IEEE/RSJ International Conference on Intelligent Robots and Systems
IROS2018.org / October 1 – 5, 2018 / Municipal Conference Centre / Madrid, Spain
MADRID 2018 IROS

IROS 2018 Workshop on Soft Robotic Modeling and Control:
Bringing Together Articulated Soft Robots and Soft-Bodied Robots
Madrid, October 5, 2018

A review on the control of flexible joint manipulators

Alessandro De Luca
Dipartimento di Ingegneria Informatica, Automatica e Gestionale (DIAG)
deluca@diag.uniroma1.it

SAPIENZA
UNIVERSITÀ DI ROMA

Summary

- Motivations and definitions
  - elastic/flexible joint, serial elastic actuation (SEA), variable stiffness actuation (VSA)
  - concentrated, collocated and distributed flexibility
- Dynamic modeling of elastic joint manipulators
  - control properties
  - differences with flexibility in the links
- Regulation tasks
  - partial state vs. full state feedback
  - PD+ control laws, with different gravity compensation/cancellation techniques
- Trajectory tracking tasks
  - inverse dynamics (feedforward)
  - feedback linearization
  - torque control
- Latest approach
  - least modification of elastic dynamics: exact gravity cancellation, link damping, ESP …

Classes of soft robots

Robots with elastic joints

- lightweight but stiff link design reduces robot inertia and preserves kinematic accuracy at end-effector level
- compliant elements can absorb impact energy
  - soft coverage of links (safe bags)
  - elastic transmissions/joints (HD, cable-driven, ...)


- elastic joints decouple instantaneously the *larger* inertia of the driving motors from the *smaller* inertia of the links (where collisions occur!)
  - robots with *relatively soft* joints need more *sensing* and better *control* laws to compensate for static deflections and dynamic vibrations

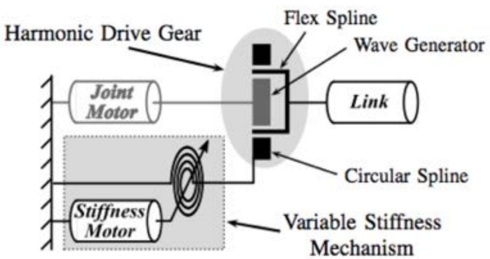



➡ torque-controlled robots (DLR LWR-III, KUKA LWR 4, KUKA iiwa, ...)

Classes of soft robots

Robots with Variable Stiffness Actuation (VSA)

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



Classes of soft robots

Robots with flexible links

- distributed link deformations in robots
  - need to design very long and slender arms for the application
  - use of lightweight materials to save weight/costs
  - due to large payloads and/or high motion speed (or large contact forces)
- as for joint elasticity, neglecting link flexibility will limit static (steady-state error) or dynamic (vibrations, poor tracking) performance
- additional control problems due to the non-collocation of typical output quantities of interest w.r.t. the input commands

Additional notes

…also terminology varies for the considered robots

- elastic joints vs. SEA (Serial Elastic Actuators)
  - consider/use the same physical phenomenon: compliance in actuation
  - compliance added on purpose in SEA, mostly is a disturbance in elastic joints
  - different range of stiffness: 5-10K Nm/rad down to 0.2-1K Nm/rad in SEA
- joint torque sensors introduce joint elasticity!
- joint deformation is often considered in the linear domain
  - modeled as a concentrated torsional spring with constant stiffness at the joint
  - nonlinear flexible joints are handled too, and share similar control properties
  - viscosity may also be present (visco-elastic joints)
  - nonlinear stiffness characteristics are needed in VSA
- (serial or antagonistic) VSA working at constant stiffness are elastic joints
- often classified as underactuated mechanical systems
  - have less commands than generalized coordinates
  - however, are controllable in the first approximation (the easy case!)

Dynamic modeling

Lagrangian formulation for the complete model

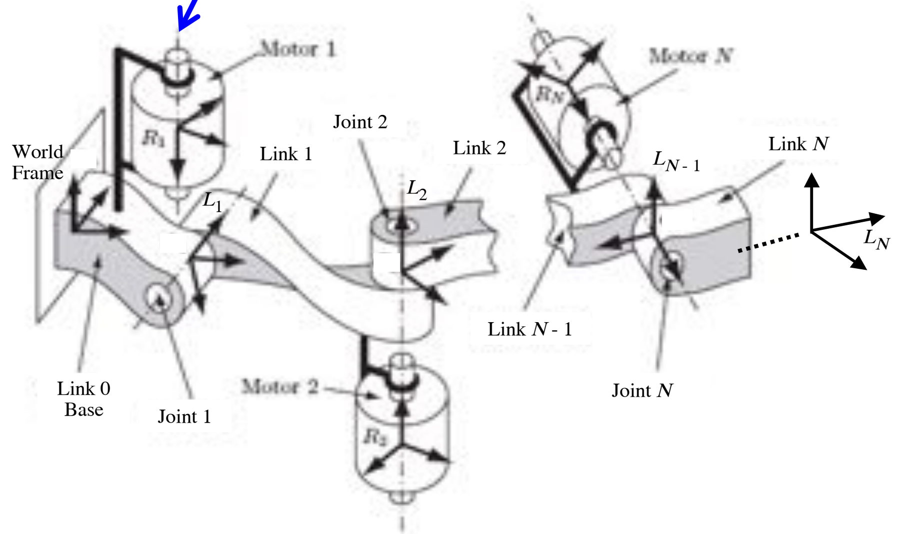
- open chain robot with N (rotary or prismatic) elastic joints and N rigid links, driven by electrical actuators
- use N motor variables θ (as reflected through the gear ratios) and N link variables q
- standing assumptions

  A1) small displacements at joints

  A2) axis-balanced motors

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

center of mass of rotors on rotation axes



2N × 2N (full) inertia matrix

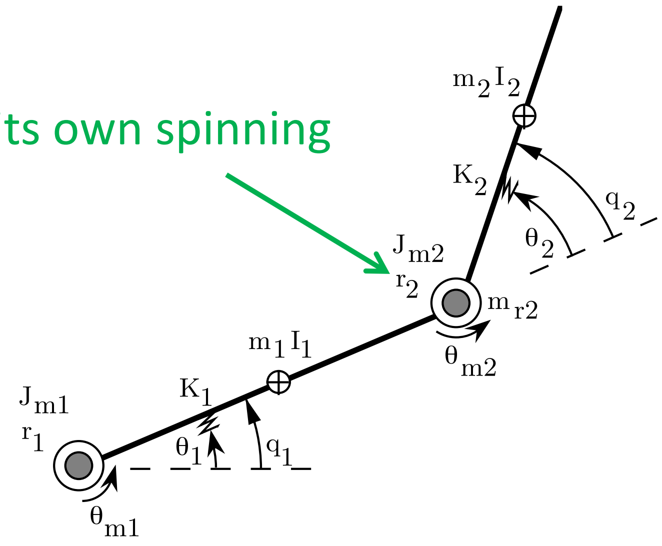
A2) ⇒ inertia matrix and gravity vector independent from θ

$$\begin{bmatrix} M_L(q) & S(q) \\ S^T(q) & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} c_1(q,\dot{q},\dot{\theta}) \\ c_2(q,\dot{q}) \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta-q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix}$$

Dynamic modeling

Approximation for the reduced model (Spong 87)

- simplifying assumption
  A4) the angular kinetic energy of each motor is due only to its own spinning



⬇

$$S(q) = 0$$

⬇

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

link equation

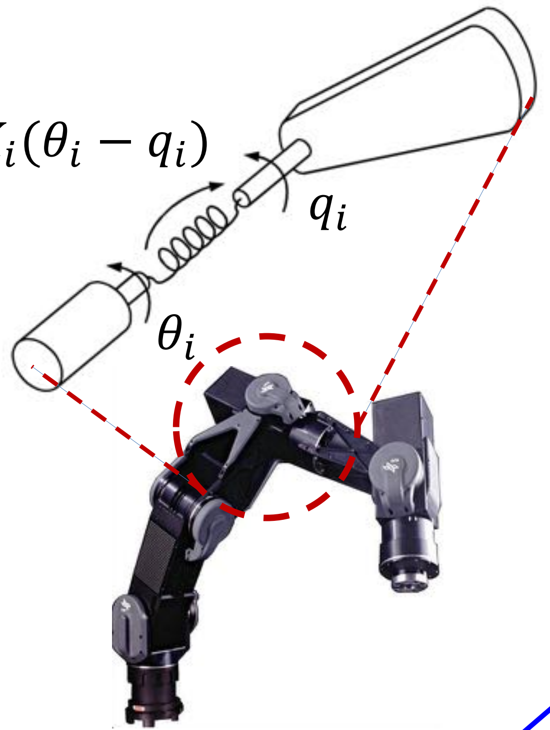
motor equation

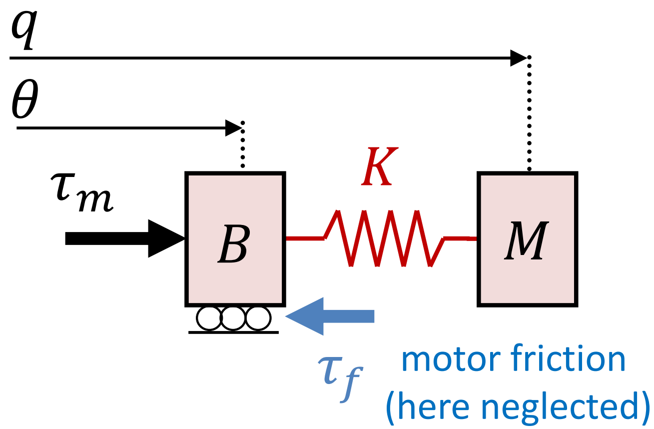
complete model	reduced model
inertial and stiffness couplings	only stiffness couplings
linearizable by **dynamic** state feedback [De Luca, Lucibello 98]	linearizable by **static** state feedback [Spong 87]
always valid (under assumptions A1-A3)	A4 valid when gear ratios are very high

Single elastic joint

Transfer functions of interest

$$\tau_i = K_i(\theta_i - q_i)$$





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

- controllable system with zeros
- passive (zeros always precede poles on the imaginary axis)
- stabilization can be achieved via output θ feedback

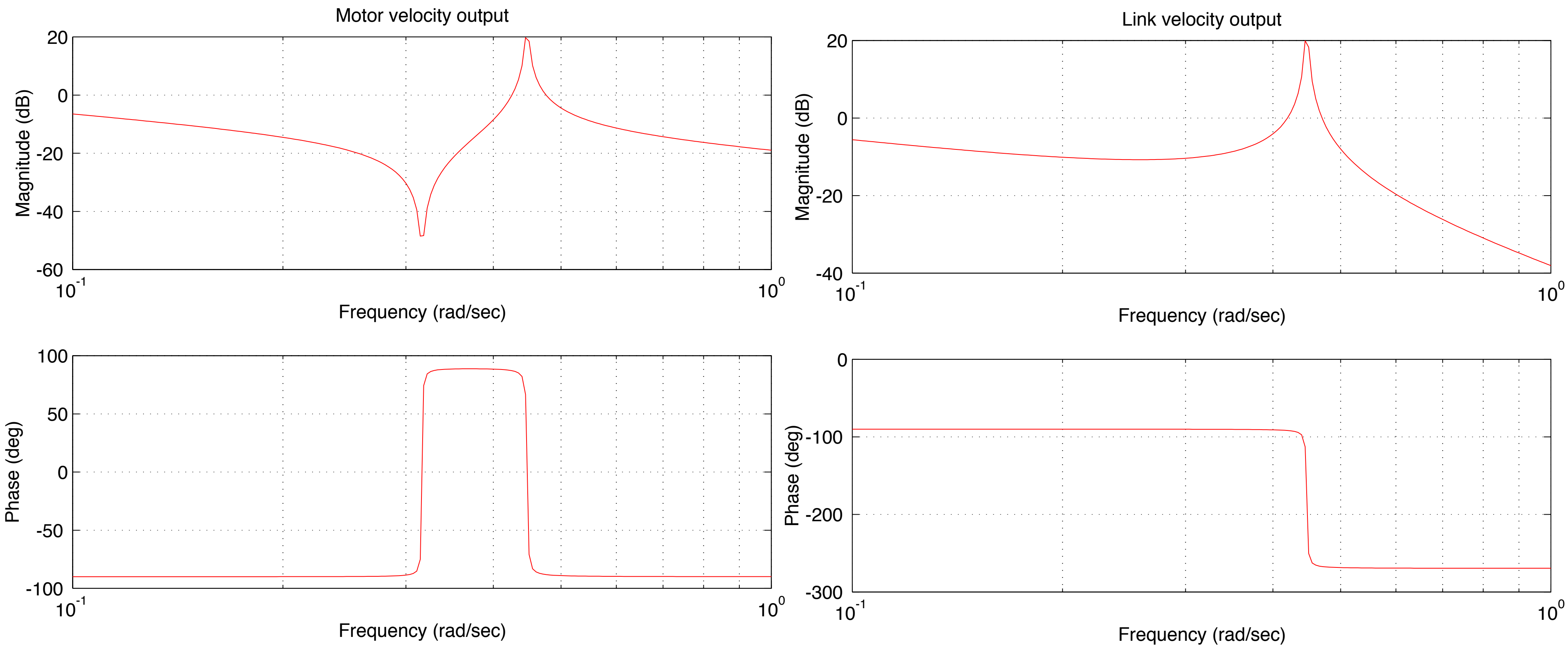
- with viscous friction on motor and/or link, complex pole/zero pairs are moved to the lhs of the $\mathbb{C}$ -plane

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

- NO zeros!!
- maximum relative degree

Single elastic joint

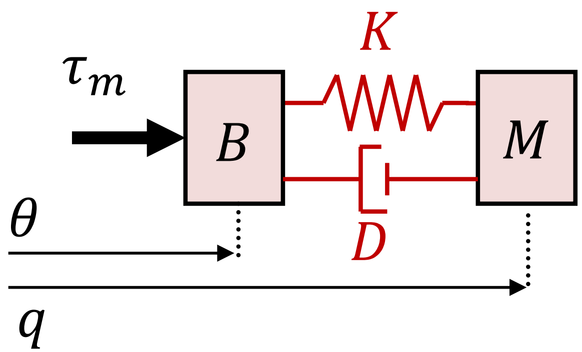
Transfer functions of interest (with some added damping…)



- typical antiresonance/resonance behavior on motor velocity output
- pure resonance on link velocity output (weak or no zeros)

Visco-elasticity of the joints

Introduces a structural change …



on Spong model

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

coupling type	consequence for the model
stiffness	basic static coupling, maximum relative degree (= 4) of output q
damping	reduced relative degree, static I/O linearization
inertia	reduced relative degree, only dynamic I/O linearization

Regulation task

Using a minimal PD action on motor side

for a desired constant link position q_d

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

$$\theta_d = q_d + K^{-1} g(q_d) \qquad \tau_m = \tau_g + K_\theta(\theta_d - \theta) - D_\theta \dot{\theta}$$

τ_g	gain criteria for stability	
$g(q_d)$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K + K_\theta \end{bmatrix} > \alpha$	[Tomei 91]
$g(\theta - K^{-1} g(q_d))$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K + K_\theta \end{bmatrix} > \alpha$	[De Luca, Siciliano, Zollo 04]
$g(\bar{q}(\theta))$, $\bar{q}(\theta)$: $g(\bar{q}) = K(\theta - \bar{q})$	$K_\theta > 0, \quad \lambda_{min}(K) > \alpha$	[Ott, Albu-Schäffer 04]
$g(q) + BK^{-1}\ddot{g}(q)$	$K_\theta > 0, \quad K > 0$	[De Luca 10]

gravity **cancellation**
(with **full state** feedback): *more on this later…*

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

Inverse dynamics

Feedforward action for following a desired trajectory in nominal conditions

given a desired smooth link trajectory $q_d(t) \in C^4$

- compute symbolically the desired motor acceleration and, therefore, also the desired link jerk (i.e., up to the fourth time derivative of the desired motion)

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

$$\tau_{m,d} = B\ddot{\theta}_d + K(\theta_d - qd)$$

$$= BK^{-1}\left[M(q_d)\, q_d^{(4)} + 2\dot{M}(q_d)\, q_d^{(3)} + \ddot{M}(q_d)\ddot{q}_d + \frac{d^2}{dt^2}\left(C(q_d,\dot{q}_d)\dot{q}_d + g(q_d)\right)\right]$$

$$+[M(q_d) + B]\ddot{q}_d + C(q_d,\dot{q}_d)\dot{q}_d + g(q_d)$$

- the inverse dynamics can be efficiently computed using a modified Newton-Euler algorithm (with link recursions up to the fourth order) running in $O(N)$
- the feedforward command can be used in combination with a PD feedback control on the motor position/velocity error, so as to obtain a local but simple trajectory tracking controller

Feedback linearization

For accurate trajectory tracking tasks

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

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

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

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

- an exactly linear and I/O decoupled closed-loop dynamics is obtained
  - to be stabilized with standard linear techniques (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 also for this problem

Torque control

A different set of state measurements can be used directly for tracking control

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

$$\tau = K(\theta - q)$$

measurable by a joint torque sensor

$$\boxed{BK^{-1}\ddot{\tau} + \tau = \tau_m - B\ddot{q}}$$

rewriting the motor dynamics

$$\tau_m = BK^{-1}\ddot{\tau}_d + \tau_d + K_T(\tau_d - \tau) + K_S(\dot{\tau}_d - \dot{\tau}) + \alpha B\ddot{q}$$

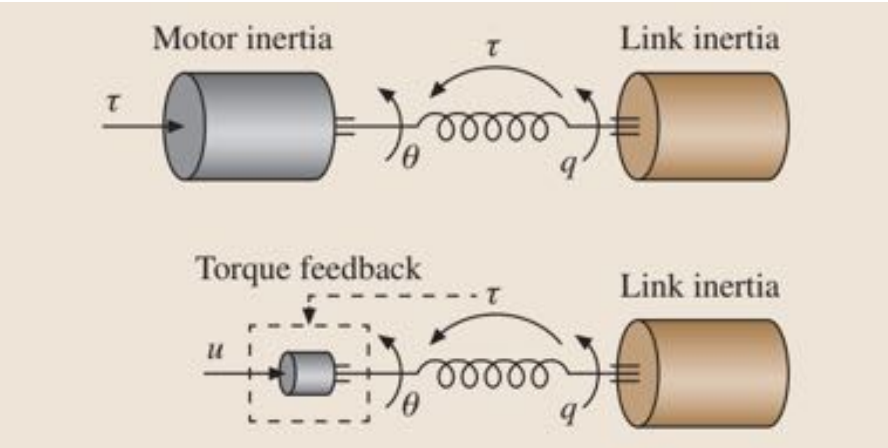
- $\alpha < 1$ for avoiding over-compensation
- useful for designing a motor side disturbance observer, e.g., to realize friction compensation
- basis for many cascaded controller designs that start from a rigid body control law $\tau_d(q, \dot{q})$
- higher derivatives are still required ($\ddot{\tau}_d, \ddot{q}$)

Torque feedback

An inner loop that largely reduces motor inertia and friction

consider a pure proportional torque feedback (+ a derivative term for the visco-elastic case)

$$\tau_m = BB_d^{-1}u + \underbrace{\left(I - BB_d^{-1}\right)}_{K_T}\tau + \underbrace{\left(I - BB_d^{-1}\right)DK^{-1}}_{K_S}\dot{\tau}$$



physical interpretation:

scaling of the motor inertia and motor friction!

[Ott, Albu-Schäffer 08]

original motor dynamics	visco-elastic case
$B\ddot{\theta} + K(\theta - q) = \tau_m$	$B\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = \tau_m$
$B_d\ddot{\theta} + K(\theta - q) = u$	$B_d\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = u$

After the torque feedback

Full-state feedback

Combining torque feedback with a motor PD regulation law

inertia scaling via torque feedback $\tau_m = (I + K_T)u - K_T\,\tau - K_S\dot{\tau}$

regulation via motor PD, e.g. with $u = g(\bar{q}(\theta)) + K_\theta(\theta_d - \theta) - D_\theta\dot{\theta}$

⇒ **joint level control structure** of the DLR (and KUKA) lightweight robots

dynamics feedforward and desired torque command

setpoint control

$$\tau_m = \tau_d - K_T(\tau - \tau_d) - K_S\dot{\tau} - K_P(\theta_d - \theta) - K_D\dot{\theta} + \tau_f + \tau_{dob}$$ (+ integral actions)

motor inertia scaling

vibration damping

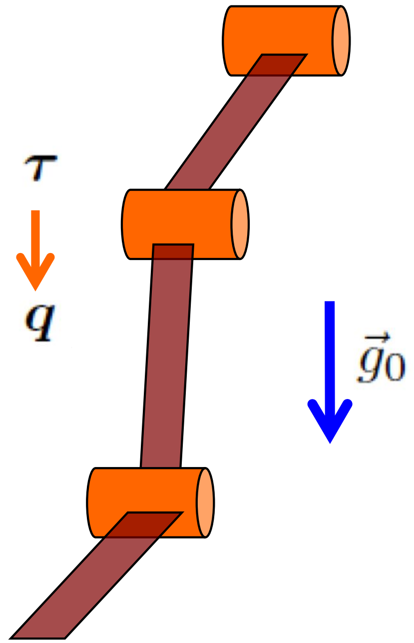
friction compensation and/or disturbance observer

torque control	**position control**	**impedance control**
$K_P = 0$	$K_P > 0$	$K_P = K_T K_\theta$
$K_D = 0$	$K_D > 0$	$K_D = K_T D_\theta$
$K_T > 0$	$K_T > 0$	$K_T = (BB_d^{-1} - I)$
$K_S > 0$	$K_S > 0$	$K_S = (BB_d^{-1} - I)DK^{-1}$
τ_d	$\tau_d = g(q)$	$\tau_d = g(\bar{q}(\theta))$

Exact gravity cancellation

A slightly different view

- for rigid robots this is trivial, due to collocation



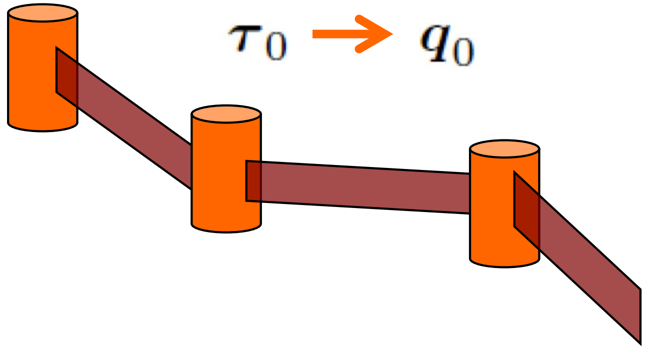
$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) = \tau$$

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

$$\Rightarrow$$

$$\tau_g = g(q)$$

$$q \equiv q_0$$

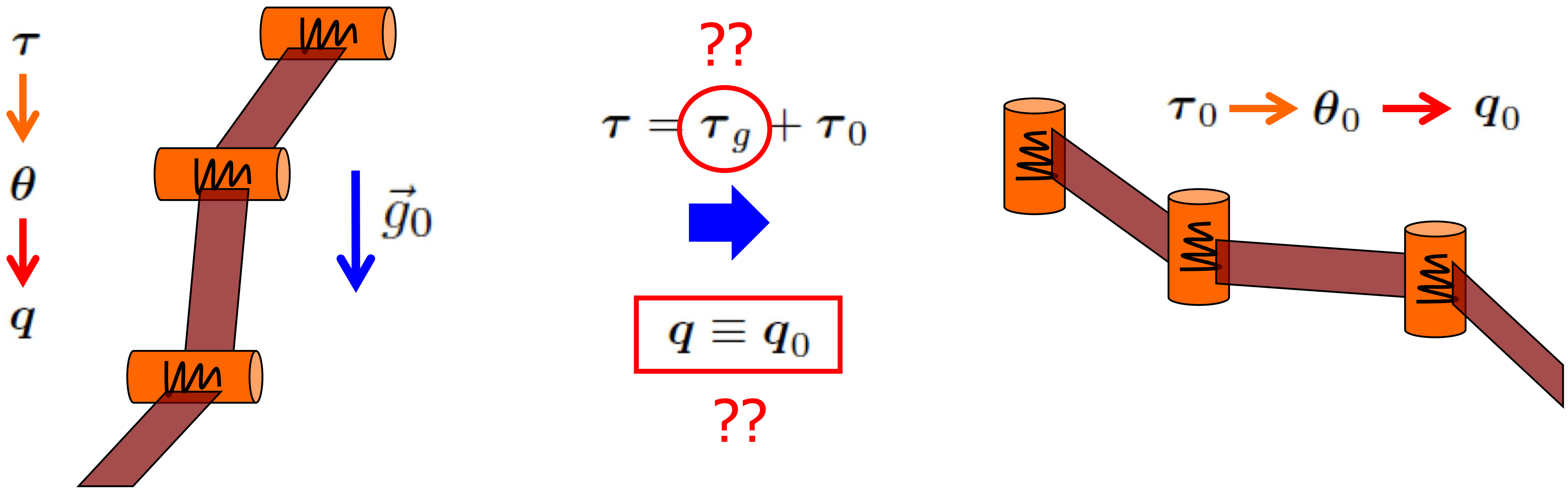


$$M(q)\ddot{q} + c(q,\dot{q}) = \tau_0$$

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

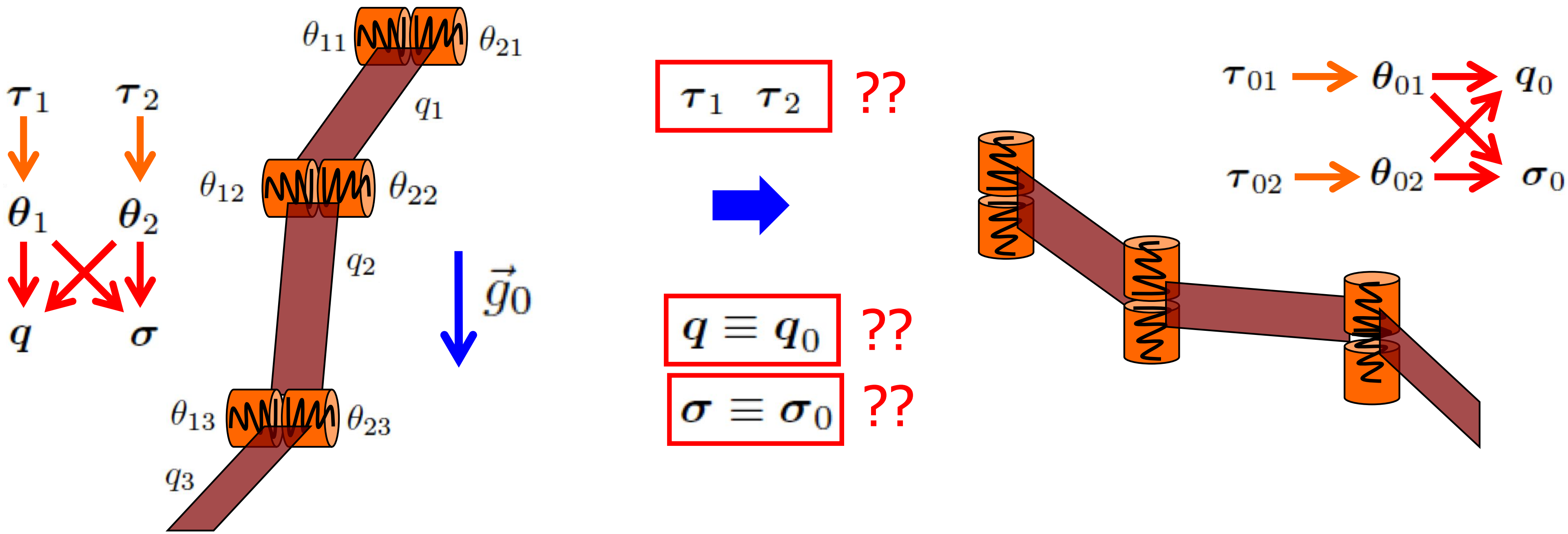


$$
\begin{aligned}
M(q)\ddot{q} + c(q,\dot{q}) + g(q) + K(q-\theta) &= 0 \\
B\ddot{\theta} + K(\theta - q) &= \tau
\end{aligned}
$$

Exact gravity cancellation

… generalized also to VSA robots

- same problem formulation holds also for VSA robots (here, in antagonistic configuration), with the additional consideration of the internal stiffness state



$\phi_i = q - \theta_i$

$i = 1, 2$

$$
\begin{aligned}
M(q)\ddot{q} + c(q,\dot{q}) + g(q) + \tau_{e1}(\phi_1) + \tau_{e2}(\phi_2) &= 0 \\
B_1\ddot{\theta}_1 - \tau_{e1}(\phi_1) &= \tau_1 \\
B_2\ddot{\theta}_2 - \tau_{e2}(\phi_2) &= \tau_2
\end{aligned}
$$

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

Flexible joint robots are feedback linearizable...

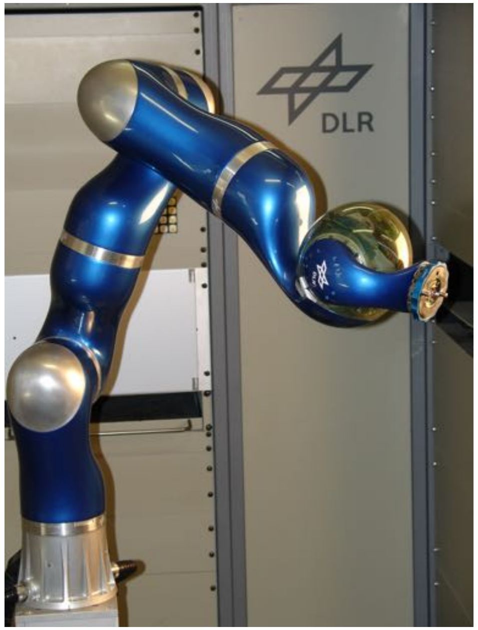
... with linearizing outputs of suitable relative degrees

- robots with elastic joints
  - also with joints having nonlinear flexibility

linearizing output = **link position (4)**

- robots with VSA-based actuation
  - antagonistic VSA-II
  - serial DLR-VS joint
  - ...

linearizing output = **link position (4)**
+ joint stiffness (2)



Exact gravity cancellation

Elastic joint robots (including link/motor damping)

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + D_q\dot{q} + K(q-\theta) = 0$$

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

$$q(t) \equiv q_0(t) \quad \forall t \geq 0 \qquad \tau = \tau_g + \tau_0$$

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

$$\dot{g}(q) = \frac{\partial g(q)}{\partial q}\,\dot{q}$$

$$\ddot{g}(q) = \frac{\partial g(q)}{\partial q} M^{-1}(q)\left(K(\theta - q) - c(q,\dot{q}) - g(q) - D_q\dot{q}\right) + \sum_{i=1}^{n} \frac{\partial^2 g(q)}{\partial q\,\partial q_i}\,\dot{q}\,\dot{q}_i$$

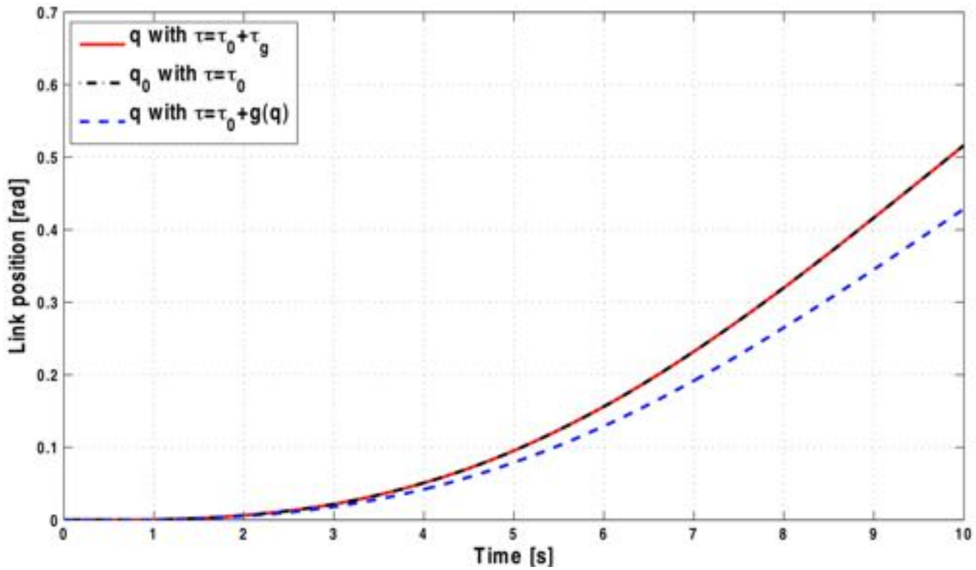
requires full state feedback

Numerical results

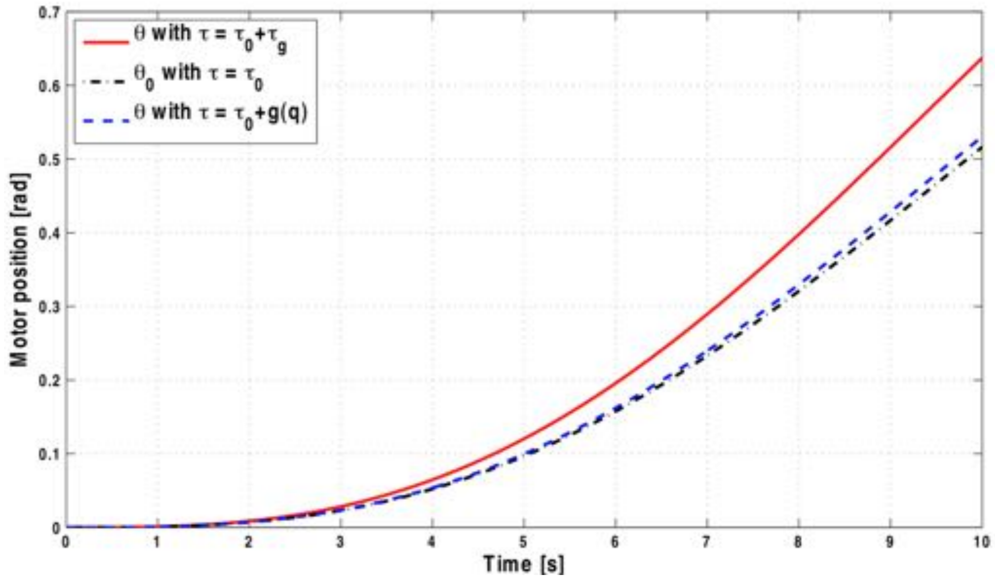
Exact gravity cancellation for a 1-DOF elastic joint

$$\tau_g = mdg_0 \left\{ \left(1 - \frac{B}{K}\dot{q}^2\right)\sin q - \frac{B}{M}\frac{mdg_0}{K}\sin q \cos q + \frac{MD_\theta - BD_q}{KM}\dot{q}\cos q + \frac{B}{M}(\theta - q)\cos q \right\}$$

$$\boxed{\tau_0 = \sin 0.1\pi t} \qquad g(q) = mdg_0 \sin q$$



exact reproduction of same link behavior
with and without gravity



different motor behavior
with and without gravity

$$\boldsymbol{\theta} = \boldsymbol{\theta}_0 + \boldsymbol{K}^{-1}\boldsymbol{g}(\boldsymbol{q})$$

A global PD-type regulator

Exact gravity cancellation combined with PD law on modified motor variables

$$\boldsymbol{\tau} = \boldsymbol{\tau}_g + \boldsymbol{\tau}_0$$

$$\boldsymbol{\tau}_g = \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}_\theta \boldsymbol{K}^{-1}\dot{\boldsymbol{g}}(\boldsymbol{q}) + \boldsymbol{B}\boldsymbol{K}^{-1}\ddot{\boldsymbol{g}}(\boldsymbol{q})$$

$$\boxed{\boldsymbol{\tau}_0 =} \; \boldsymbol{K}_P(\boldsymbol{\theta}_{d0} - \boldsymbol{\theta}_0) - \boldsymbol{K}_D\dot{\boldsymbol{\theta}}_0$$

$$= \boxed{\boldsymbol{K}_P(\boldsymbol{q}_d - \boldsymbol{\theta} + \boldsymbol{K}^{-1}\boldsymbol{g}(\boldsymbol{q})) - \boldsymbol{K}_D(\dot{\boldsymbol{\theta}} - \boldsymbol{K}^{-1}\dot{\boldsymbol{g}}(\boldsymbol{q}))}$$

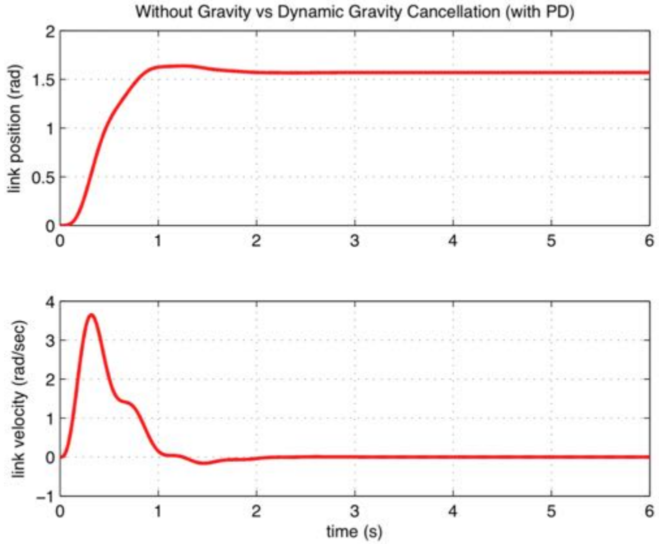
Global asymptotic stability can be shown using a Lyapunov analysis under "minimal" sufficient conditions (also without viscous friction)

$\boxed{\boldsymbol{K}_P > 0}$ $\boxed{\boldsymbol{K} > 0}$ i.e., **no** strict positive lower bounds and $\boldsymbol{K}_D > 0$

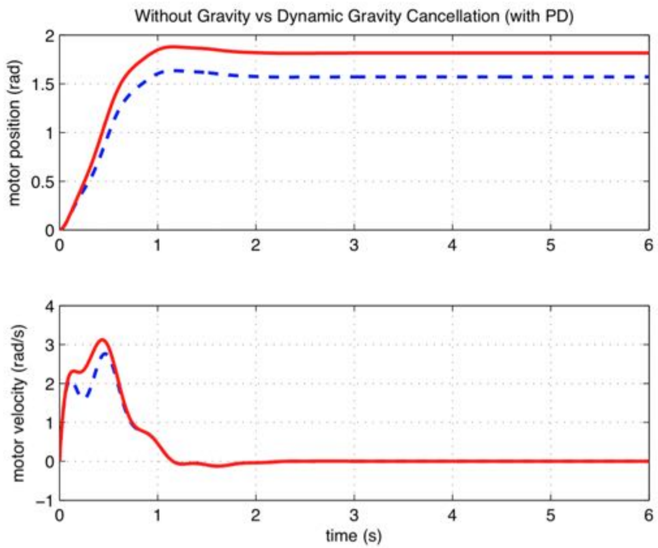
Numerical results

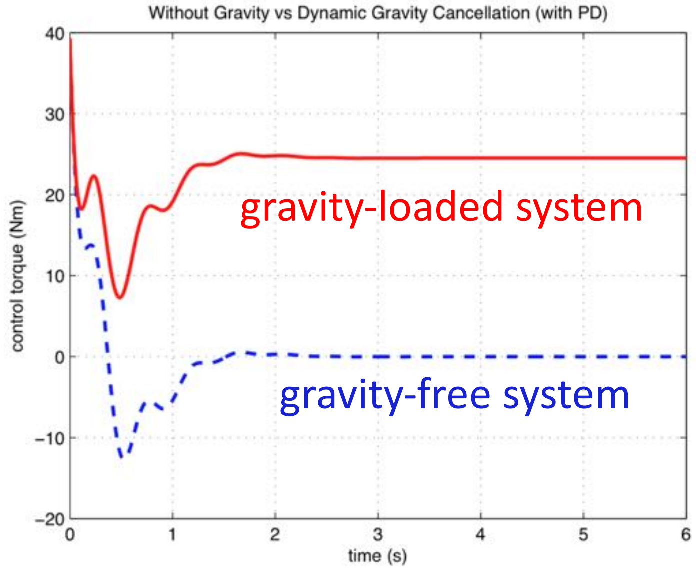
Regulation of a 1-DOF arm with elastic joint under gravity

identical link behavior



different motor behavior



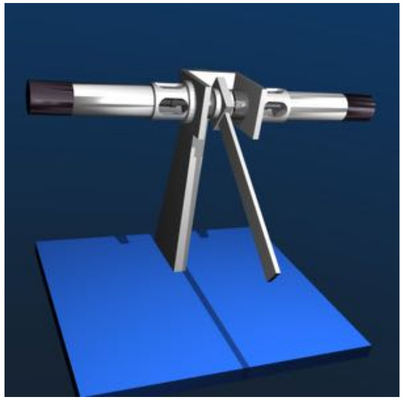


total **control torque**

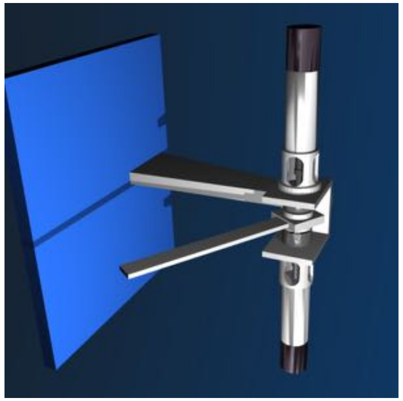
gravity-loaded system under PD
+ gravity cancellation
vs.
gravity-free system under PD
(with same gains)

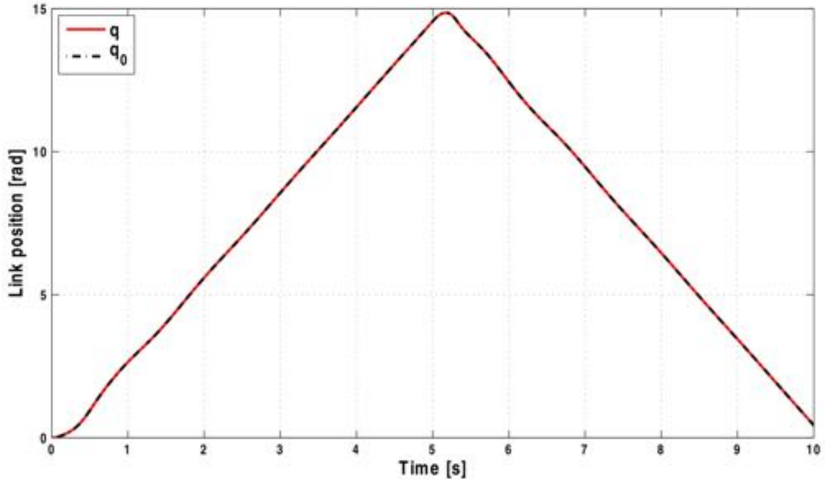
Numerical results

Exact gravity cancellation for the VSA-II of UniPisa

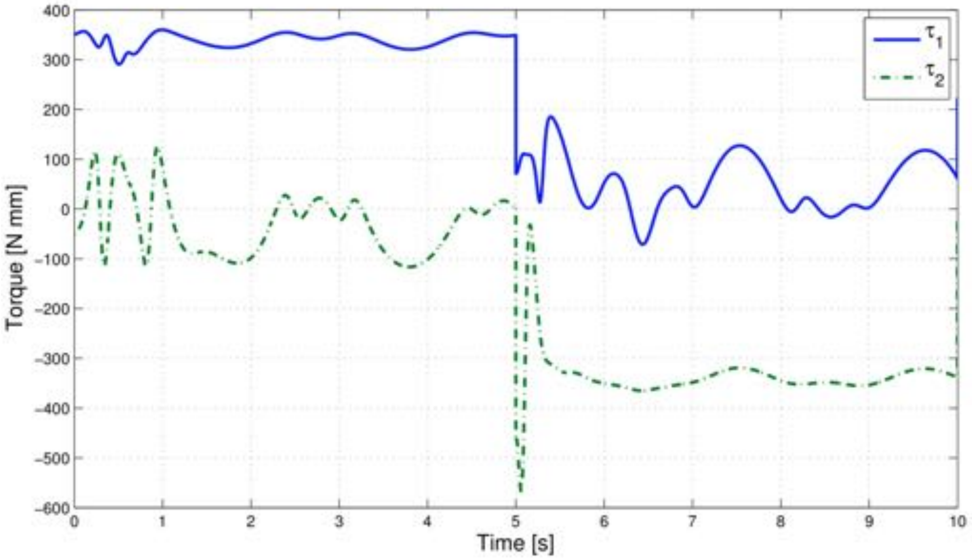


via feedback

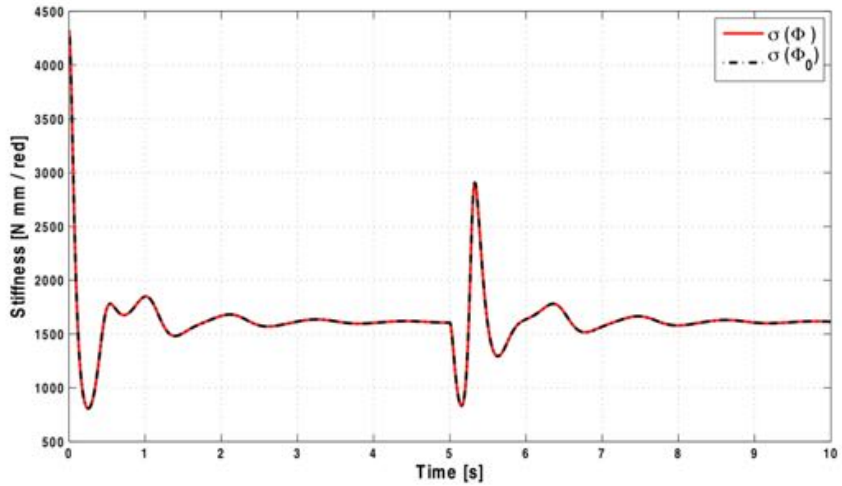




exact reproduction of link behavior



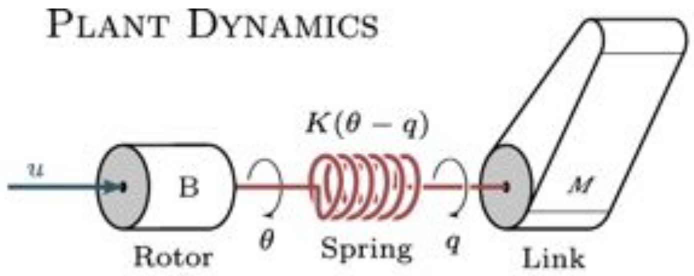
applied torques for gravity cancellation



exact reproduction of stiffness behavior

Link vibration damping

DLR method for VSA-driven bimanual humanoid torso David [Keppler et al. 16]



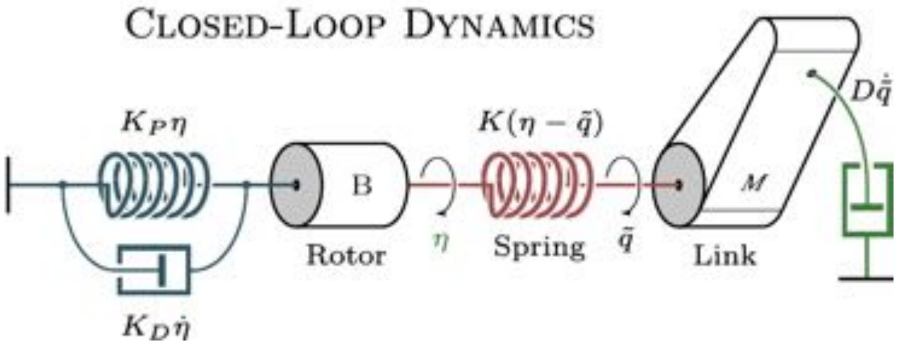
$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta - q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix}$$

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

state transformation

$$\frac{d^2}{dt^2}$$

$$\tau_m = u - D\dot{q} - BK^{-1}\frac{d^2}{dt^2}D\dot{q}$$



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

- same principle of **feedback equivalence** (including state transformation)
- **ESP** = Elastic Structure Preserving control
- generalizations to **trajectory tracking**, to nonlinear joint flexibility, and to viscoelastic joints

Short outlook

- Mature control field recently revamped by the new “explosion” of interest for compliant and soft robots
  - simpler control laws are always welcome
  - sensing requirements could be a bottleneck
  - iterative learning on repetitive tasks already in place for flexible manipulators
- Control ideas assessed for concentrated elasticity at the joints can migrate to other classes of soft-bodied manipulators
  - but intrinsic constraints and control limitations should be kept in mind (e.g., instabilities in the system inversion of tip trajectories for flexible link robots)
- Emerging notion: not fighting against the natural dynamics!
  - and trying also not to give up too much of the desirable performance …