Structure preserving control: reconciliation of passivity based and feedback linearization approaches

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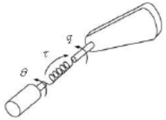
ICRA 2007 Tutorial

General Chair
ICRA 2007

Nonlinear Control of Flexible Joint Robots

Full Day Tutorial at
2007 IEEE International Conference on
Robotics and Automation (ICRA'07)



ICRA07

Organizers:

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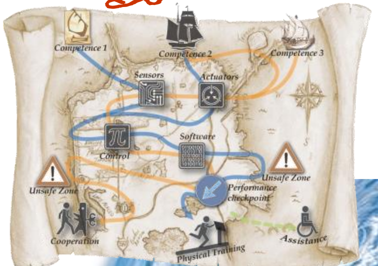
Dipartimento di Informatica e Sistemistica "A. Ruberti"
http://www.dis.uniroma1.it/~labrob/people/deluca/deluca.html

German *Helmholtz Humboldt Research*. *Award 2005*

The -PH-R- Projects Physical-Human-Robot

PHRIDOM

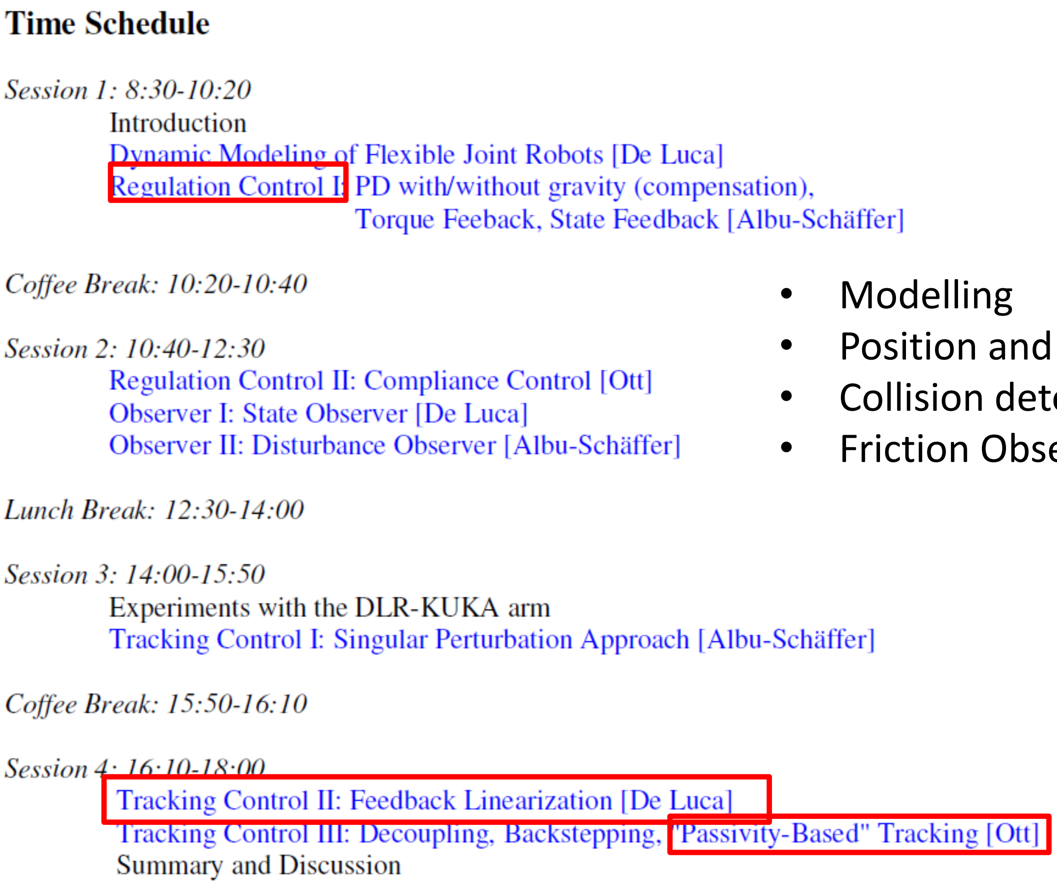


PHRIENDS

SAPHARI

Safe and Autonomous Physical Human-Aware Robot Interaction

ICRA 2007 Tutorial



Time Schedule

Session 1: 8:30-10:20

Introduction
Dynamic Modeling of Flexible Joint Robots [De Luca]
Regulation Control I: PD with/without gravity (compensation),
Torque Feeback, State Feedback [Albu-Schäffer]

Coffee Break: 10:20-10:40

Session 2: 10:40-12:30

Regulation Control II: Compliance Control [Ott]
Observer I: State Observer [De Luca]
Observer II: Disturbance Observer [Albu-Schäffer]

Lunch Break: 12:30-14:00

Session 3: 14:00-15:50

Experiments with the DLR-KUKA arm
Tracking Control I: Singular Perturbation Approach [Albu-Schäffer]

Coffee Break: 15:50-16:10

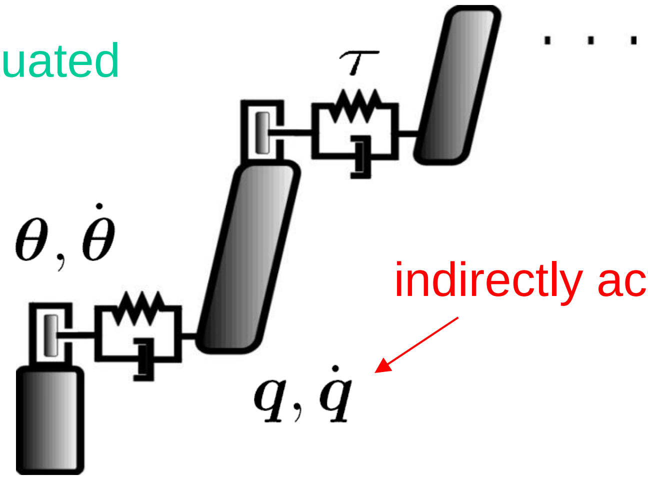
Session 4: 16:10-18:00

Tracking Control II: Feedback Linearization [De Luca]
Tracking Control III: Decoupling, Backstepping, "Passivity-Based" Tracking [Ott]
Summary and Discussion

- Modelling
- Position and compliance control
- Collision detection
- Friction Observer and Compensation

Compliant Robots: Under-actuated Systems

Directly actuated



indirectly actuated

full rank – controllable linearization at

$$q = q_d, \dot{q} = 0$$

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + \frac{\partial U(q)}{\partial q} = \begin{bmatrix} \tau_m \\ 0 \end{bmatrix}$$

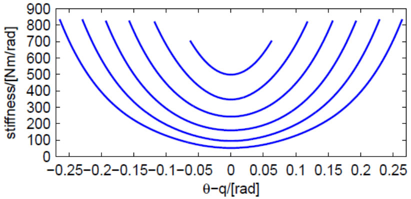
$$U = U_{elastic} + U_{gravity}$$

constant stiffness

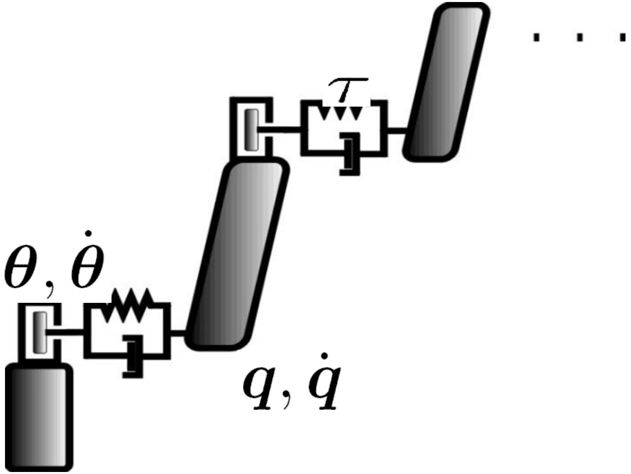
$$\frac{\partial U_{Elastic}(q)}{\partial q} = \tau = K(\theta - q)$$

variable stiffness

$$\frac{\partial U_{Elastic}(q)}{\partial q} = \tau(\theta - q, \sigma)$$



Compliant Robots: Under-actuated Systems



$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + \frac{\partial U(q)}{\partial q} = \begin{bmatrix} \tau_m \\ 0 \end{bmatrix}$$

$$U = U_{elastic} + U_{gravity}$$

M nondiagonal (Tomei’91)

$$M(q) = \begin{bmatrix} B & S^T(q) \\ S(q) & M_{L1}(q) \end{bmatrix}$$

Dynamic state feedback linearizable (De Luca & Lucibello ‘98, ICRA Best Paper Award)

M diagonal (Spong’87 simplification)

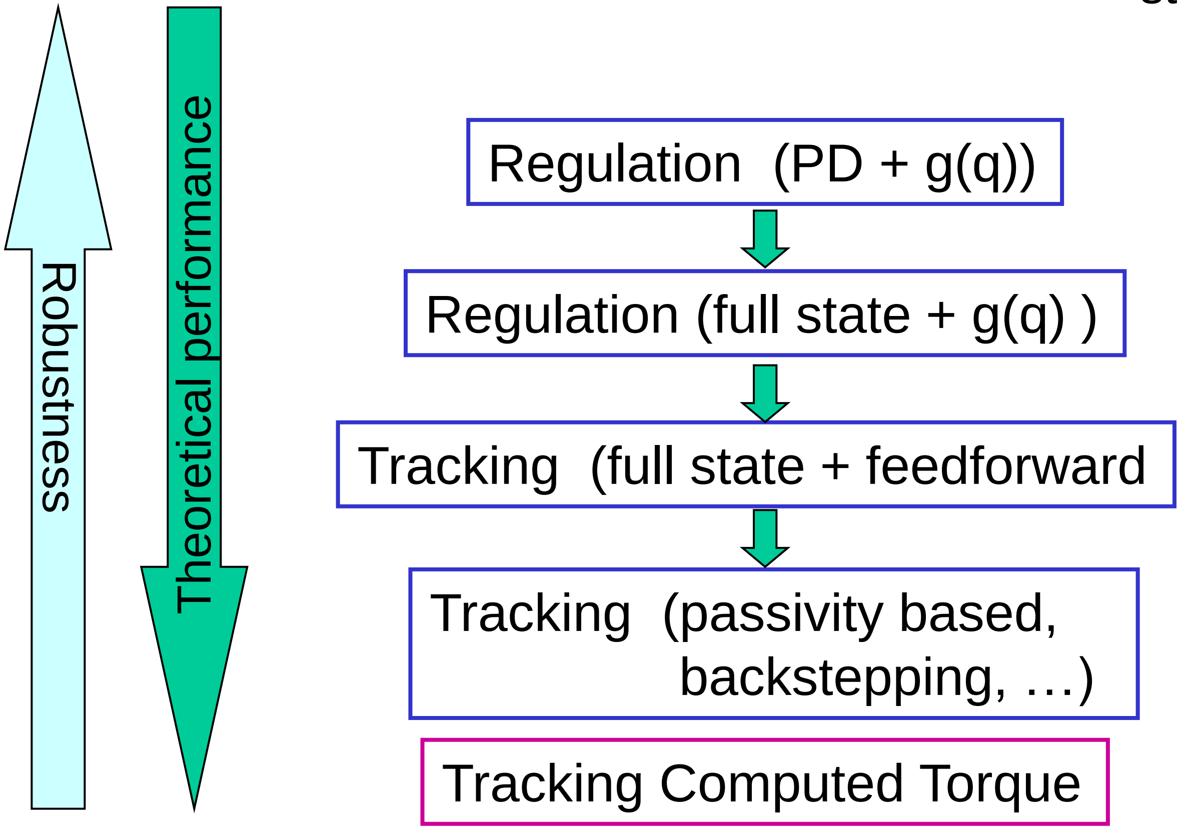
$$M(q) = \begin{bmatrix} B & 0 \\ 0 & M_{L2}(q) \end{bmatrix}$$

static state feedback linearizable

$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix}\begin{bmatrix} \ddot{q} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c(q,\dot{q}) \\ 0 \end{bmatrix} + \begin{bmatrix} g(q) \\ 0 \end{bmatrix} + \begin{bmatrix} \tau \\ -\tau \end{bmatrix} + d(\dot{x}) = \begin{bmatrix} \tau_{\text{ext}} \\ \tau_m \end{bmatrix}$$

Some State Feedback Controllers

state vectors
$$x_1 = (\theta, \dot{\theta}, q, \dot{q})$$
$$x_2 = (\theta, \dot{\theta}, \tau, \dot{\tau})$$
$$x_3 = (q, \dot{q}, \ddot{q}, \dddot{q})$$



Regulation (PD + g(q)) — g.a.s. for q_d constant

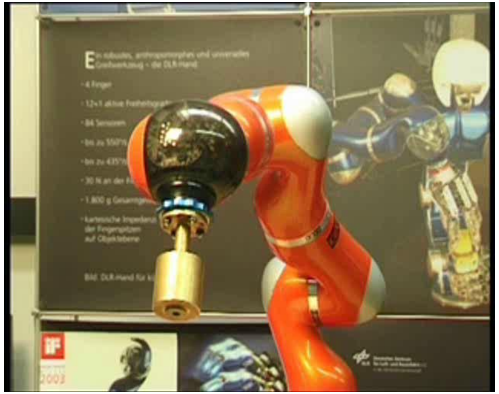
Regulation (full state + g(q)) — g.a.s. for q_d constant

Tracking (full state + feedforward — l.s.

Tracking (passivity based, backstepping, …) — g.a.s.

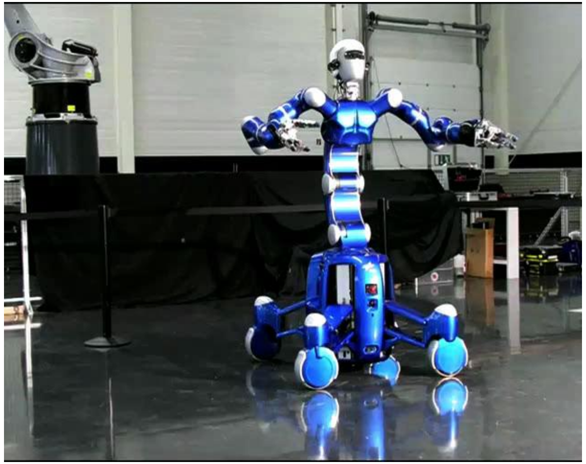
Tracking Computed Torque — g.e.s. linear, decoupled

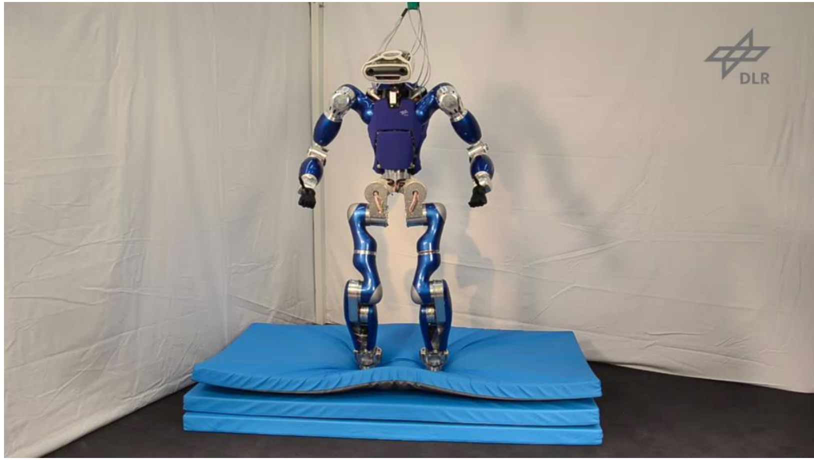
Performance for Torque Controlled Robots



Vibration Damping OFF

Vibration ON

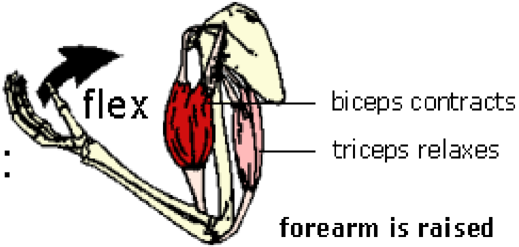




https://www.youtube.com/watch?v=Z-ho7_sUkp0

Passivity based regulation controllers with feed-forward for tracking perform good enough on torque controlled HD robots

DLR Hand Arm System



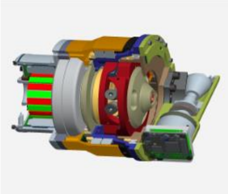
Anthropomorphic light weight robot:

- **size**, **kinematics**, **force** and **dynamics** of human arm and hand
- **variable stiffness** in all joints

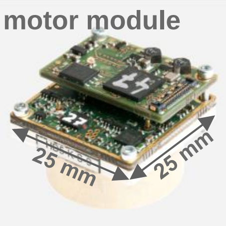
- *53 degrees of freedom!*
- *106 motors*
- *212 position sensors*

Tendon driven fingers

Antagonistic finger actuation



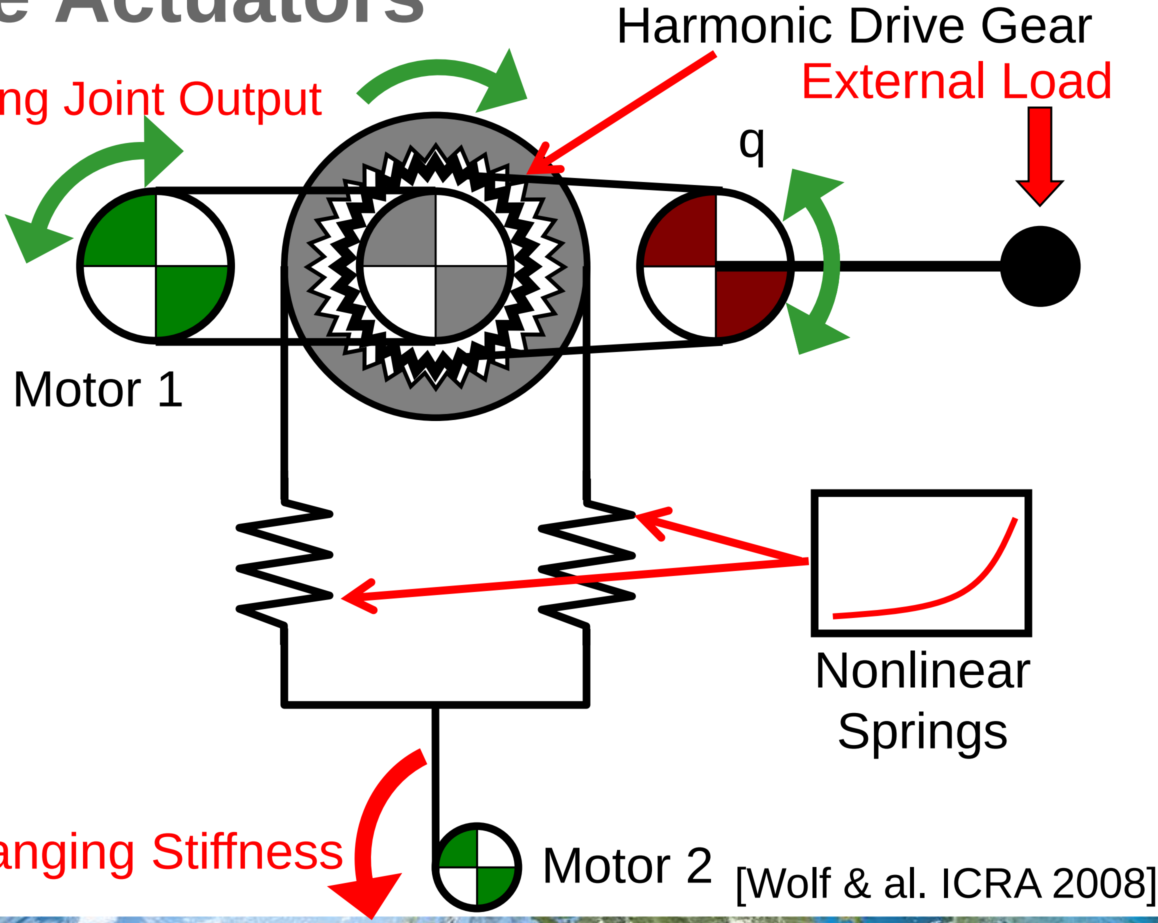
Variable stiffness arm actuators



Highly integrated electronics

Variable Impedance Actuators
(upper arm)

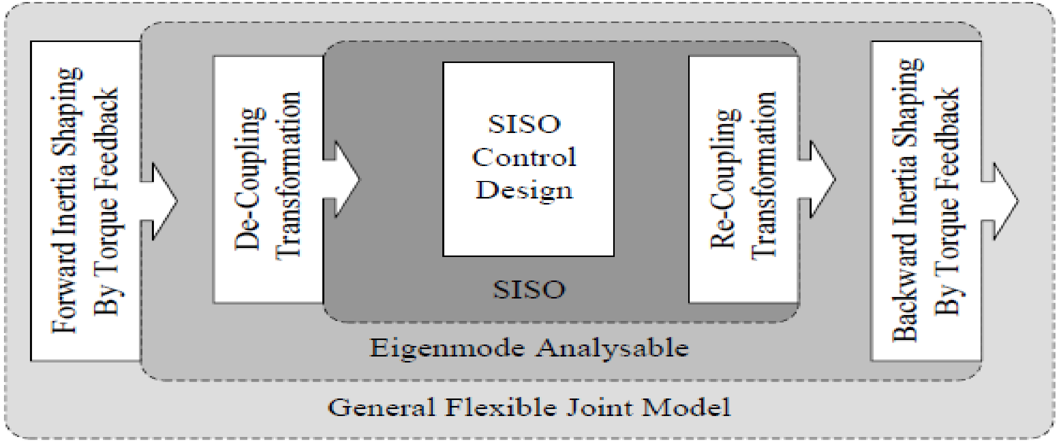
- one big motor1 moves the joint
- *one small motor2 changes joint stiffness*
- ***without motor2 we have a serial elastic joint***



[Wolf & al. ICRA 2008]

Decoupling Damping Control in Modal Coordinates

Generalization of passivity based flexible joint concepts to VIA robots



Forward Inertia Shaping By Torque Feedback

De-Coupling Transformation

SISO Control Design

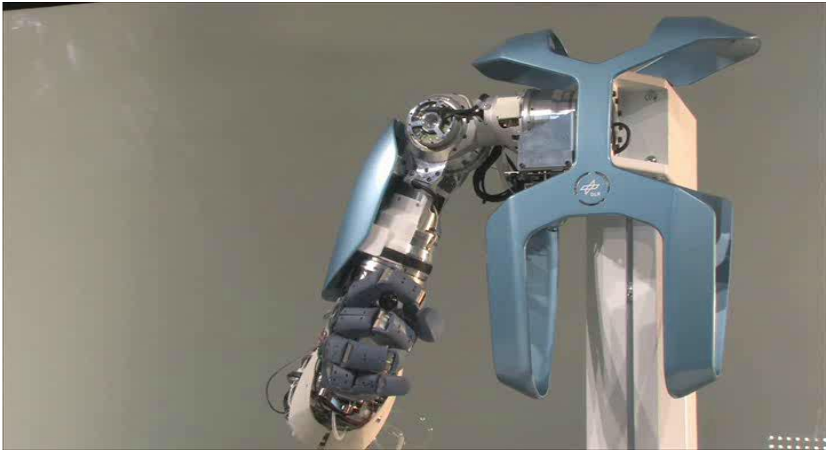
SISO

Re-Coupling Transformation

Backward Inertia Shaping By Torque Feedback

Eigenmode Analysable

General Flexible Joint Model



state feedback controller in modal coordinates, with diagonal gain matrices.

$$u = K_P \widetilde{\theta} \; - K_D \dot{\theta} - K_T K^{-1} \tau - K_S K^{-1} \dot{\tau}$$

[Albu-Schäffer & al. ICRA 2010]

Minimalistic Link Side Damping

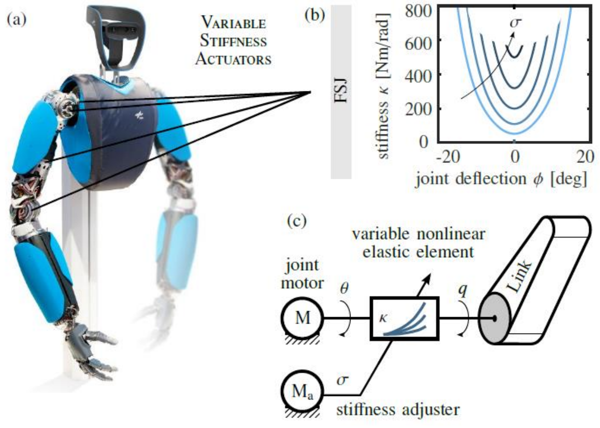
- also VIA robots are state feedback linearizable (Spong'87, De Luca '97), however purely Passive controllers come to their limits

Approach:

- Use the linearizability to adjust only those features which really matter
  (gravity compensation, damping, TCP-stiffness)

- For practical robustness, change the rest of the dynamics as little as possible!!!

So it's all about how to design the desired closed-loop dynamics!



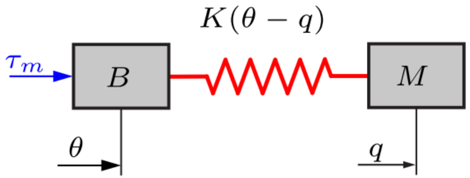
Ott Springer 2008
De Luca & Flacco, CDC2010

Elastic Structure Preserving Control (ESP)

Achieve active damping by changing the plant properties as little as possible

Motor Dynamics

$$B(\ddot{\theta}) + K(\theta - q) = \tau_m$$



$$M\ddot{q} = \boxed{K(\theta - q)}$$

Control input:

$$\tau_m = \boxed{-BK^{-1}Dq^{(3)} - D\dot{q}}\boxed{- K_p(\eta - \eta_d) - K_D\dot{\eta}}$$

Dynamic shaping

(motor side)

PD control

(new motor coord.)

Coordinate transformation:

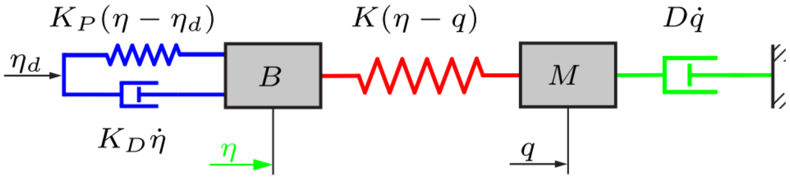
$$\boxed{K(\theta - q) = K(\eta - q) - D\dot{q}}$$

η . . . new motor coordinate

$\eta_d := q_d$ . . . desired position

Link Dynamics

$$B(\ddot{\eta}) + K(\eta - q) = -K_P(\eta - \eta_d) - K_D\dot{\eta}$$



$$M\ddot{q} = \boxed{K(\eta - q) - D\dot{q}}$$

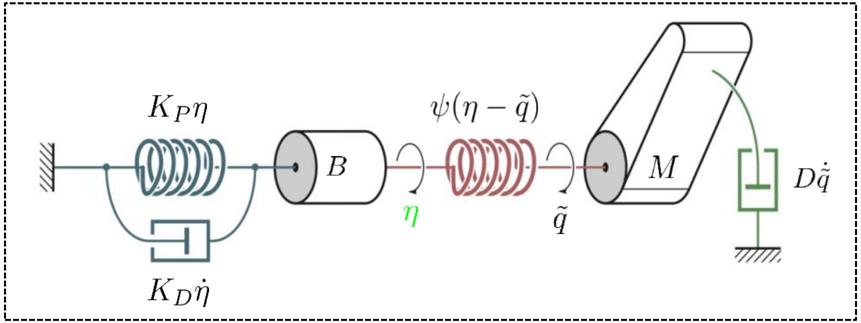
$\eta = \theta + K^{-1}D\dot{q}$

M B K

M. Keppler & al, ICRA 2016, CDC 2016

Stability and Passivity Analysis

- Non-autonomous system: $\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x})$



$$
\begin{aligned}
\boldsymbol{M}(t,\tilde{\boldsymbol{q}})\ddot{\tilde{\boldsymbol{q}}} + \boldsymbol{C}(t,\tilde{\boldsymbol{q}},\dot{\tilde{\boldsymbol{q}}})\dot{\tilde{\boldsymbol{q}}} \quad &= \boldsymbol{\psi}(\boldsymbol{\eta} - \tilde{\boldsymbol{q}}) - \boldsymbol{D}\dot{\tilde{\boldsymbol{q}}} + \boldsymbol{\tau}_{ext} \\
\boldsymbol{B}\ddot{\boldsymbol{\eta}} + \boldsymbol{\psi}(\boldsymbol{\eta} - \tilde{\boldsymbol{q}}) &= -\boldsymbol{K}_P\boldsymbol{\eta} - \boldsymbol{K}_D\dot{\boldsymbol{\eta}}
\end{aligned}
$$

- Passivity of closed-loop system ($\dot{\tilde{\boldsymbol{q}}}^{\mathrm{T}}\boldsymbol{\tau}_{ext}$)

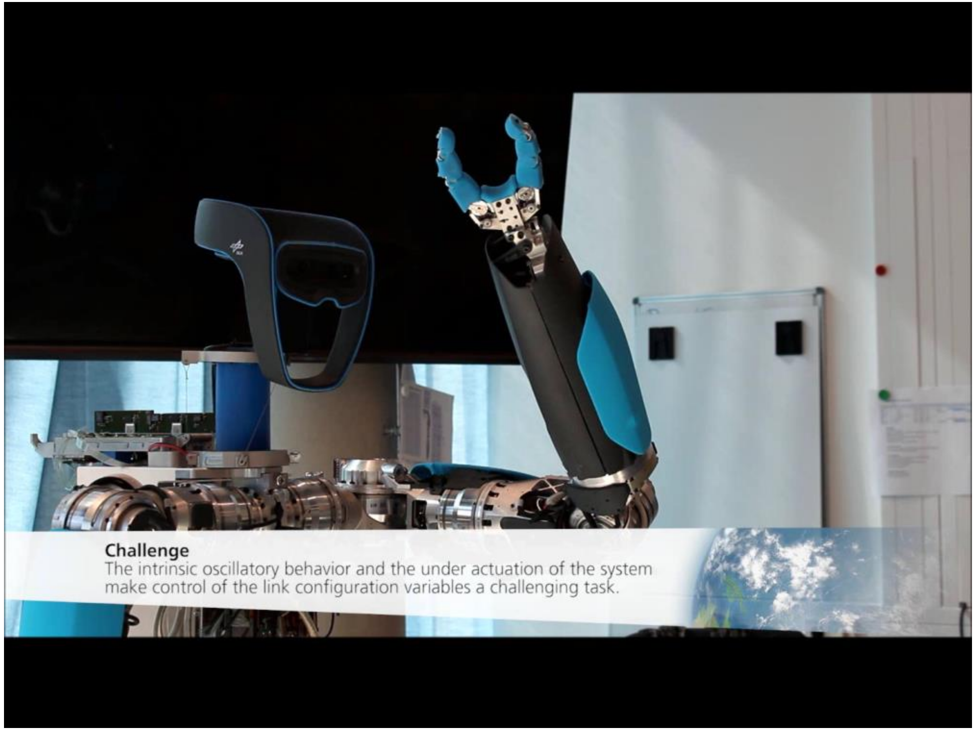
$$S(t,\boldsymbol{\eta},\dot{\boldsymbol{\eta}},\tilde{\boldsymbol{q}},\dot{\tilde{\boldsymbol{q}}}) := \frac{1}{2}\left(\dot{\tilde{\boldsymbol{q}}}\boldsymbol{M}\dot{\tilde{\boldsymbol{q}}} + \dot{\boldsymbol{\eta}}^T\boldsymbol{B}_\eta\dot{\boldsymbol{\eta}} + \boldsymbol{\eta}^T\boldsymbol{K}_P\boldsymbol{\eta}\right) + U_s(\boldsymbol{\eta} - \tilde{\boldsymbol{q}})$$

- Global uniform asymptotic stability (Matrosov)

$$\boxed{\lim_{t\to\infty} \tilde{\boldsymbol{q}}(t) = \mathbf{0}} \qquad \boxed{\lim_{t\to\infty} \boldsymbol{\eta}(t) = 0}$$

$$\boxed{\lim_{t\to\infty} \dot{\tilde{\boldsymbol{q}}}(t) = \mathbf{0}} \qquad \boxed{\lim_{t\to\infty} \dot{\boldsymbol{\eta}}(t) = 0}$$

Active Link Side Damping, no Inertia and Stiffness Change



Challenge
The intrinsic oscillatory behavior and the under actuation of the system make control of the link configuration variables a challenging task.

https://www.youtube.com/watch?v=PATvv47QfQs

Exploiting Elasticity for Robustness: Hammer-Drilling in a Concrete Plate

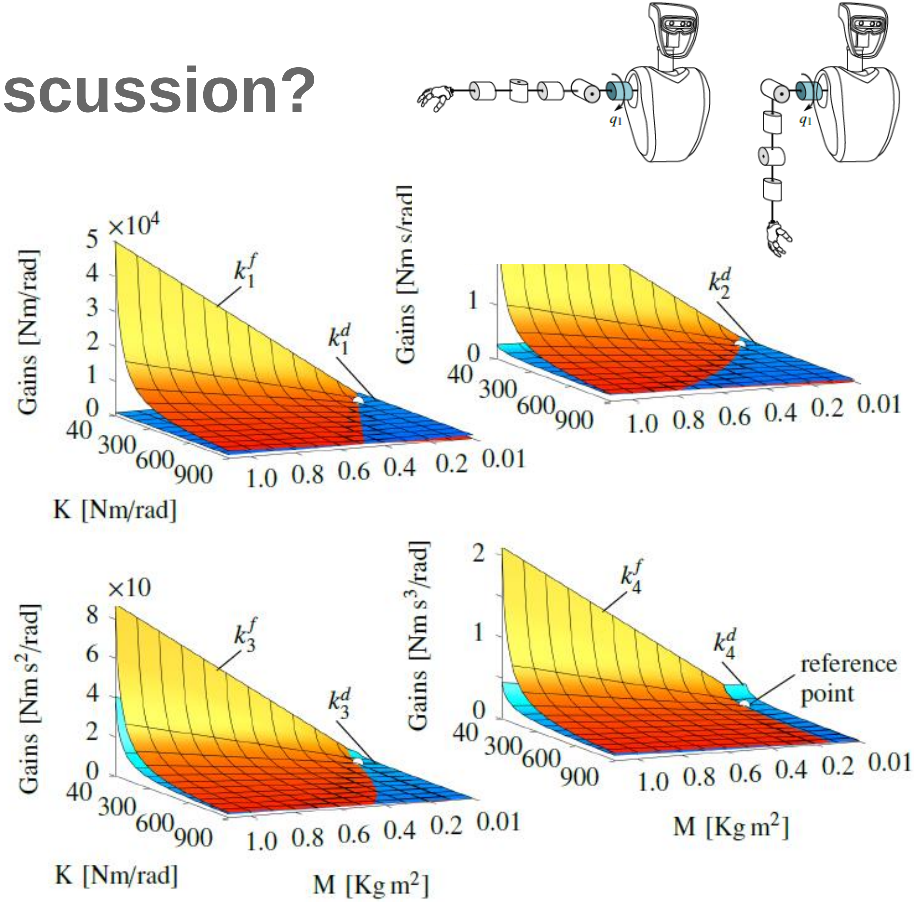
https://www.youtube.com/watch?v=JVdufPRK4NI&t=6s

Why Does it Work Better – a Discussion?

$M_{min} = 0.01 \ \mathrm{kg\,m^2}$ $M_{max} = 1.1 \ \mathrm{kg\,m^2}$

$K_{min} = 40 \ \mathrm{Nm\,rad^{-1}}$ $K_{max} = 900 \ \mathrm{Nm\,rad^{-1}}$

$\boldsymbol{x} = [\ q \ \dot{q} \ \ddot{q} \ q^{(3)}\ ]$



Comparison of gains for feedback linearization with

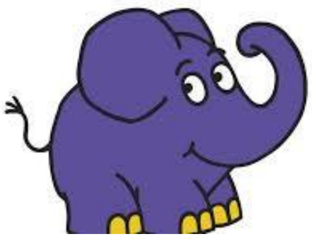
- **decoupled, constant error dynamics**
- **structure preserving error dynamics**

In practice, gains are limited by unmodelled dynamics, actuator saturation, discretization,…

M. Keppler & al TRO, accepted for publication

Conclusion

- Robot control had a tremendous development over the last decades …
We even can in principle control an elephant to jump like a flea



- However, with age, one learns that sometimes less is more …

Formalizing this concept for nonlinear systems would be a nice **joint challenge** for the next future!

Happy Anniversary Alessandro !!!