q})$	$K_P > 0, \quad \lambda_{min}(K) > \alpha$	[Ott, Albu-Schäffer, 2004]
$g(q) + BK^{-1}\ddot{g}(q)$	$K_P > 0, \quad K > 0$	[De Luca, Flacco, 2010]

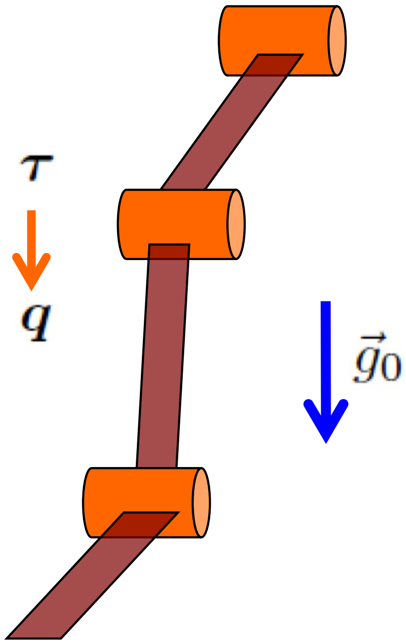
exact gravity cancellation
(with **full state** feedback)

$$\alpha = \max\left(\left\|\frac{\partial g(q)}{\partial q}\right\|\right)$$

Exact gravity cancellation

A slightly different view

- for rigid robots this is trivial, due to collocation

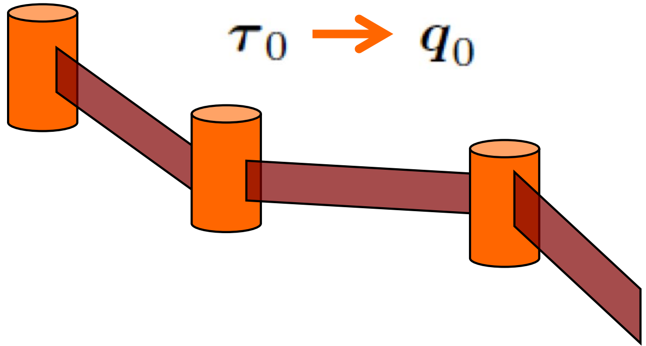


$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) = \tau$$

$$\tau = \tau_g + \tau_0$$

$$\tau_g = g(q)$$

$$q \equiv q_0$$

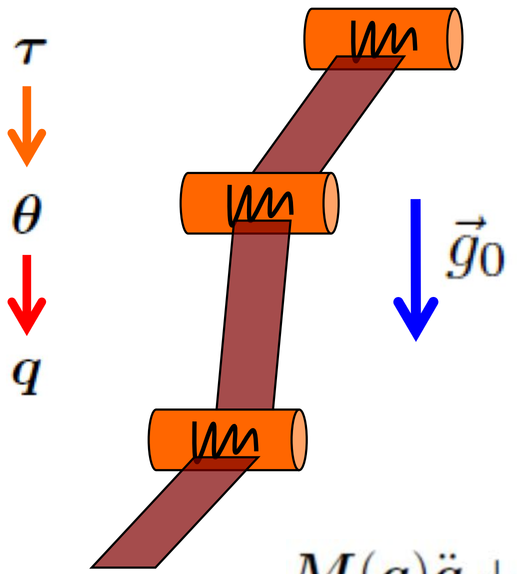


$$M(q)\ddot{q} + c(q,\dot{q}) = \tau_0$$

Exact gravity cancellation

... based on the concept of feedback equivalence between nonlinear systems

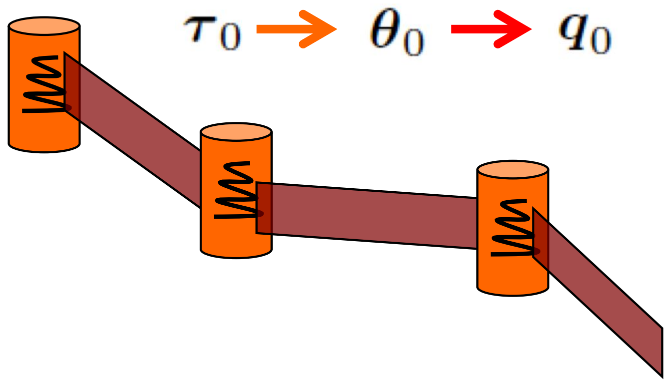
- for elastic joint robots, **non-collocation** of input torque and gravity term



??

$$\tau = \tau_g + \tau_0$$

$$q \equiv q_0$$



$$\begin{aligned} M(q)\ddot{q} + c(q,\dot{q}) + g(q) + D_q\dot{q} + K(q-\theta) &= 0 \\ B\ddot{\theta} + D_\theta\dot{\theta} + K(\theta - q) &= \tau \end{aligned}$$

$$\boxed{\tau_g = g(q) + D_\theta K^{-1}\dot{g}(q) + BK^{-1}\ddot{g}(q)}$$

Feedback equivalence

Exploit the system property of being feedback linearizable (without forcing it!)

$$u = \tilde{\alpha}(x) + \tilde{\beta}(x) u_0$$
$$x_0 = T_0^{-1}(T(x)) = \tilde{T}(x)$$

$$\dot{x} = f(x) + G(x) u$$

gravity-loaded system

$$\dot{x}_0 = f_0(x_0) + G_0(x_0) u_0$$

gravity-free system

feedback transformations
static **state feedback**
+ **change of coordinates**
both invertible

$$u = \alpha(x) + \beta(x) v$$
$$z = T(x)$$

$$u_0 = \alpha_0(x_0) + \beta_0(x_0) v$$
$$z = T_0(x_0)$$

$$\dot{z} = Az + Bv$$

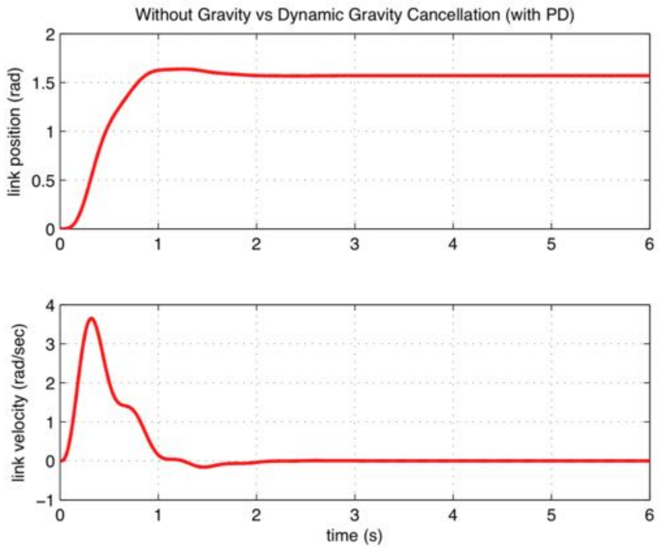
linear, controllable system

z ≈ **linearizing** outputs

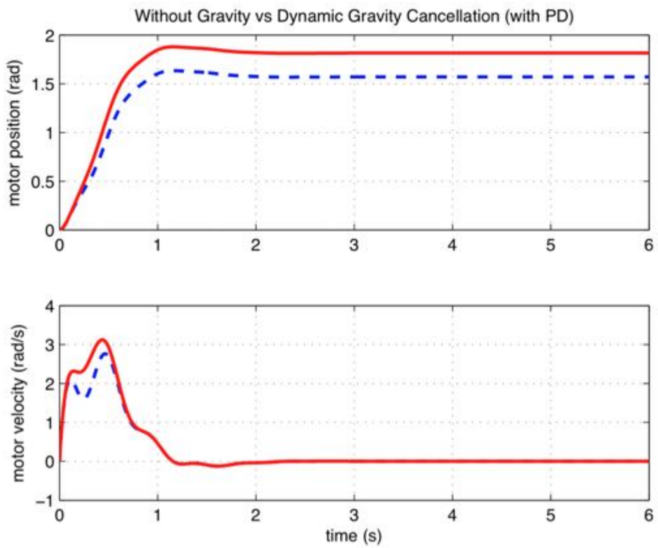
A global PD-type regulator

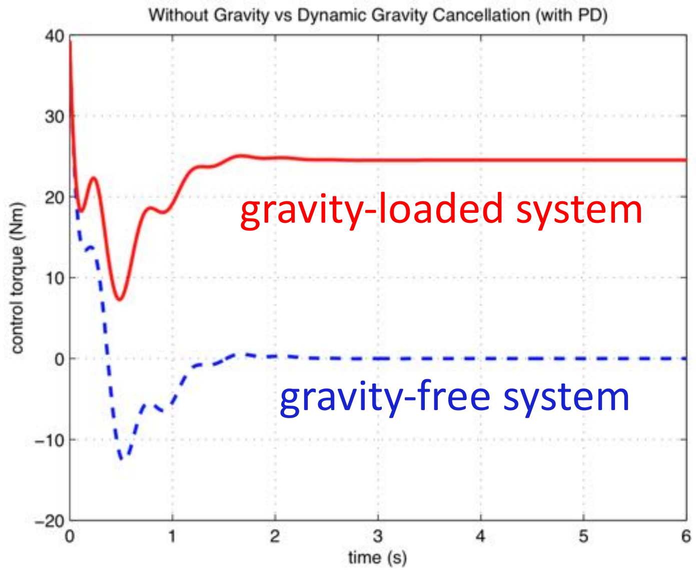
Exact gravity cancellation + PD law on modified motor variables: A 1-DOF arm

identical link behavior



different motor behavior





total **control torque**

gravity-loaded system under PD
+ gravity cancellation
vs.
gravity-free system under PD
(with **same gains**)

$K_P > 0$ $K > 0$

works **without** strictly positive lower bounds (**good** also for **VSA!**)

Vibration damping on lightweight robots

DLR-III or KUKA LWR-IV with relatively low joint elasticity (use of Harmonic Drives)

Vibration damping **OFF**

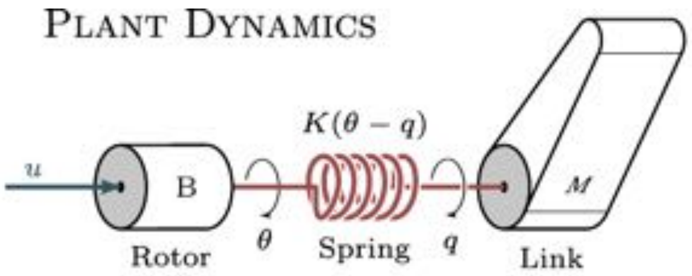
Cartesian vibration damping **ON**

[Albu Schäffer *et al*, 2007]

For relatively **large** joint elasticity (low stiffness), as encountered in VSA systems, vibration damping via joint torque feedback + motor damping is **insufficient** for high performance!

Damping injection on the link side

Method for the VSA-driven bimanual humanoid torso David



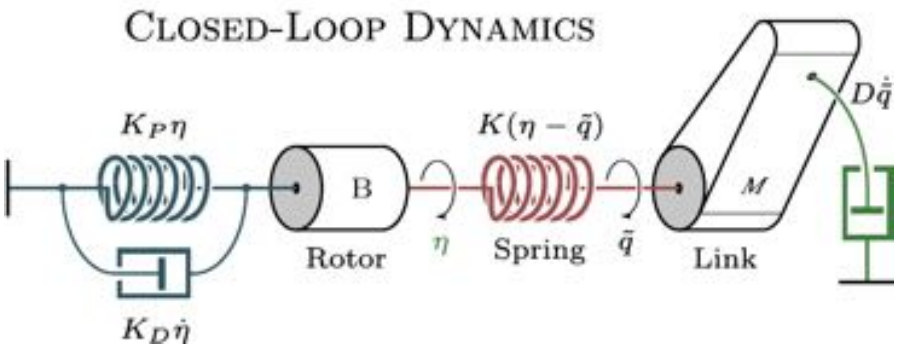
$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta - q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau \end{pmatrix}$$

$$\boldsymbol{K(q-\theta) = K(q-\theta_0) + D\dot{q}}$$

state transformation

$$\boldsymbol{\tau = \tau_0 - D\dot{q} - BK^{-1}D\ddot{q}}$$

feedback control



$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\boldsymbol{\theta}}_{\boldsymbol{0}} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\boldsymbol{\theta_0}) \\ K(\boldsymbol{\theta_0} - q) \end{pmatrix} = \begin{pmatrix} -\boldsymbol{D\dot{q}} \\ \tau_0 \end{pmatrix}$$

- same principle of **feedback equivalence** (including state transformation)
- **ESP** = Elastic Structure Preserving control by DLR **[Keppler *et al*, 2016]**
- generalizations to **trajectory tracking**, to nonlinear joint flexibility, and to visco-elastic joints

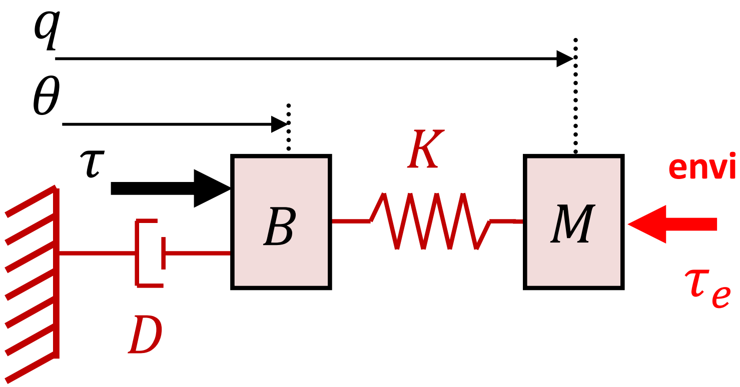
Damping injection on the link side

Method for VSA-driven bimanual humanoid torso David at DLR

[Keppler *et al*, 2017]

Environment interaction via impedance control

Matching a generalized (fourth order) impedance model: A simple 1-DOF case



$$M\ddot{q} + K(q-\theta) = \tau_e$$
$$B\ddot{\theta} + D\dot{\theta} + K(\theta - q) = \tau$$

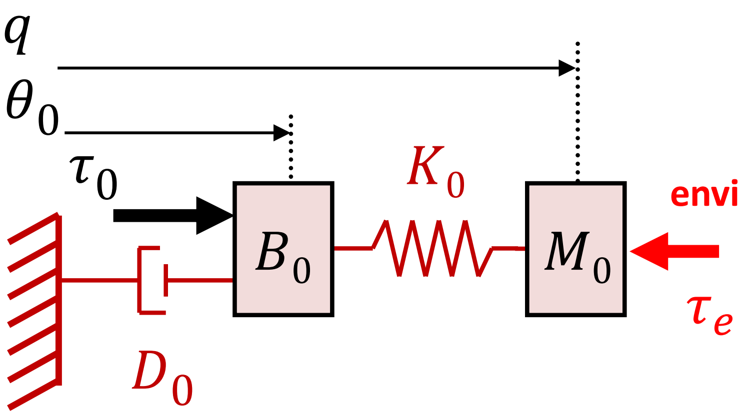
feedback control

assume that $M_0 = M$ in order to avoid **derivatives** of the measured force $\boldsymbol{\tau_e}$

$$\tau = K(\theta - q) + D\dot{\theta} - BK^{-1}\left\{\begin{aligned}&(K-K_0)M^{-1}\left(\boldsymbol{\tau_e} + K(\theta-q)\right)\\ &\quad + K_0 B_0^{-1}\left(\tau_0 - D_0\dot{\theta}_0 - K(\theta - q)\right)\end{aligned}\right\}$$

$$\dot{\theta}_0 = \dot{q} + KK_0^{-1}(\dot{\theta} - \dot{q})$$

state transformation



$$M_0\ddot{q} + K_0(q-\theta_0) = \tau_e$$
$$B_0\ddot{\theta}_0 + D_0\dot{\theta}_0 + K_0(\theta_0 - q) = \tau_0$$

- again, by the principle of **feedback equivalence** (including the state transformation)

Outlook

Control of flexible robots in 2020+

- Mature field revamped by a new “explosion” of interest
  - simpler control laws for compliant and soft robots are very welcome
  - sensing requirements could be a bottleneck
  - combine (learned) feedforward and feedback to achieve robustness
  - iterative learning on repetitive tasks is available for flexible manipulators
  - optimal control (min time, min energy, max force, …) still open for fun
- Revisiting model-based control design
  - do not fight too much against the natural dynamics of the system
    - it is unwise to stiffen what was designed/intended to be soft on purpose
  - still, don’t give up too much of desirable performance!
- Ideas assessed for joint elasticity may migrate to many application domains and other classes of soft-bodied robots
  - locomotion, shared manipulation, physical interaction in complex tasks, …
  - keep in mind intrinsic constraints and control limitations (e.g., instabilities in the system inversion of tip trajectories for flexible link robots)