ADRL
Agile & Dexterous Robotics Lab

ETH Zürich

Torque and Impedance Control for Articulated Robots

by Dr. Thiago Boaventura

Torque Controlled Humanoids Robots Workshop

HUMANOIDS 2013

Atlanta, 15th of October 2013

Why Torque control in legged robots?

- Stance phase: **to control contact forces!**
  - Robot balance
  - Avoid slippage
  - Adapt stiffness and damping to situation and/or terrain
- Flight phase: **to be compliant!**
  - Good position tracking & be compliant at the same time!

Versatility!

ASIMO – Honda

Presentation Outline

- Natural velocity feedback in force dynamics
- Model-based torque controller design
- Impedance controller design
- Passivity & Z-width
- Results
- Summary

Presentation Outline

- **Natural load velocity feedback in force dynamics**
- Model-based torque controller design
- Impedance controller design
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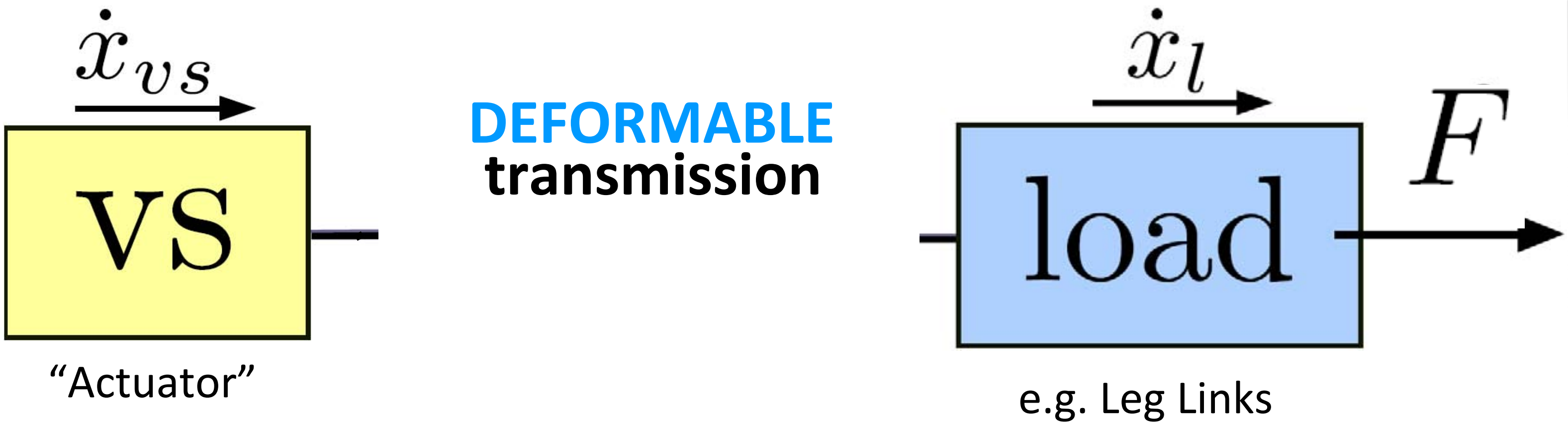
Natural Velocity Feedback



$$\dot{F} = K_t \left(\dot{x}_{vs} - \dot{x}_l \right)$$

Intrinsic negative feedback of the load velocity!

It does not depend on the actuation system!

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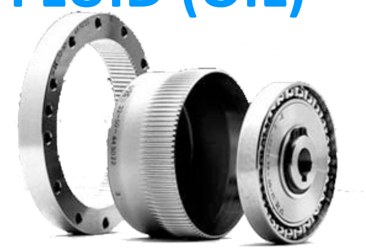
NATURAL VELOCITY FEEDBACK

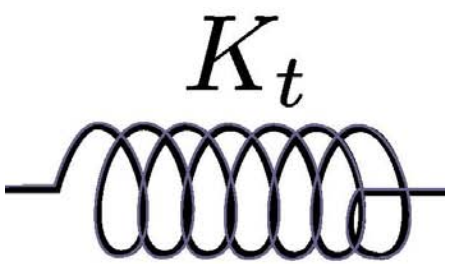
OUTLINE

VS

VS in Electric motors: **ROTOR**
Actuator: **stator**

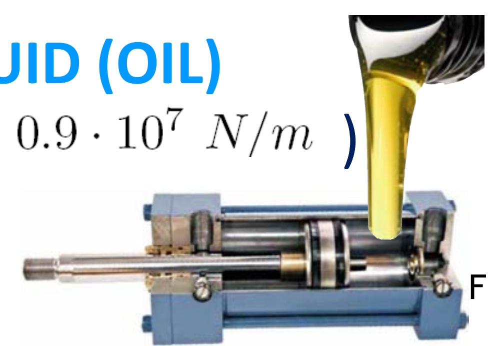
VS in Hydraulic Cylinder: **FLUID (OIL)**
Actuator: **pump + valve**





Electric motors: **HARMONIC GEAR**
($K_{te} = 2.7 \cdot 10^4 \; Nm/rad$)

Hydraulics: **FLUID (OIL)**
($K_{th} > 0.9 \cdot 10^7 \; N/m$)



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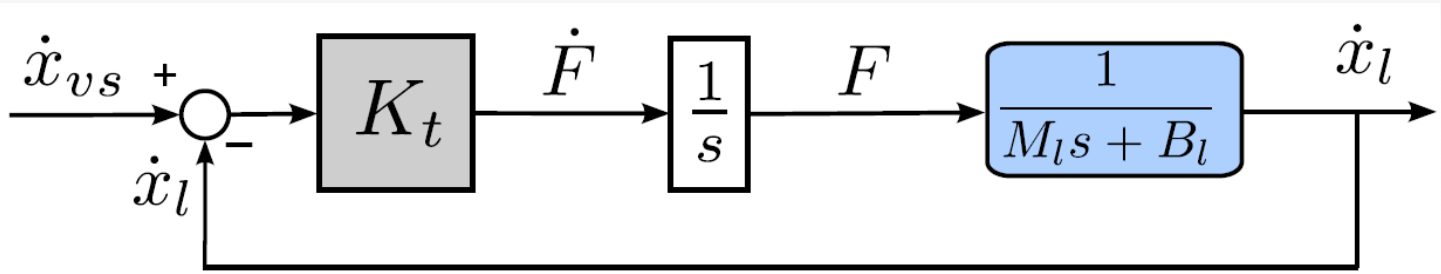
NATURAL VELOCITY FEEDBACK

Generic Case:



Transfer function:

$$\frac{F(s)}{\dot{x}_{vs}(s)} = \frac{K_t\,(M_l s + B_l)}{s\,(M_l s + B_l) + K_t}$$

The zero introduced by the load dynamics limits the response!

It does not depend on the actuation system!

[T. Boaventura et al, 2012, "On the role of load motion compensation in high-performance force control", IROS]

Presentation Outline

- Natural velocity feedback in force dynamics
- **Model-based torque controller design**
- Impedance controller design
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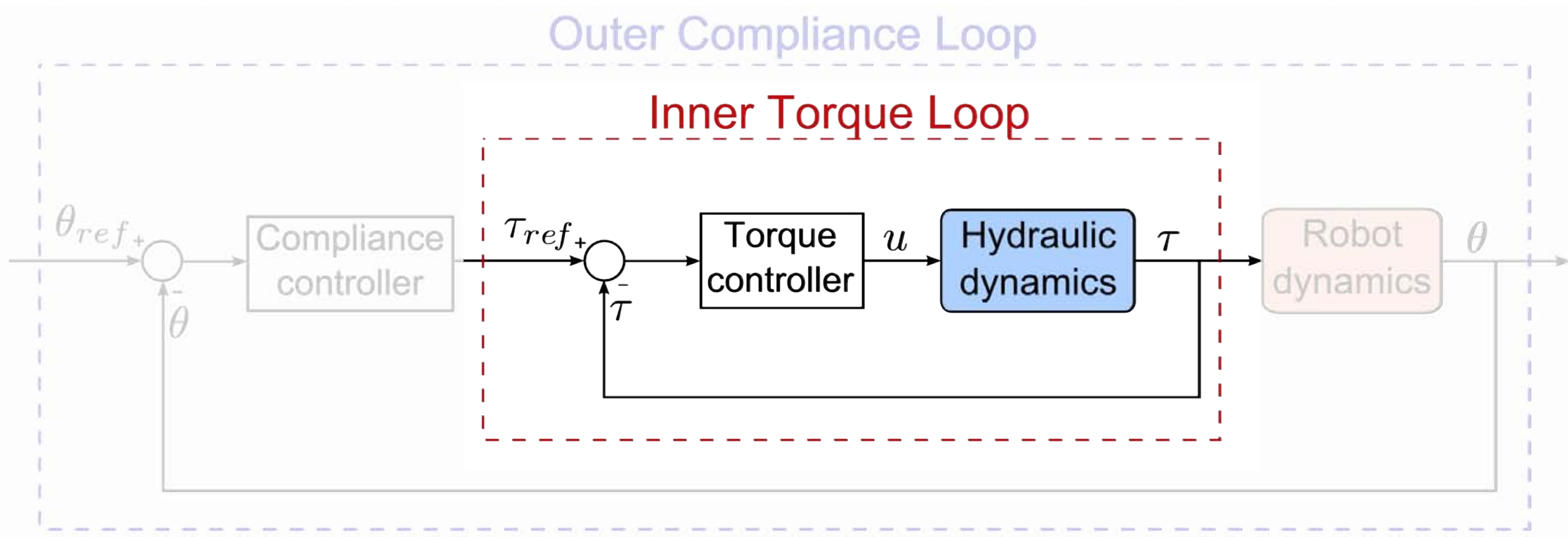
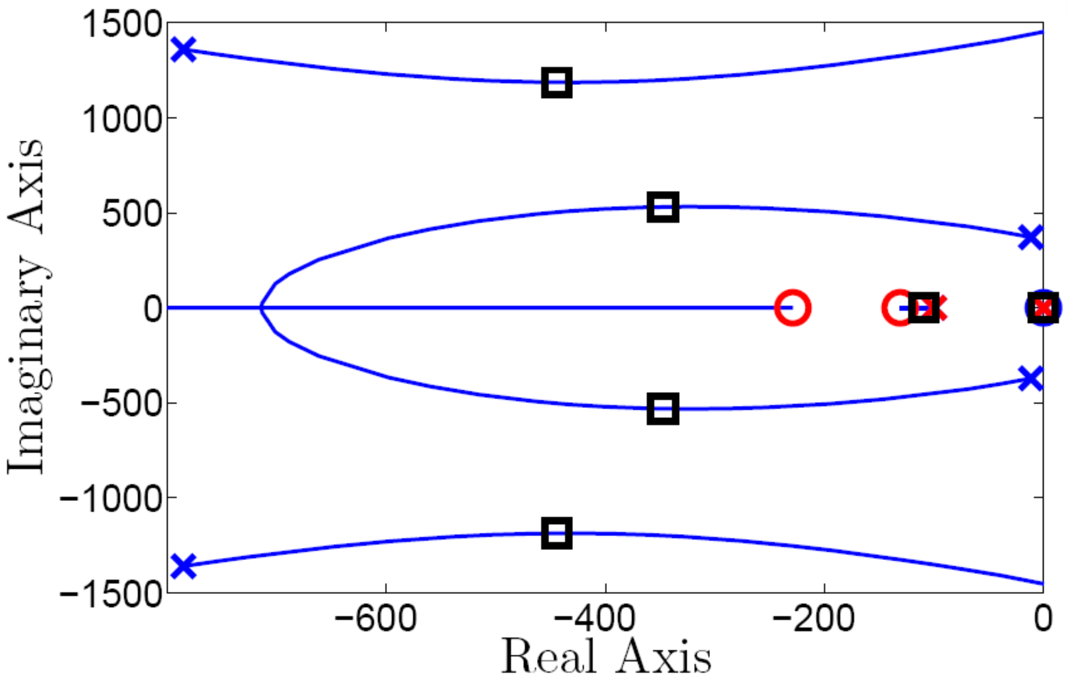
LOW-LEVEL CONTROL ARCHITECTURE

- Cascade impedance control



PID Force Controller

Closed-loop root locus



Legend:

Open-loop poles

Open-loop zero

PID controller poles

PID controller zeros

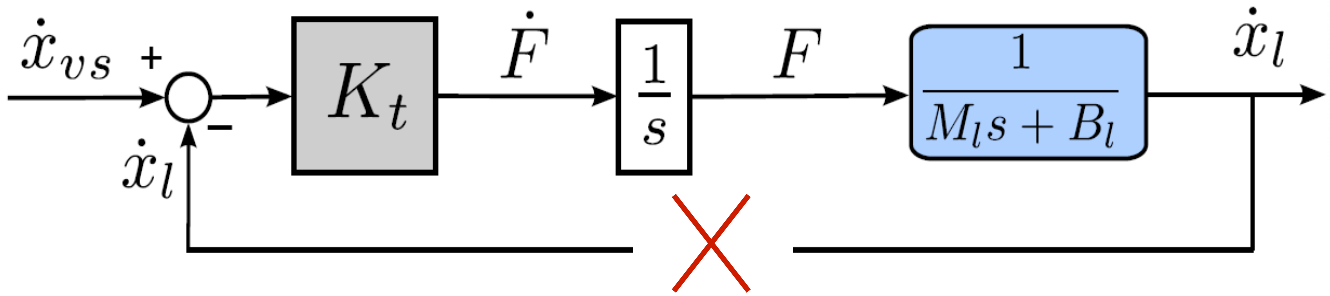
Closed-loop poles

$$\frac{u_{PID}(s)}{e_f(s)} = K_p + \frac{K_i}{s} + K_d\left(\frac{N}{s+N}\right)$$

A FORCE PID CONTROLLER BEHAVES AS A SIMPLE PD CONTROLLER

Velocity Compensation

Generic Case:

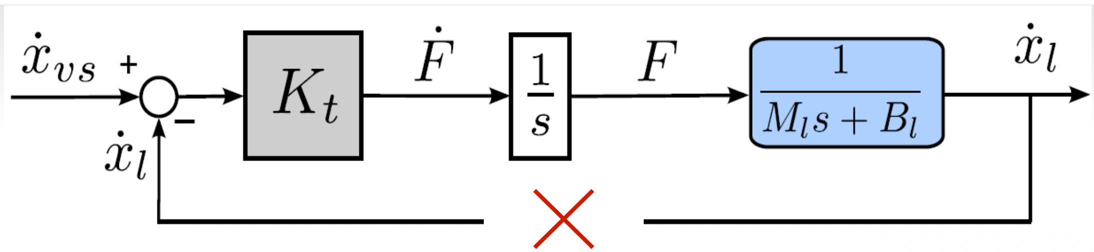


Transfer function:

$$\frac{F(s)}{\dot{x}_{vs}(s)} = \frac{K_t}{s}\,\frac{K_t\,(M_l s + B_l)}{M_l s + B_l) + \cancel{K_t}}$$

[T. Boaventura et al, 2012, "On the role of load motion compensation in high-performance force control", IROS]

Velocity Compensation



$$\dot{F} = K_t\left[(\dot{x}_{vs} + \dot{x}_{ex}) - \dot{x}_l\right]$$

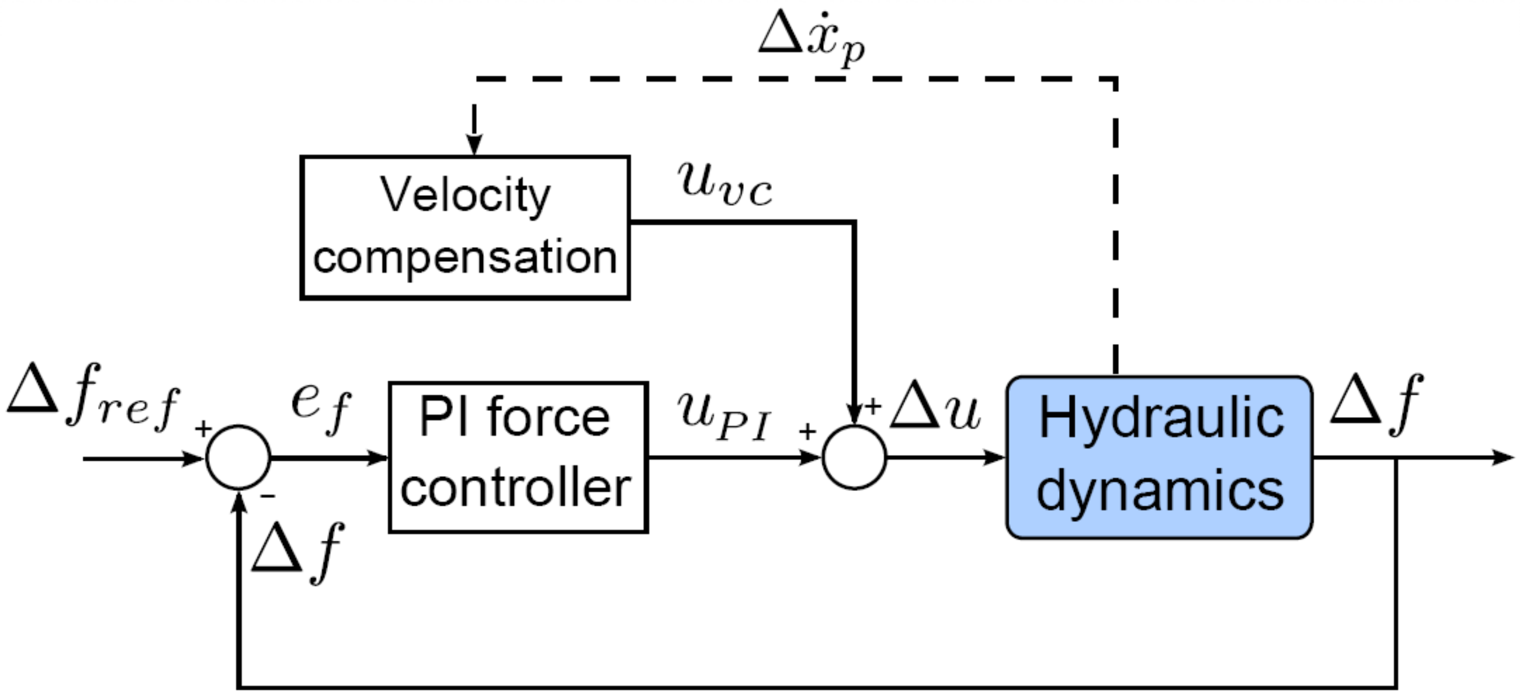
By measuring $\dot{x}_l$: $\dot{x}_{ex} = \dot{x}_l$

In hydraulics: $$u_{vc} = \frac{A_{e\oslash}\Delta\dot{x}_p}{K_{qe}}$$

[T. Boaventura et al, 2012, "On the role of load motion compensation in high-performance force control", IROS]

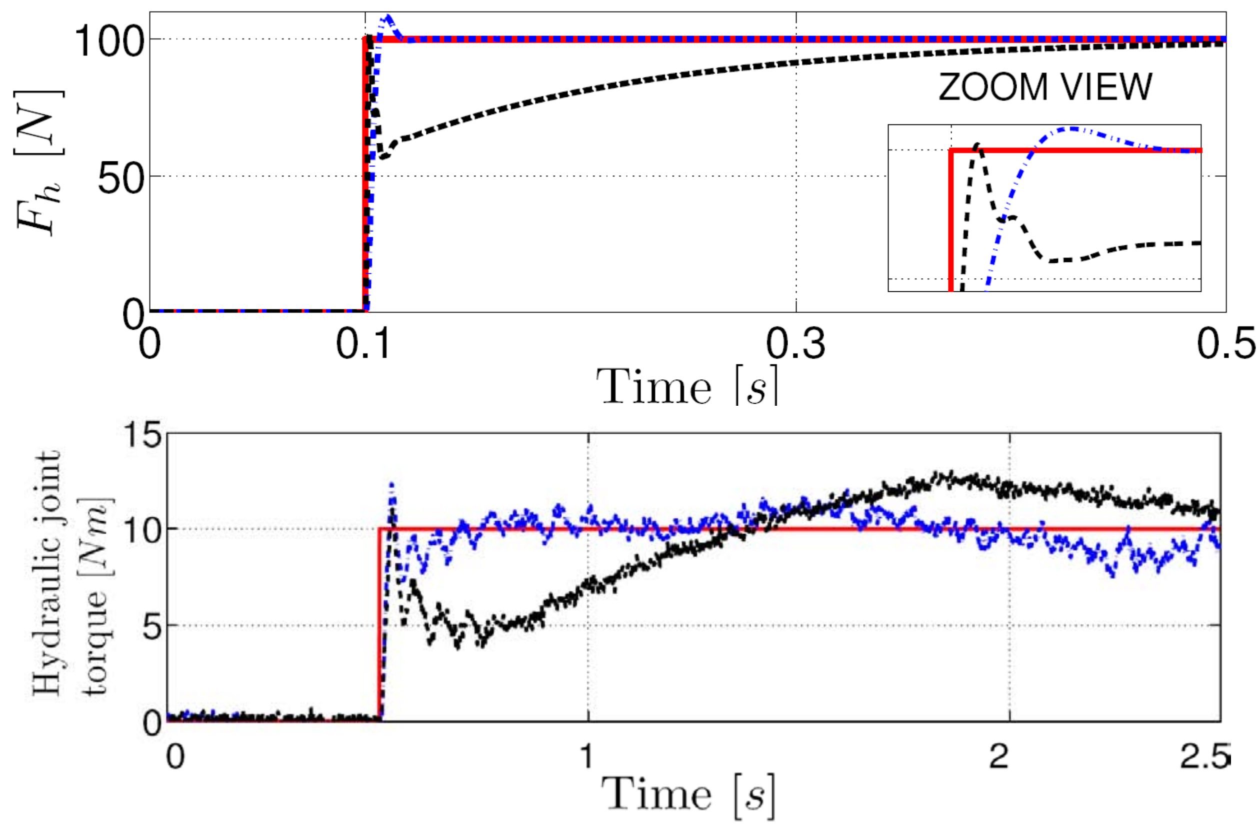
Velocity Compensation

Load velocity compensation acts as a **model-based feed forward controller**!



VELOCITY COMPENSATION

Red: reference; Dashed blue: with compensation; Dashed black: no compensation



[T. Boaventura et al, 2012, "On the role of load motion compensation in high-performance force control", IROS]

OUTLINE

Natural velocity feedback

Torque controllers

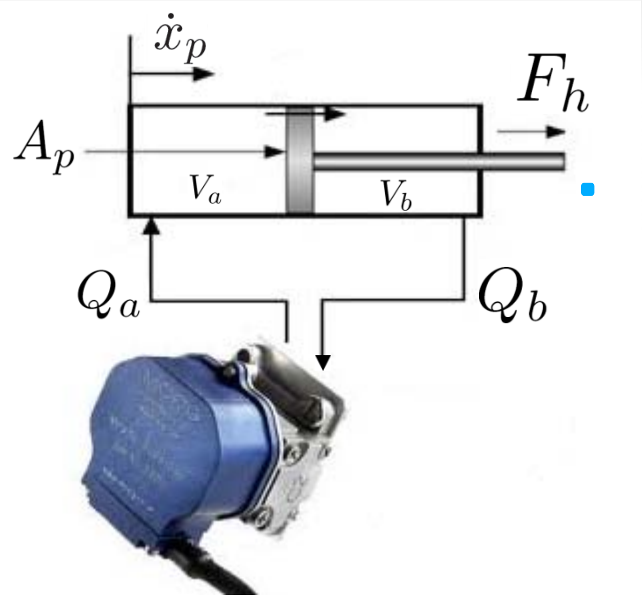
Impedance controller

Passivity & Z-width

Results

Summary

Force Feedback Linearization



Model-based controller

$$\dot{F}_h = f(x_p, \dot{x}_p, \ddot{x}_p) + g(P, x_p)u_v$$

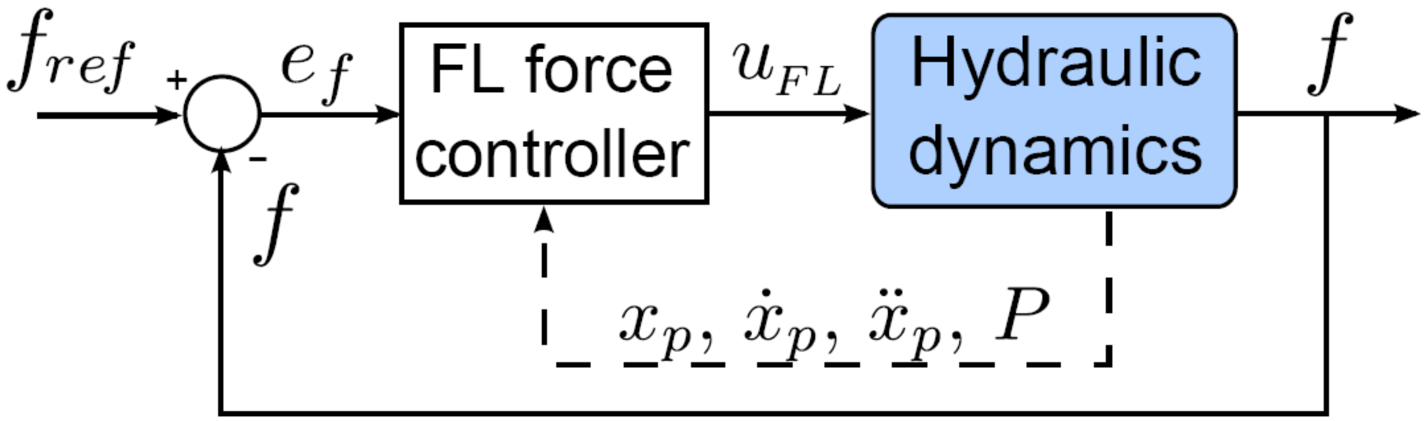
$$f(x_p, \dot{x}_p, \ddot{x}_p) = \beta_e A_p^2 \left(\frac{1}{v_a} + \frac{\alpha^2}{v_b} \right) \dot{x}_p - B\ddot{x}_p$$

$$g(P, x_p) = \beta_e A_p K_v \left(\frac{\sqrt{p_s - p_a}}{v_a} + \frac{\alpha\sqrt{p_b - p_t}}{v_b} \right)$$

Force Feedback Linearization

Compensates for the natural velocity feedback!

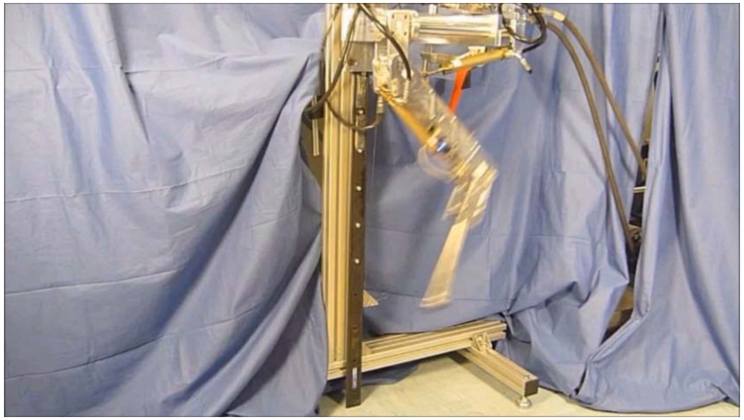
$$u_{FL} = \frac{1}{g(P, x_p)} \left(v - f(x_p, \dot{x}_p, \ddot{x}_p)\right)$$

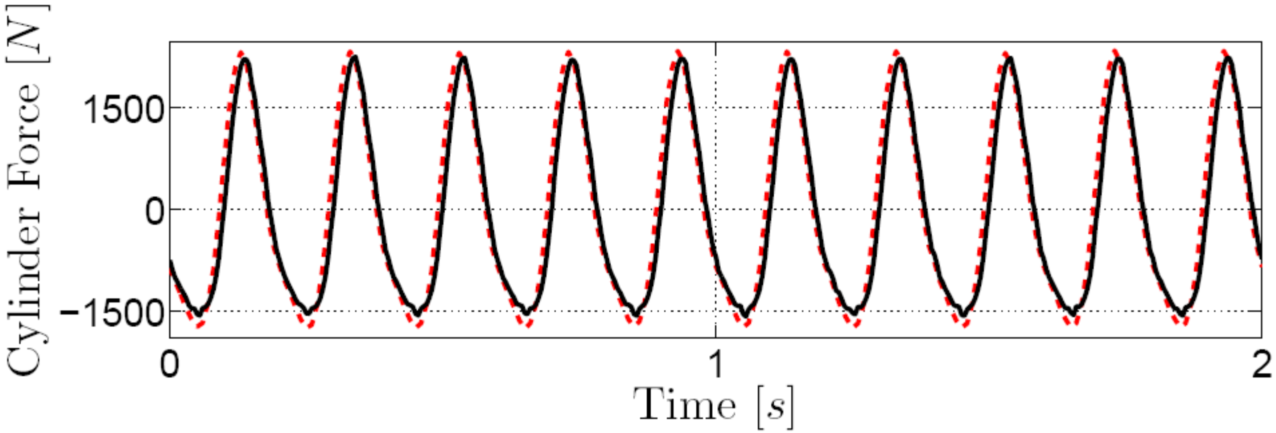


[T. Boaventura et al, 2012, "Dynamic torque control of a hydraulic quadruped robot", ICRA]

Force Feedback Linearization

Hip joint force tracking during a **5 Hz** periodic motion





Dashed Red: force reference;
Solid black: actual force

TORQUE CONTROLLER

Zero force reference

PRESENTATION OUTLINE

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- **Impedance controller design**
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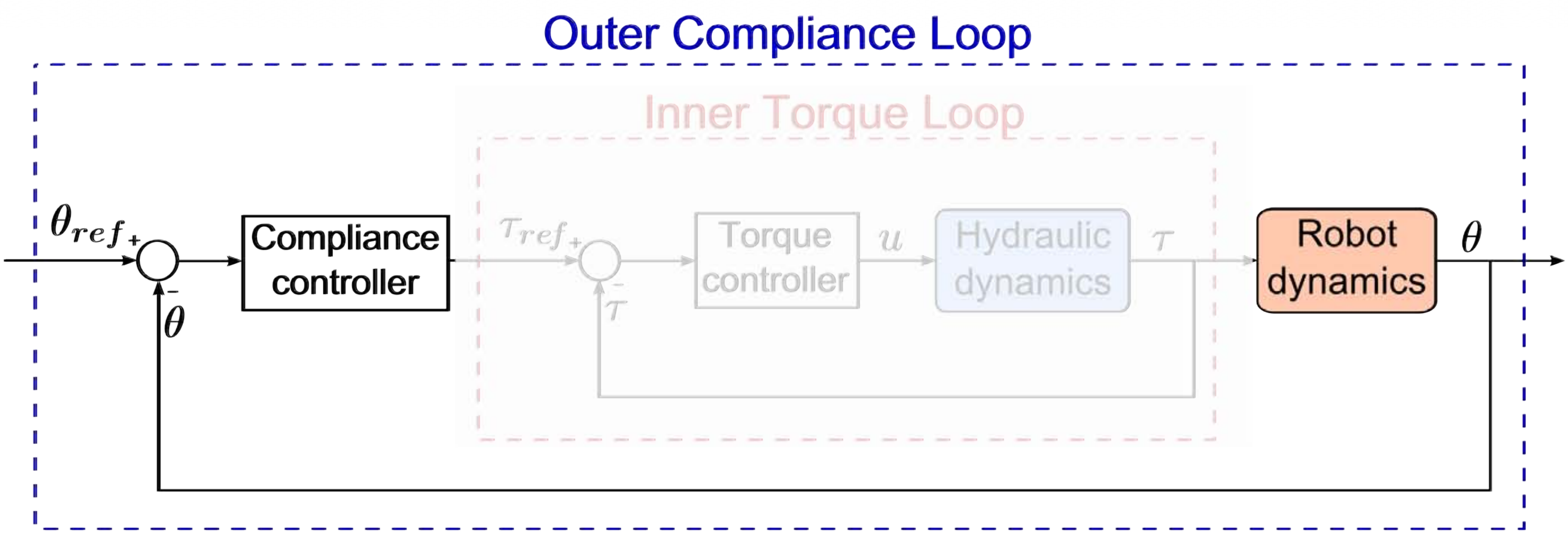
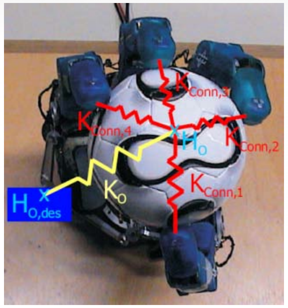
HyQ Low-level Controller

- Impedance cascade control

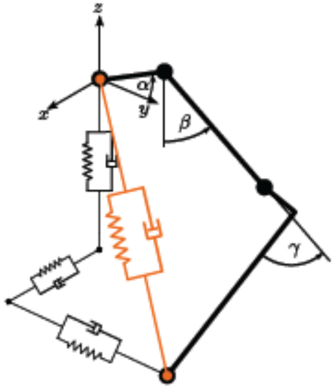


Impedance Controller

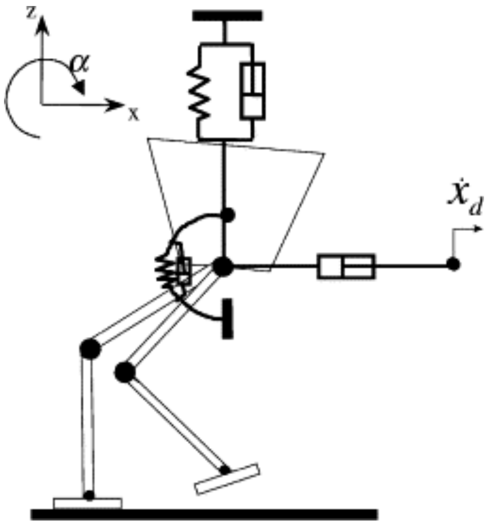
- Impedance control approaches..
  - Rigid body inverse dynamics
  - Virtual Model Control
  - Impedance Control
  - Operational Space Control



DLR

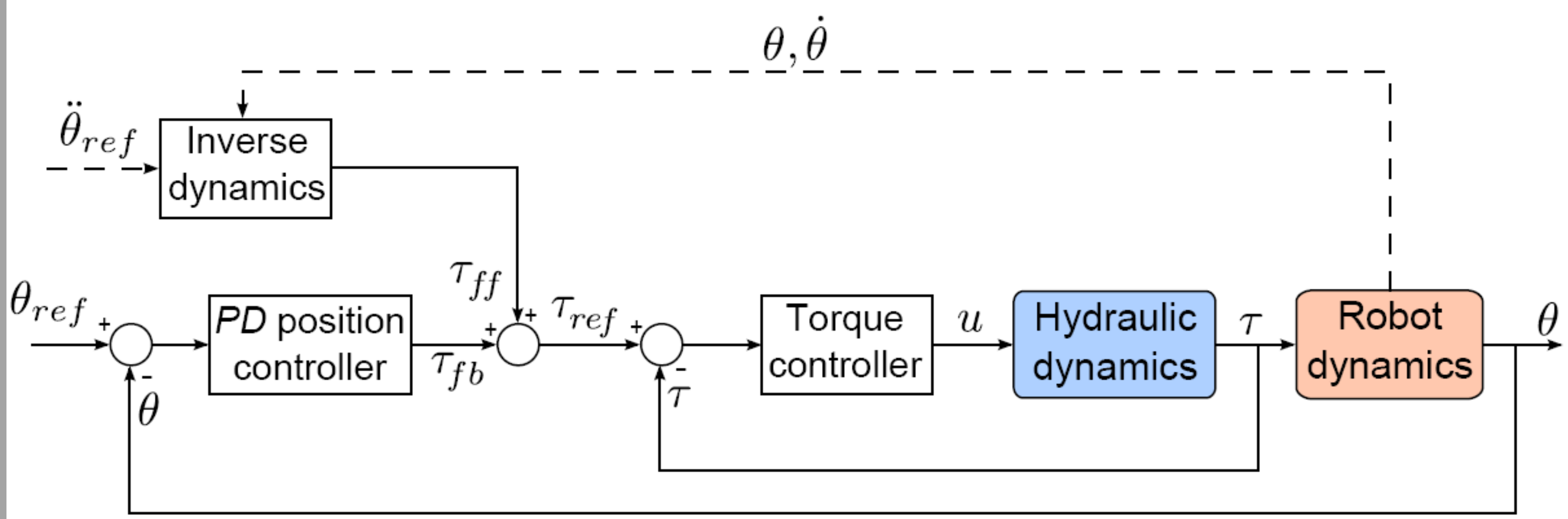


TORQUES AS OUTPUT



PD + Rigid Body Inverse Dynamics

- **Inverse dynamics:** very powerful tool!
  - Model-based feed forward controller
  - It permits to lower the PD position gains
  - Position tracking with low-compliance



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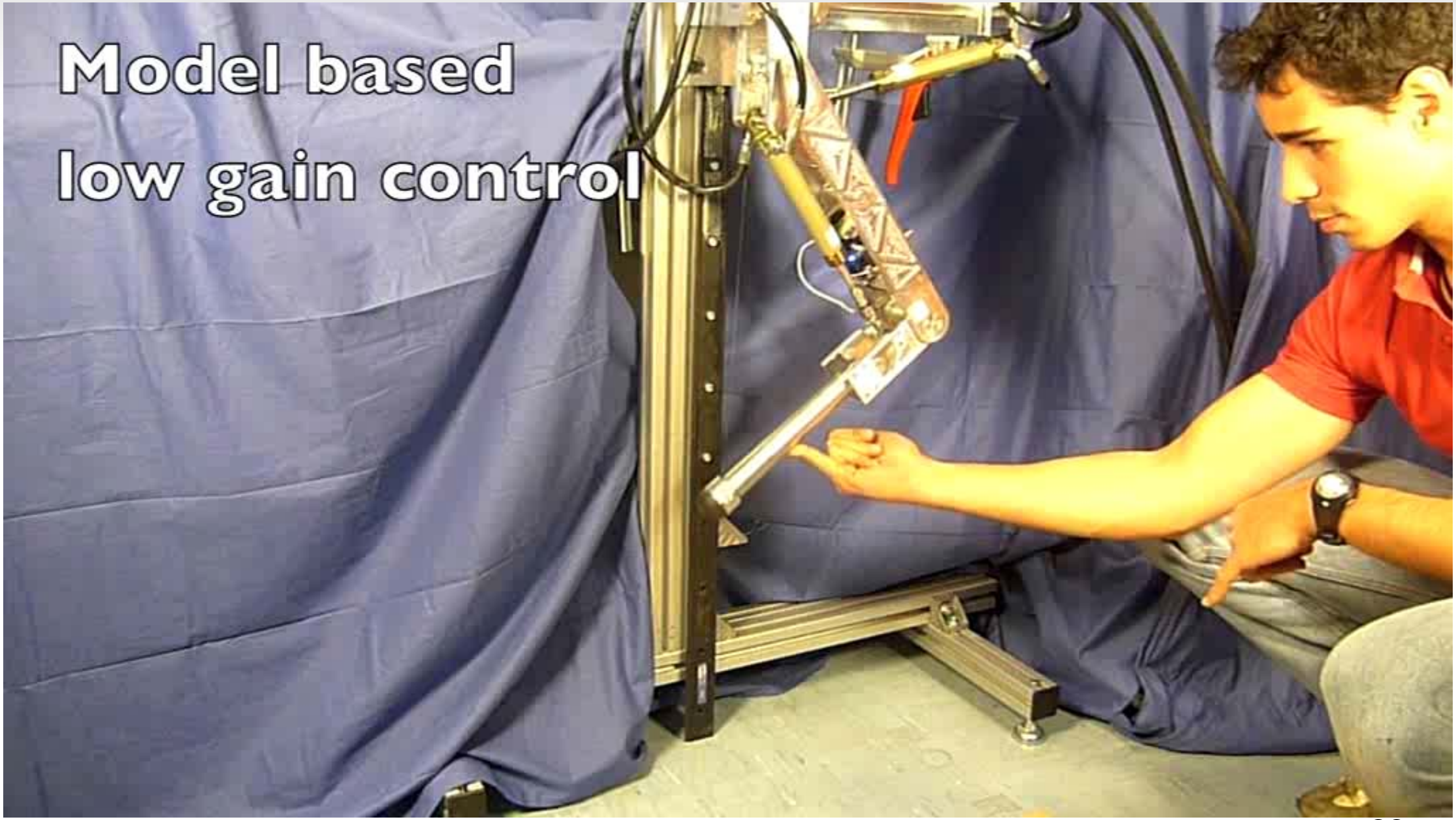
PD + Rigid Body Inverse Dynamics



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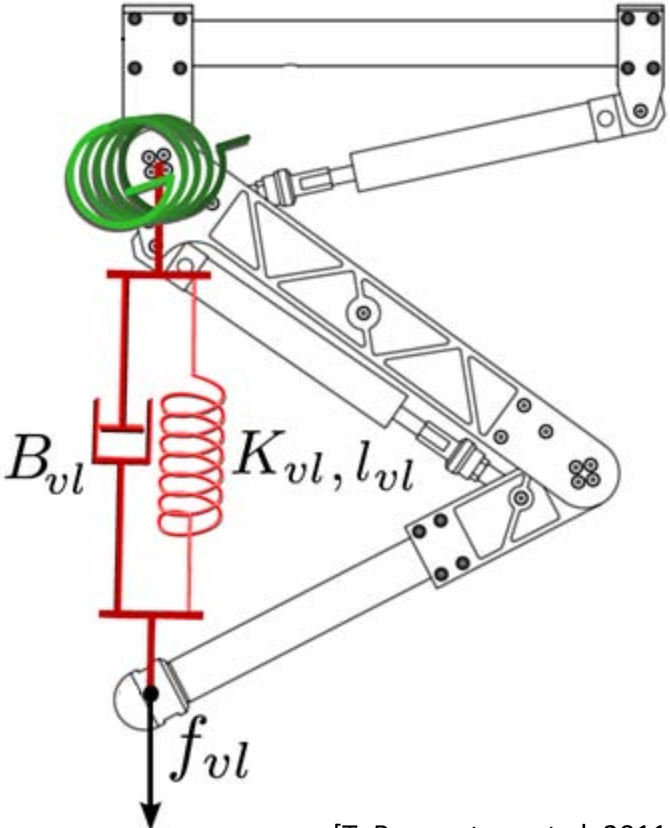
VIRTUAL MODEL CONTROL

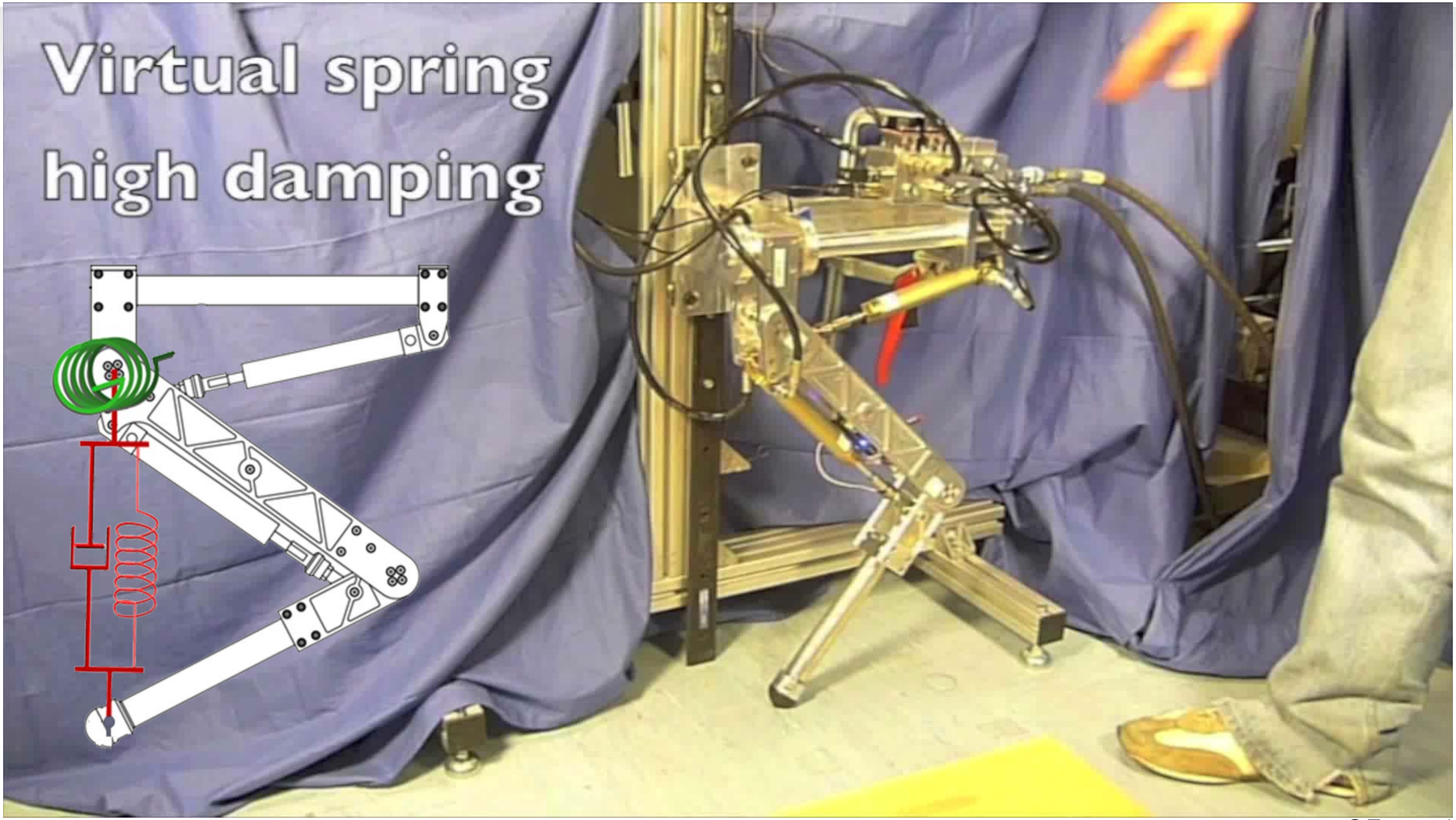
[Pratt, J. et al, "Virtual model control: An intuitive approach for bipedal locomotion", 2001]



- Virtual components
  - Springs
  - Dampers
- Flexibility
  - Change stiffness and damping ***ON THE FLY***!

[T. Boaventura et al, 2011, "Actively-compliant leg for dynamic locomotion", AMAM]

Virtual Model Control



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ACTIVE VS. PASSIVE COMPLIANCE

OUTLINE

Natural velocity feedback

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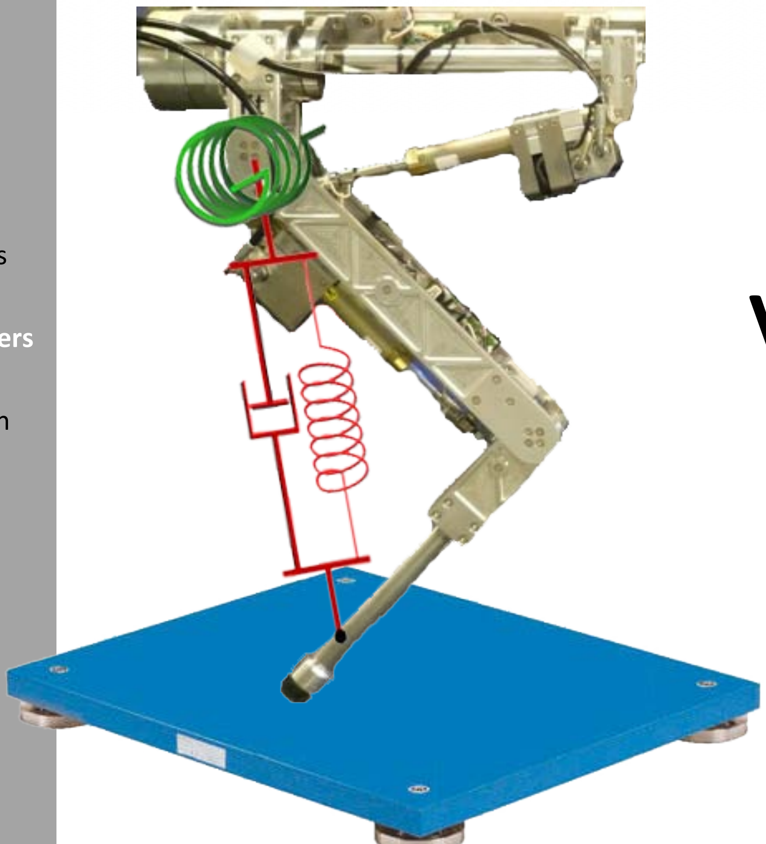
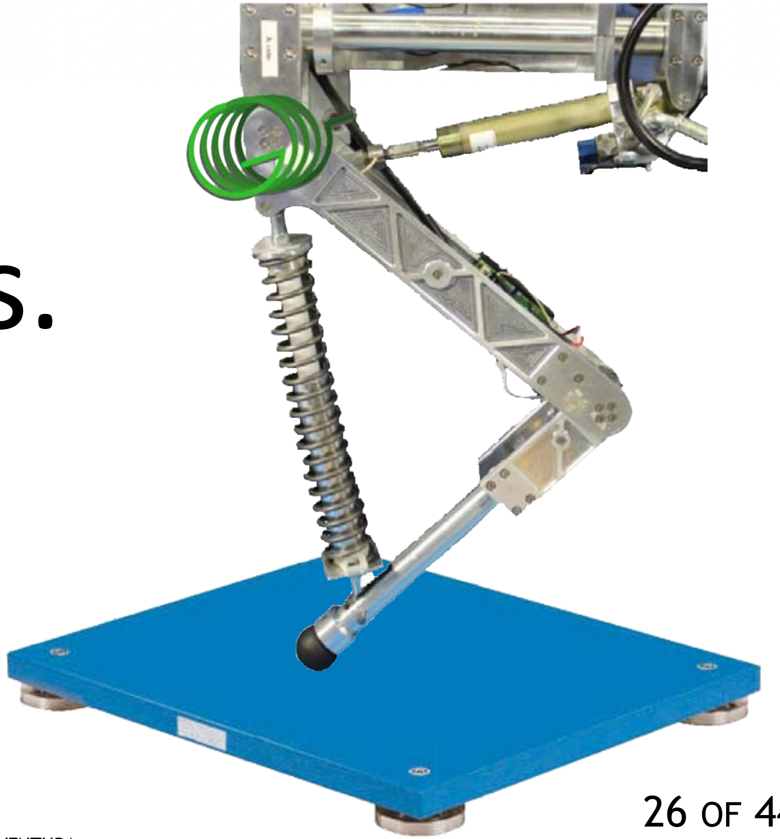
Actively-compliant
(virtual spring-damper!)



VS.

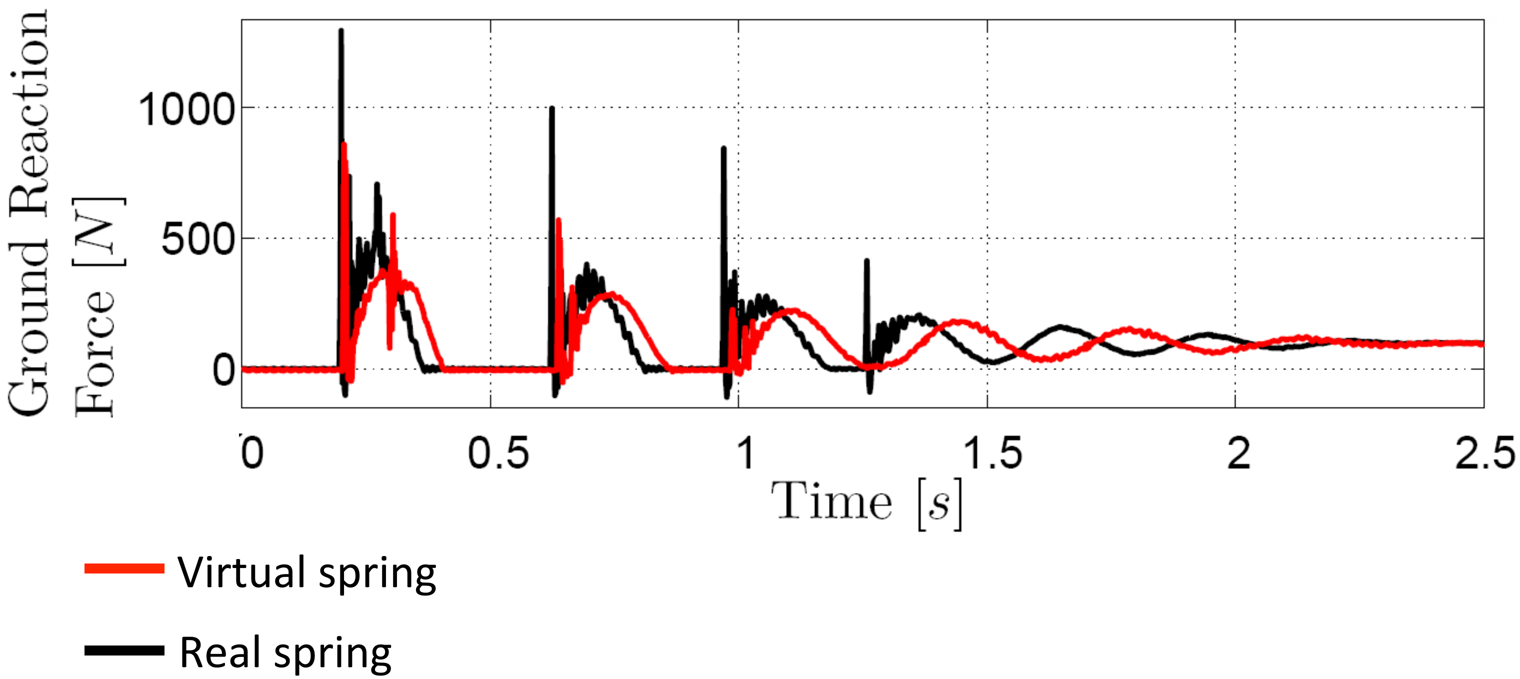
Passively-compliant
(real spring-damper!)



Active vs. Passive Impedance

Active vs. Passive Compliance

Experimental results



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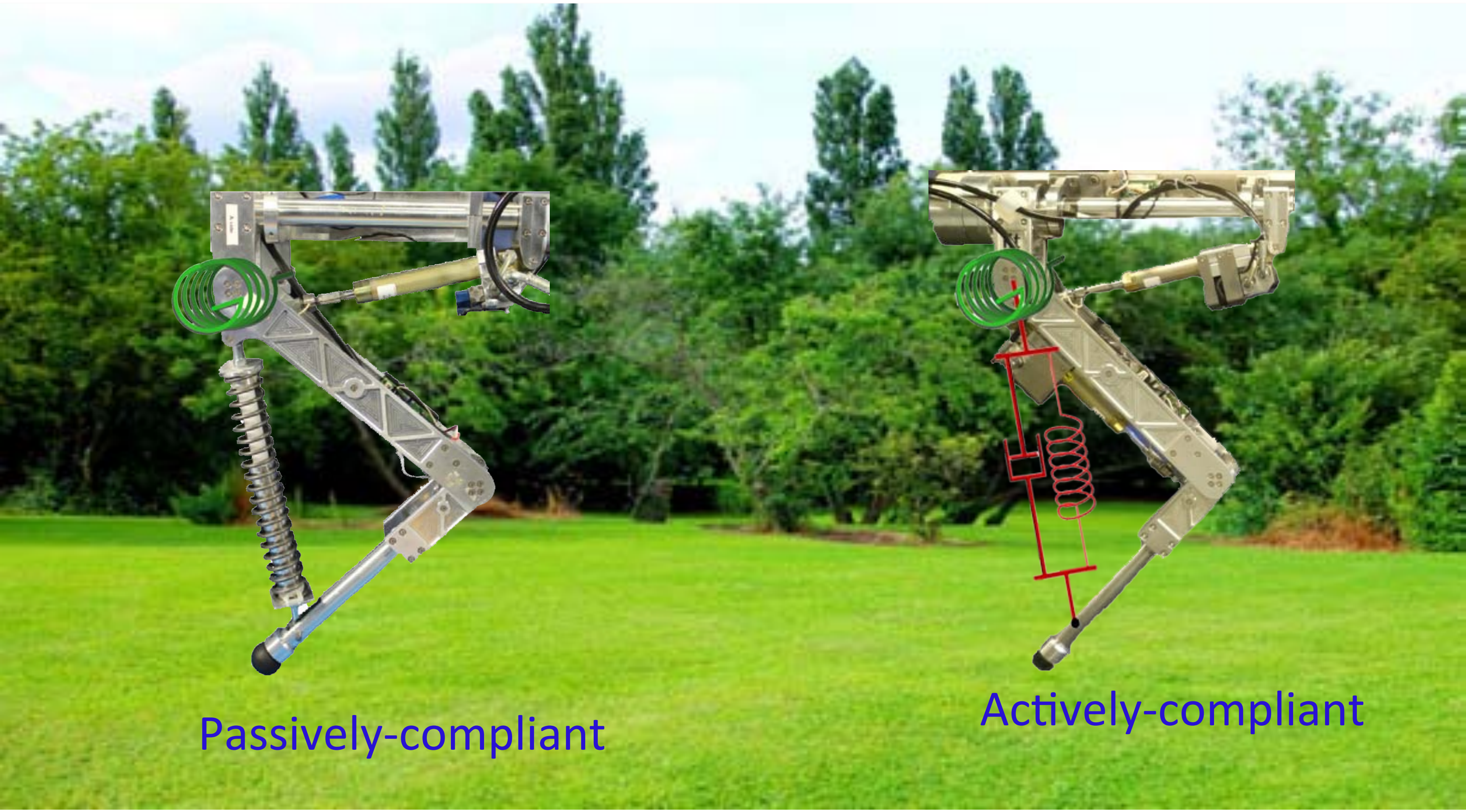
Passivity of an Actively-compliant system



Passivity of an Actively-Compliant System

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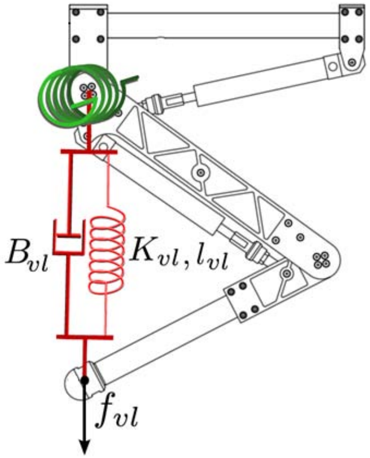
+

= **STABLE INTERACTION**

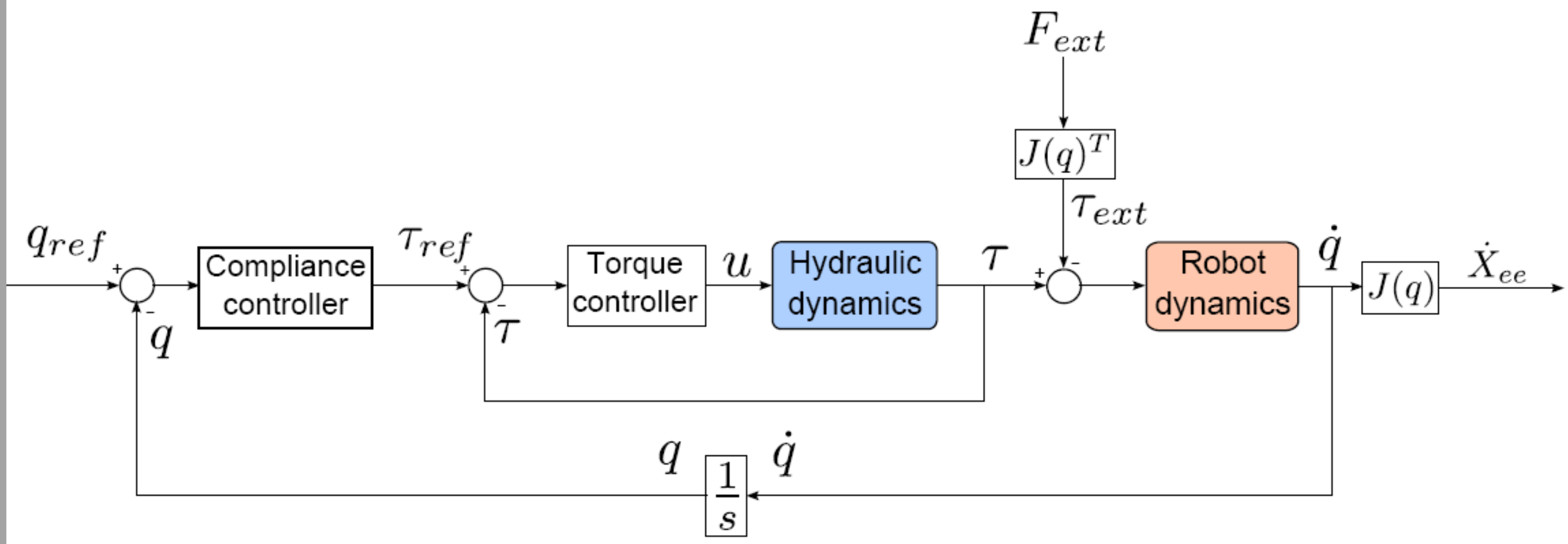
Passive system **Passive environment**



- **Z-width**
  - Range of **stiffness** and **damping** that keeps the system **passive**

[Colgate, J. E. and Brown, J. M. (1994). "Factors affecting the z-width of a haptic display"]

Passivity of an Actively-compliant system



$$\dot{\boldsymbol{X}}_{ee} = \boldsymbol{Y}(\boldsymbol{s})\ \boldsymbol{F}_{ext}(\boldsymbol{s}) \Leftrightarrow \begin{bmatrix} \dot{X}_{ee_x} \\ \dot{X}_{ee_z} \end{bmatrix} = \begin{bmatrix} Y_{xx}(s) & Y_{xz}(s) \\ Y_{zx}(s) & Y_{zz}(s) \end{bmatrix} \begin{bmatrix} F_{ext_x}(s) \\ F_{ext_z}(s) \end{bmatrix}$$

[Colgate, J. E. (1994), “Coupled stability of multiport systems - theory and experiments”]

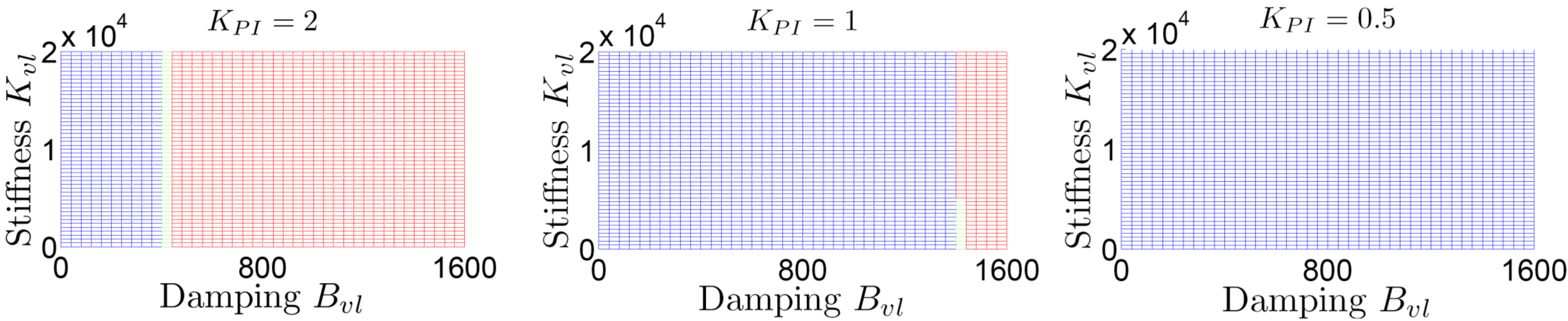
Z-width & Torque Controller

- Force loop: **PI + Velocity compensation**

$$C_{pi} = K_{PI} \frac{0.03838\,(z - 0.9953)}{z - 1}$$

Legend:

- Passive range (blue)
- Stable, but not passive range (green)
- Unstable range (red)



The higher the torque loop gain, the smaller the Z-width!

Torque performance & Impedance tracking

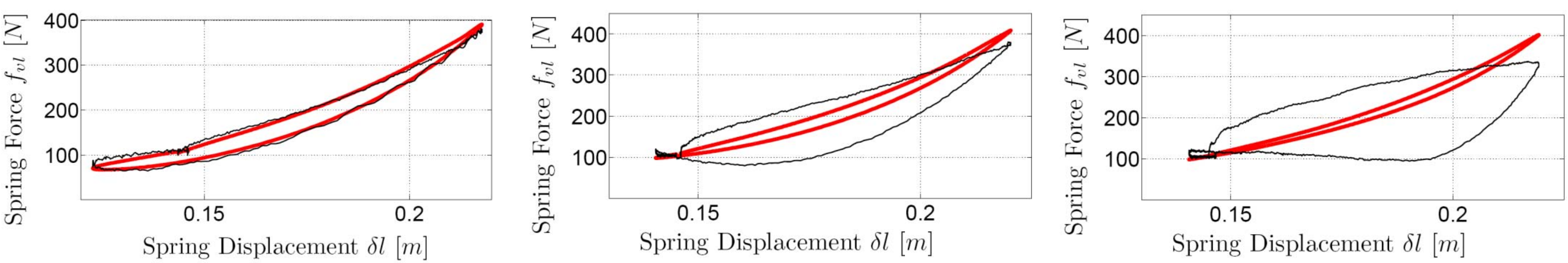
Z-WIDTH

TORQUE CONTROLLER GAINS

IMPEDANCE TRACKING CAPABILITIES

Exponential spring-damper tracking:

(red line: reference ; black line: actual)



(a) Force gain $K_{pc} = 1$

(b) Force gain $K_{pc} = 0.5$

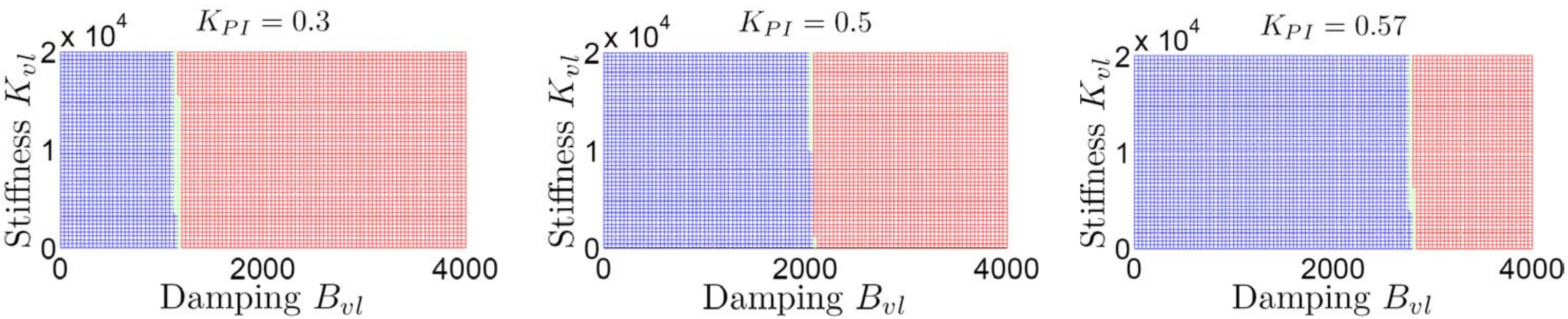
(c) Force gain $K_{pc} = 0.25$

Z-width & Actuator Dynamics

- Force closed-loop **bandwidth**: **40 Hz**
- Different valve dynamics..

$$\frac{\Delta f(s)}{\Delta u(s)} = \left(\frac{1}{\frac{1}{\omega_v^2}s^2 + \frac{2D_v}{\omega_v}s + 1} \right) \left(\frac{K_{u_v}(M_l s + B_l)}{(s - K_{f_h})(M_l s + B_l + B) - K_{\dot{x}_p}} \right)$$

$$\omega_v = 2\pi F_v$$



(a) Valve bandwidth $F_v = 50\ Hz$ (b) Valve bandwidth $F_v = 150\ Hz$ (c) Valve bandwidth $F_v = 250\ Hz$

The higher the actuator bandwidth, the larger the Z-width!

Insights from Passivity Analyses

Cascade impedance controller design..

1. **Estimation of Z-width** needed by the robot
   (e.g. versatile robots as HyQ most likely require a larger Z-width than a task-specific robot..)

2. Tune the inner torque controller to give **the maximum stable closed-loop torque bandwidth** which satisfies 1.

3. In case the selected Z-width limits too much the compliance performance, a faster actuator can be selected.

Suitable trade-off between stability and performance

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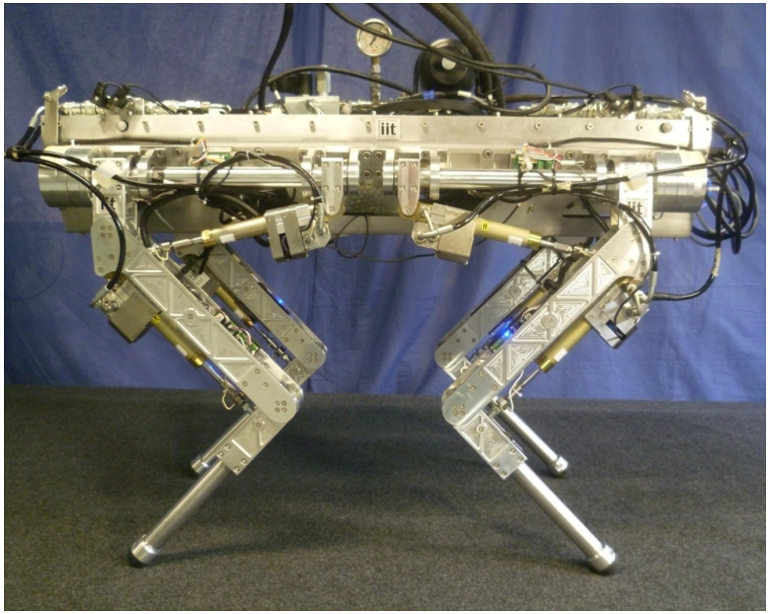
HyQ – A RESEARCH PLATFORM

- Quadruped robot for ***versatile locomotion***



- Electric and hydraulic actuation
- Dimensions [*m*]: 1.0 x 0.5 x 1.0 (L x W x H)
- Weight: 75 *kg*

[C. Semini et al, *IMechE Part I: J. of Systems and Control Engineering*, vol 225, no. 6, 2011]

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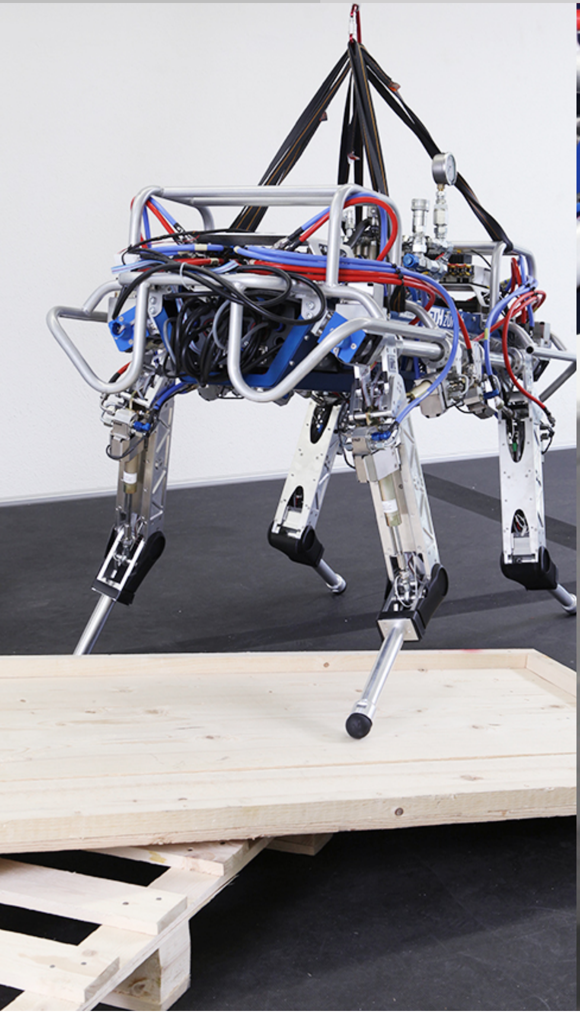
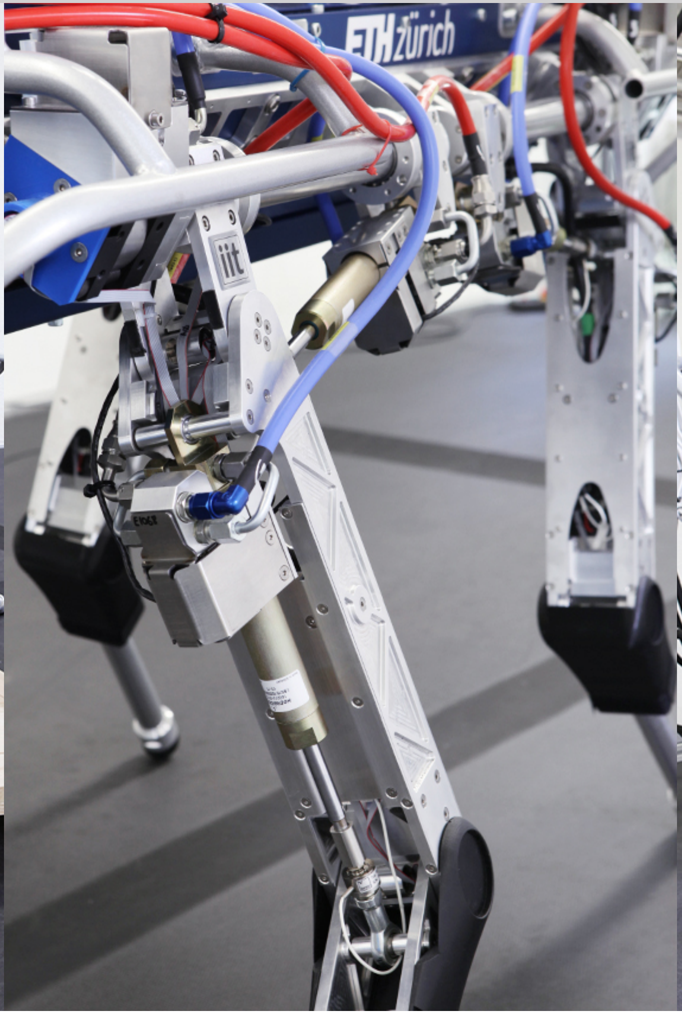
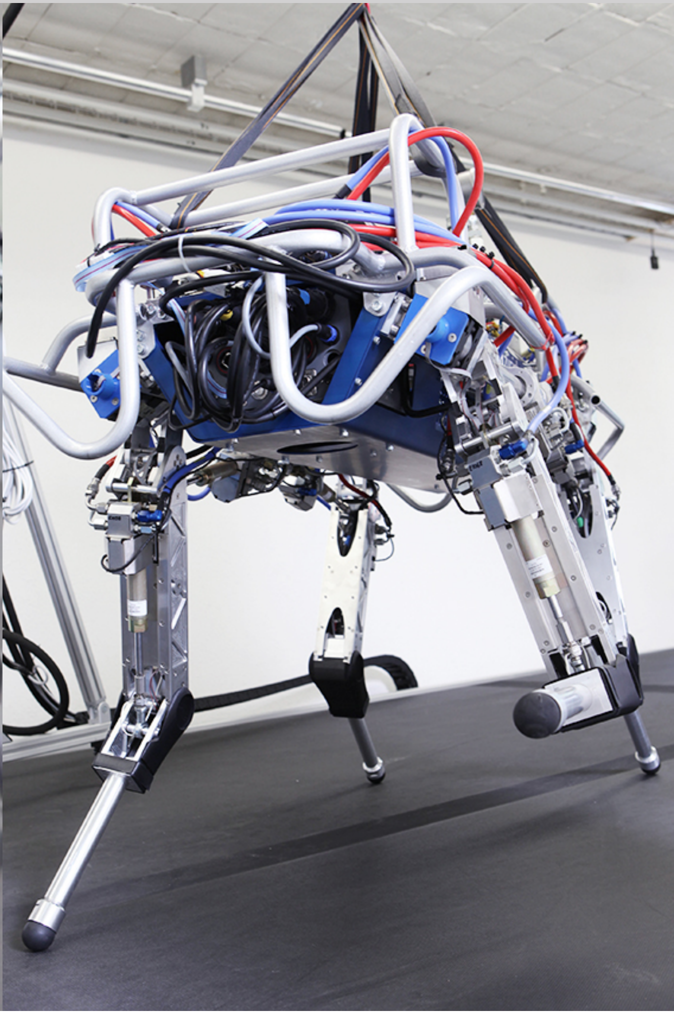
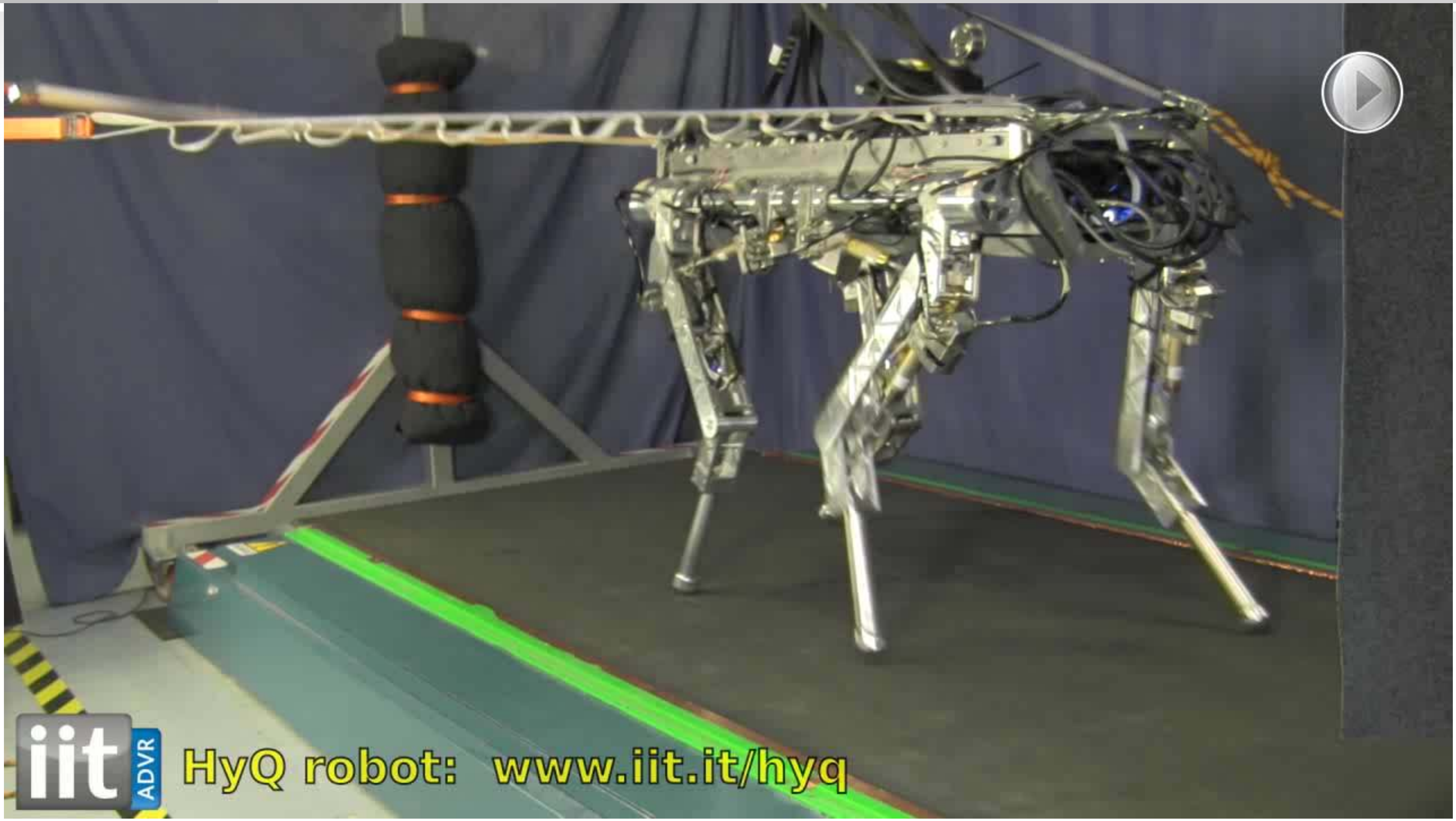
HyQ Blue @ ETH Zurich



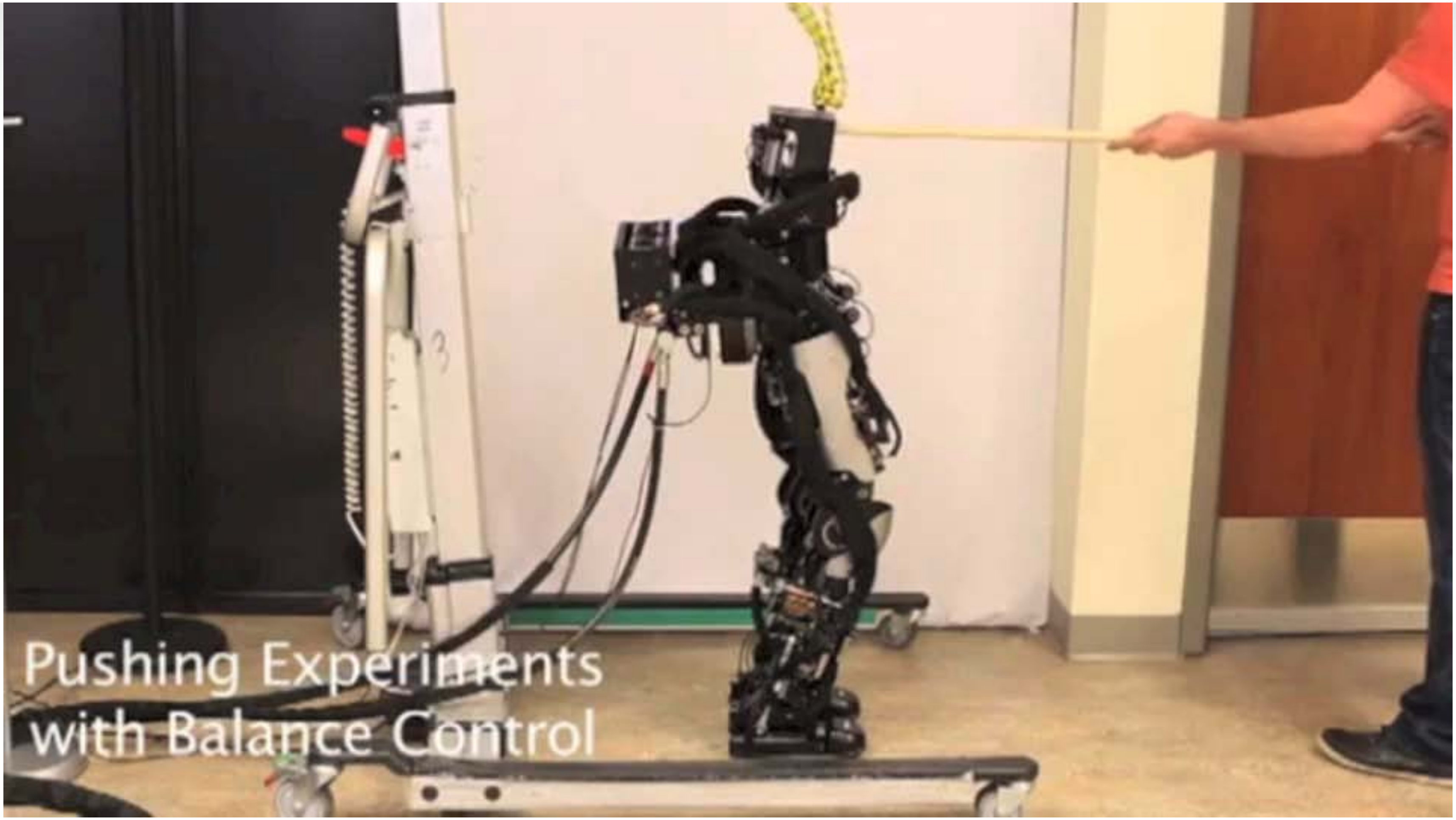




Results with HyQ



Sarcos Humanoid



[Herzog, A.; Righetti, L.; Grimminger, F.; Pastor, P.; Schaal S. (2013). Momentum-based Balance Control for Torque-controlled Humanoids, Arxiv preprint]

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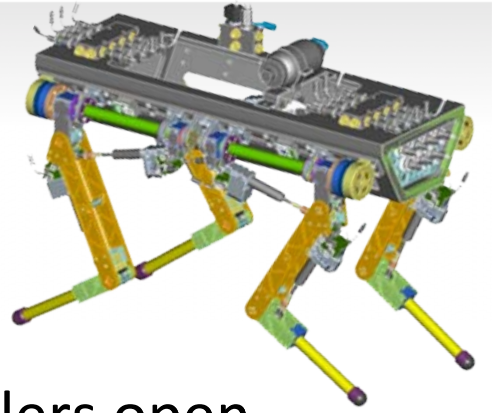
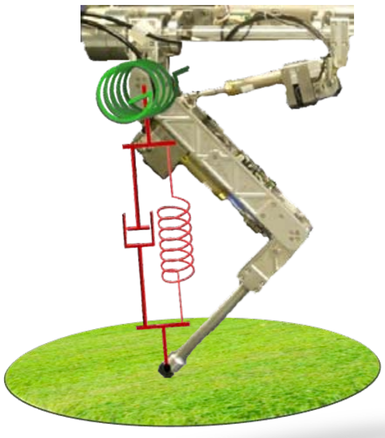
Take-home messages



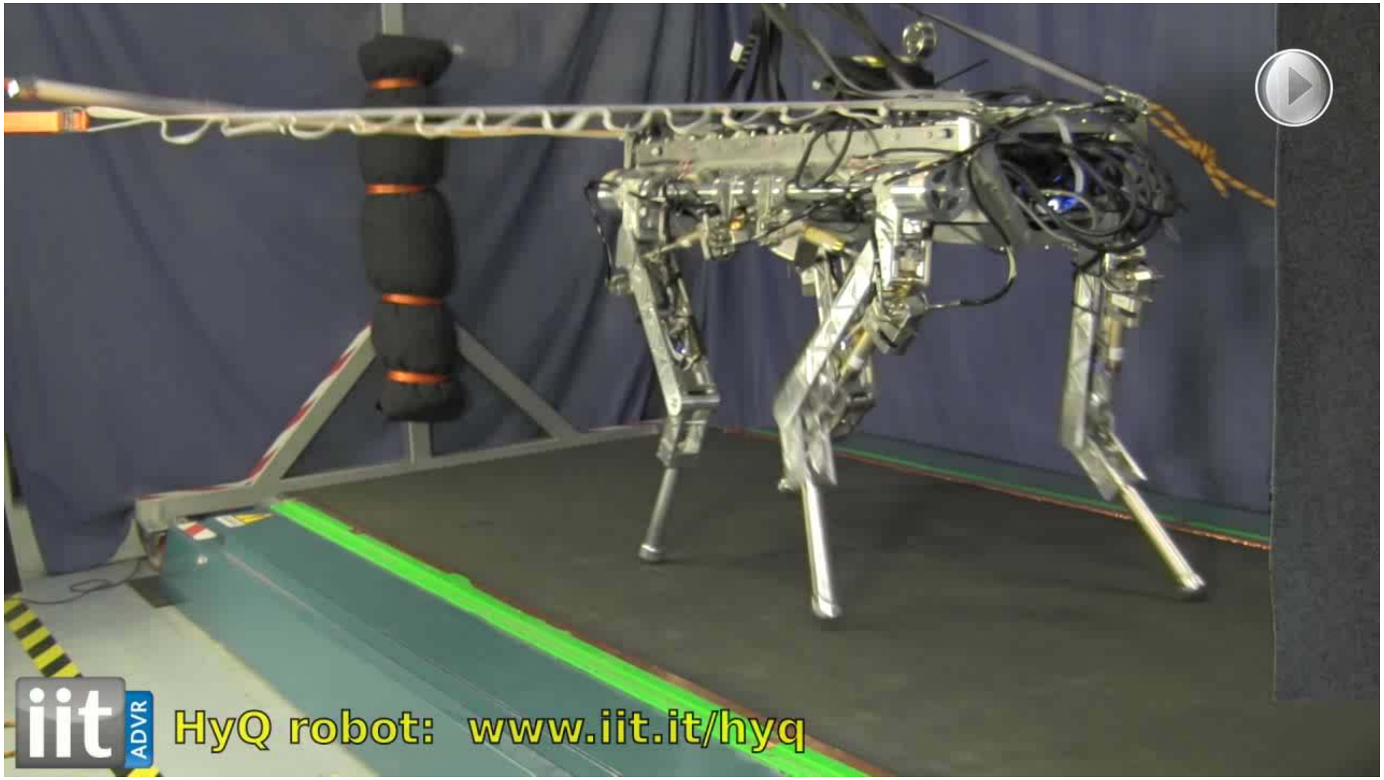
- **Fast actuators & model-based control** are the **key** for achieving high-performance torque control
- **High-performance** torque controllers open doors for several high-level controllers (e.g. impedance control, balance control, etc.)



TRULY COMPLIANT WITH NO REAL SPRINGS!

QUESTIONS?

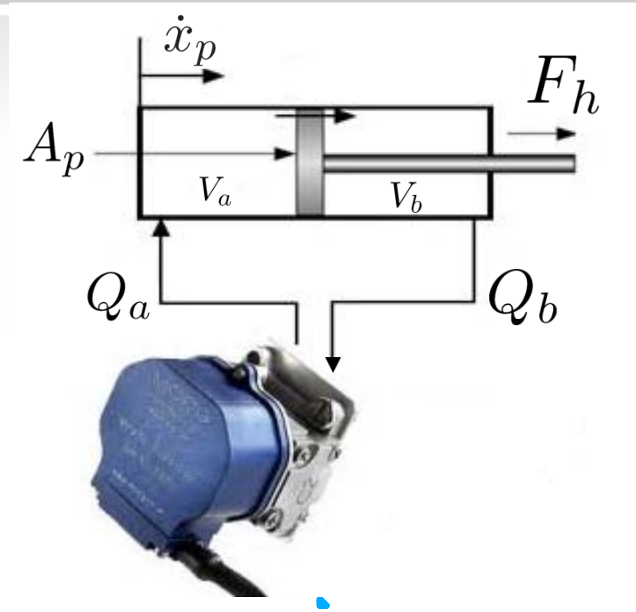
Thank you for your attention!



Actively-compliant Legs

Impedance: dynamic relation between the motion and forces generated at the contact point.

Natural Velocity Feedback



ic case:

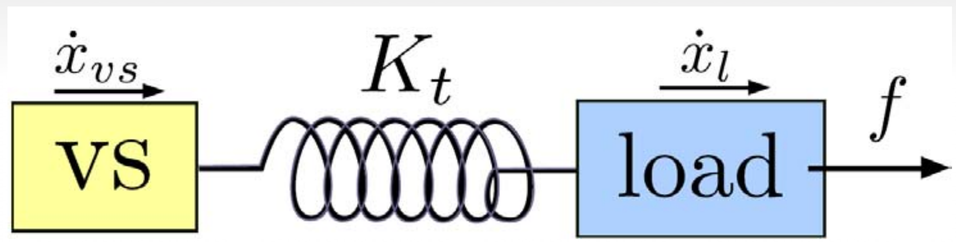
$$\ldots t\left(\dot{x}_{vs} - \dot{x}_l\right)$$

$$\dot{F}_h = \frac{A_p\beta}{V_a}\left(Q_a - A_p\dot{x}_p\right) - \frac{\alpha A_p\beta}{V_b}\left(-Q_b + \alpha A_p\dot{x}_p\right)$$

$$\dot{F}_h = K_{th}\left(Q_e - A_e\dot{x}_p\right)$$

Natural Velocity Feedback

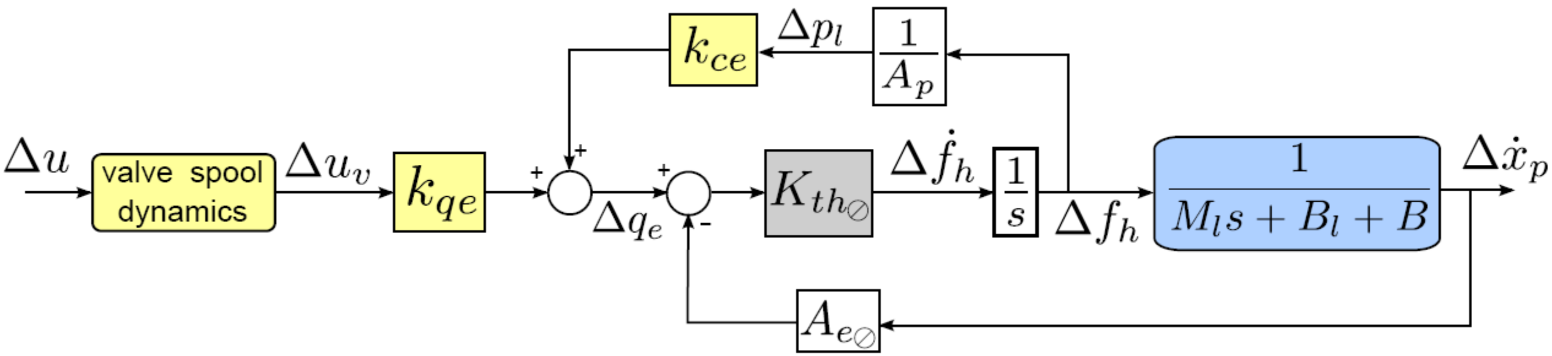
From the generic case:



"Actuator"

e.g. Leg Links

Hydraulic cylinder:



[T. Boaventura et al, 2012, "On the role of load motion compensation in high-performance force control", IROS]

PD + Rigid Body Inverse Dynamics

Hip position and torque tracking at **5 Hz**: