WIEFP 2022

Principles of

Force and Impedance Control

of hydraulically-actuated robots

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interaction control

basic principles

impedance control

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Control of

physical interaction!

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BostonDynamics

How can **physical interaction** be characterised?

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Energy flow

Ideal energetic elements

kinetic
energy

elastic
potential energy

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Energy Flow

Power

= energy flow

$$P = \frac{dE}{dt}$$

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$$P = \frac{dE}{dt}$$

Temporal dependency described by:

O.D.E

Transfer Function

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POWER = EFFORT X FLOW

Mechanic = FORCE X VELOCITY

Electric = VOLTAGE X CURRENT

Fluid power = PRESSURE X FLOW

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POWER = EFFORT X FLOW

Mechanic = FORCE X VELOCITY

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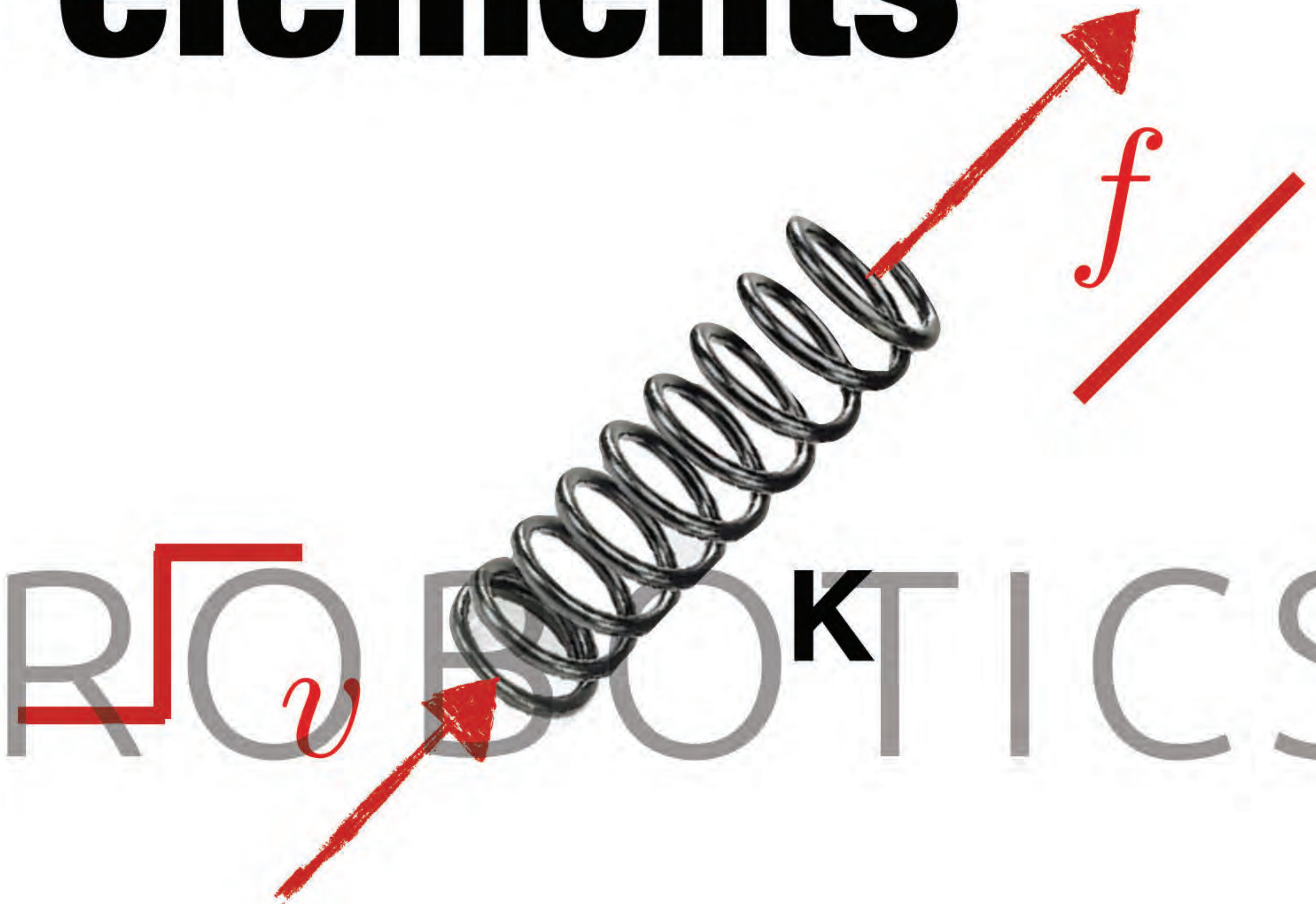
Ideal mechanical elements



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$$\dot{v} = \frac{1}{m} f$$

$$\dot{f} = K v$$

Output **Input**

$$v = \int \frac{1}{m} f \, dt$$

Output **Input**

$$f = \int K v \, dt$$

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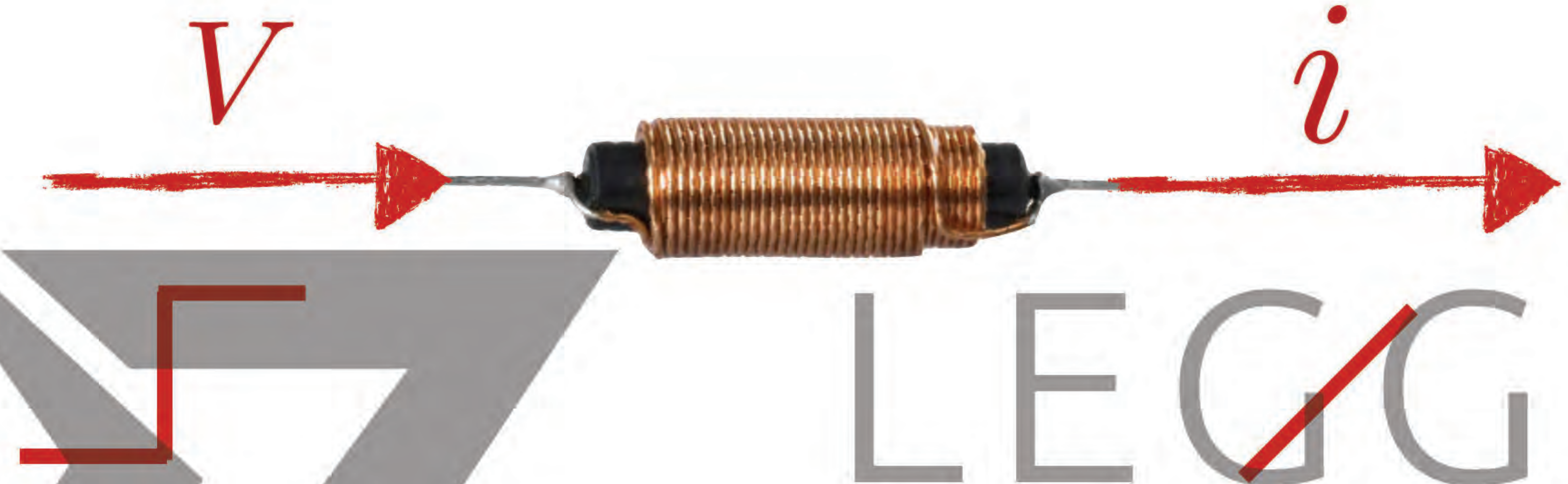
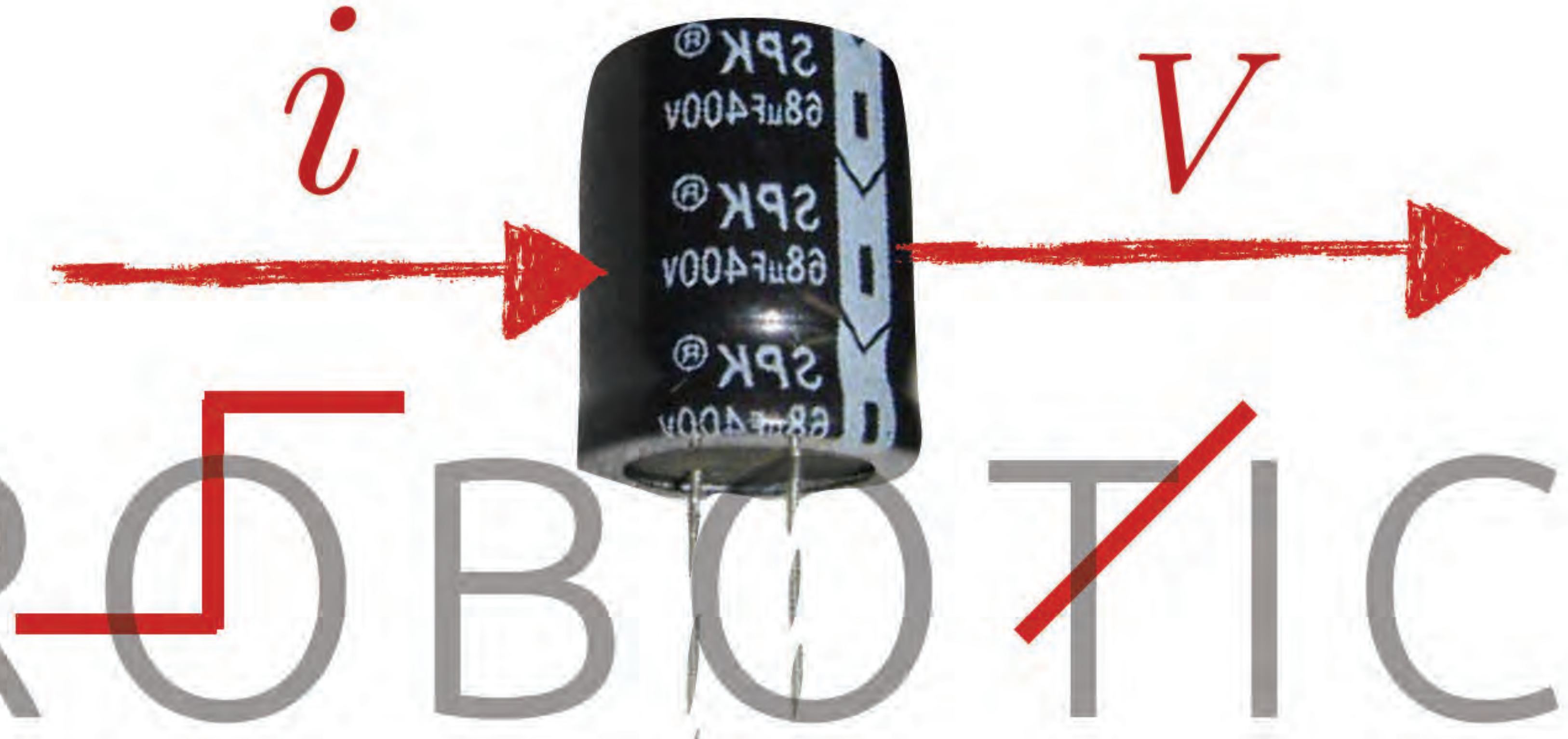
Ideal electric elements





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$$V = L\frac{di}{dt}$$

Output **Input**

$$i = \frac{1}{L}\int V\,dt$$

$$V = \frac{Q}{C}$$

Output **Input**

$$V = \frac{1}{C}\int i\,dt$$

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Impedance and admittance

Describe a **dynamic** relation between **EFFORT/FLOW**

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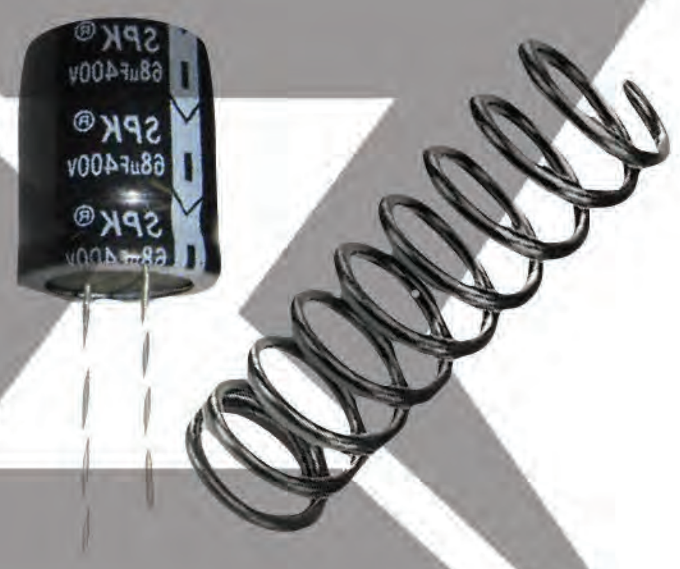

	INPUT	OUTPUT
impedance	FLOW	EFFORT
admittance	EFFORT	FLOW

$$Z(s) = \frac{F(s)}{V(s)}$$

$$Y(s) = \frac{V(s)}{F(s)} = \frac{1}{Z(s)}$$

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Impedance and admittance

$$Z(s) = \frac{F(s)}{V(s)} \qquad Y(s) = \frac{V(s)}{F(s)} = \frac{1}{Z(s)}$$

Element	Impedance	Admittance
Capacitor 	$Z(s) = \frac{1}{Cs}$	$Y(s) = Cs$
Inductor 	$Z(s) = Ls$	$Y(s) = \frac{1}{Ls}$
Spring 	$Z(s) = \frac{k}{s}$	$Y(s) = \frac{s}{k}$
Mass 	$Z(s) = ms$	$Y(s) = \frac{1}{ms}$

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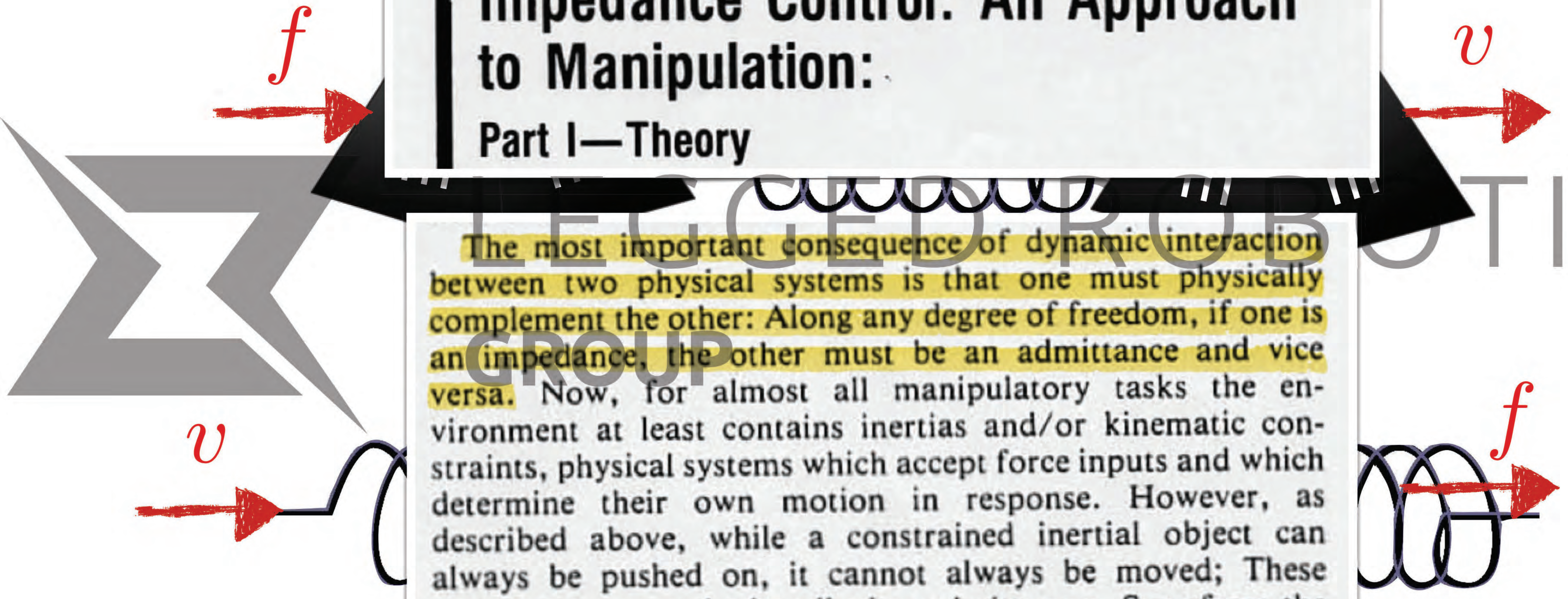
Input/Output ⇔ Causality



Impedance Control: An Approach to Manipulation:

Part I—Theory

The most important consequence of dynamic interaction between two physical systems is that one must physically complement the other: Along any degree of freedom, if one is an impedance, the other must be an admittance and vice versa. Now, for almost all manipulatory tasks the environment at least contains inertias and/or kinematic constraints, physical systems which accept force inputs and which determine their own motion in response. However, as described above, while a constrained inertial object can always be pushed on, it cannot always be moved; These systems are properly described as admittances. Seen from the manipulator, the world is an admittance.

[Hogan, 1985]

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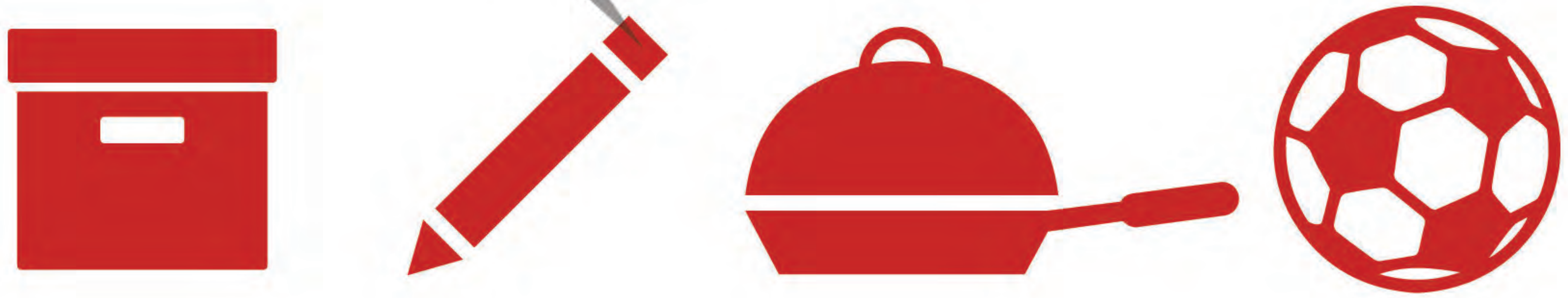
Inertia

minimum model for most **objects**



prefer causality of **admittance**

Kinematic constraint

$$\dot{x} = \ddot{x} = 0$$

simplest description of **contacts**

require causality of **admittance**

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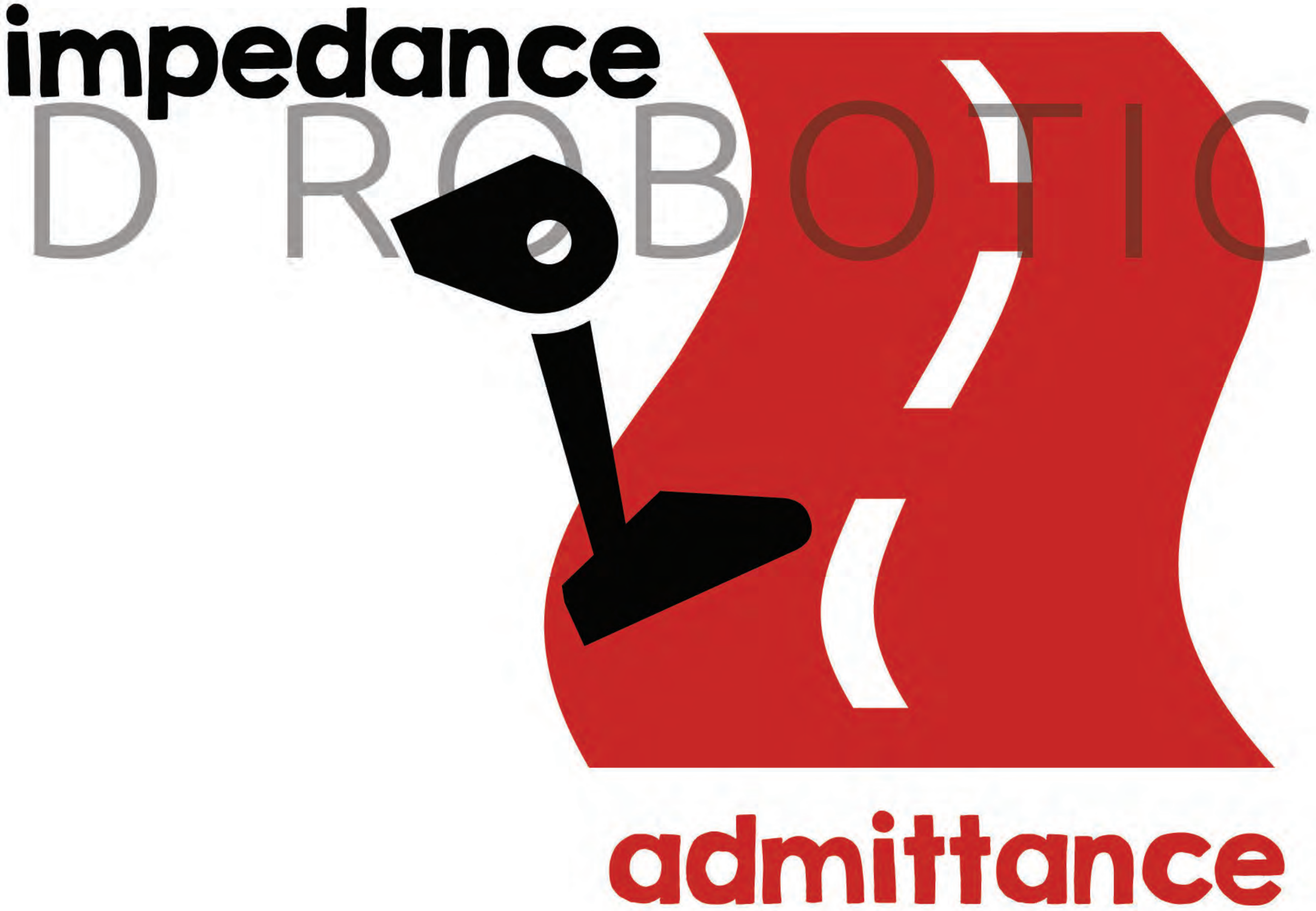

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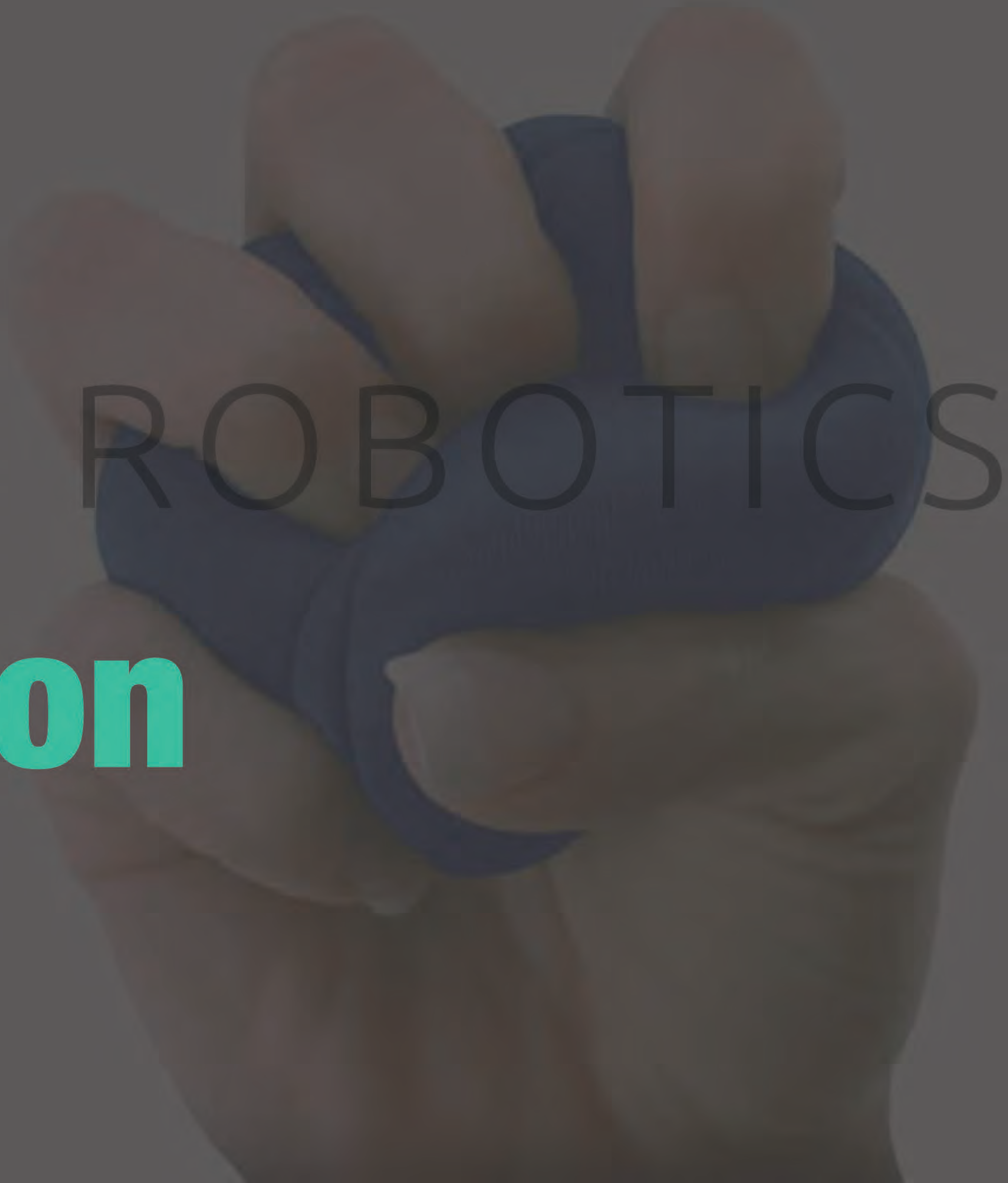
During

physical interaction,

can we control

force and position

independently?



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NO!

The object dynamics defines the force/motion relation

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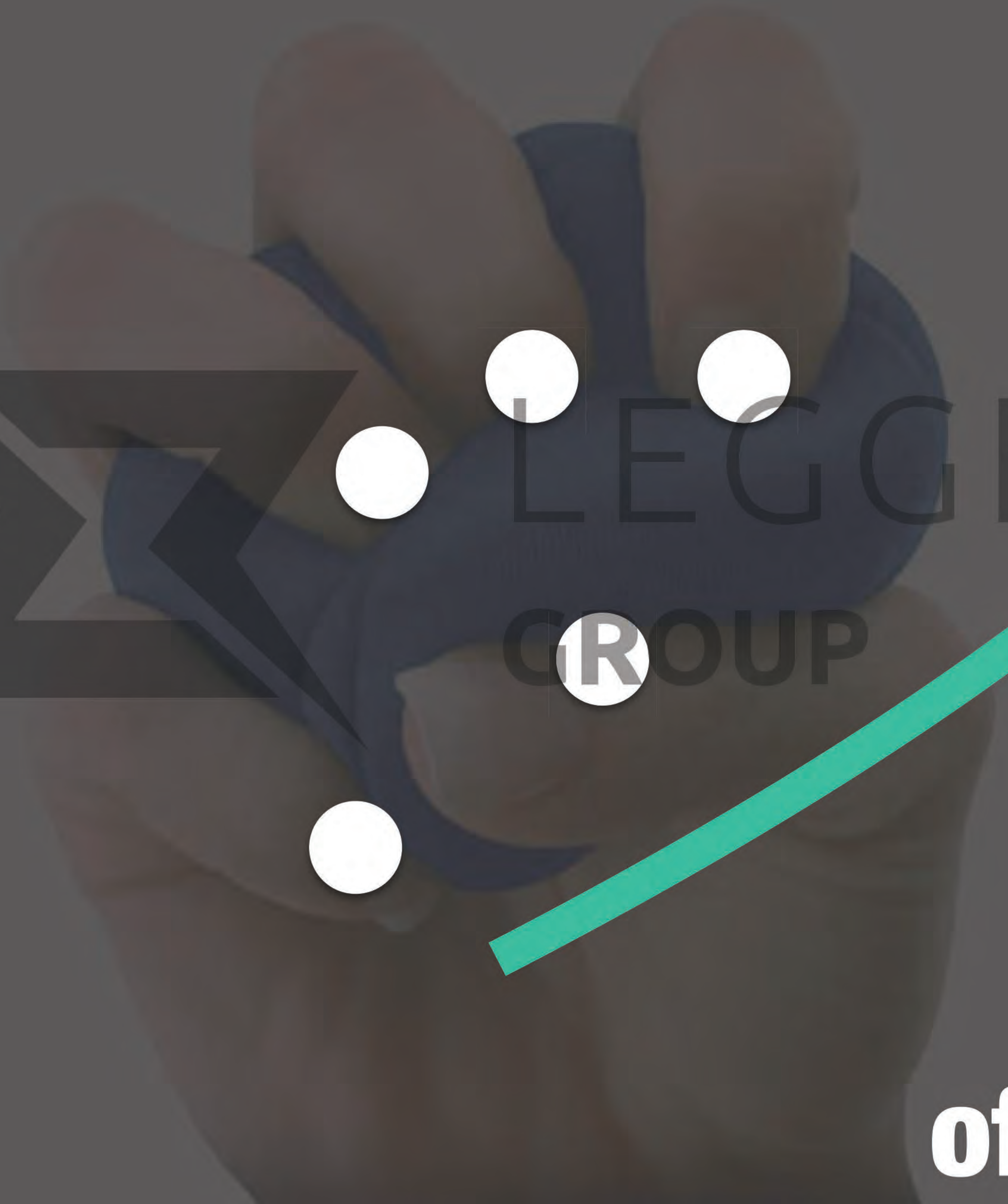

não é afetado pelo contato e interação

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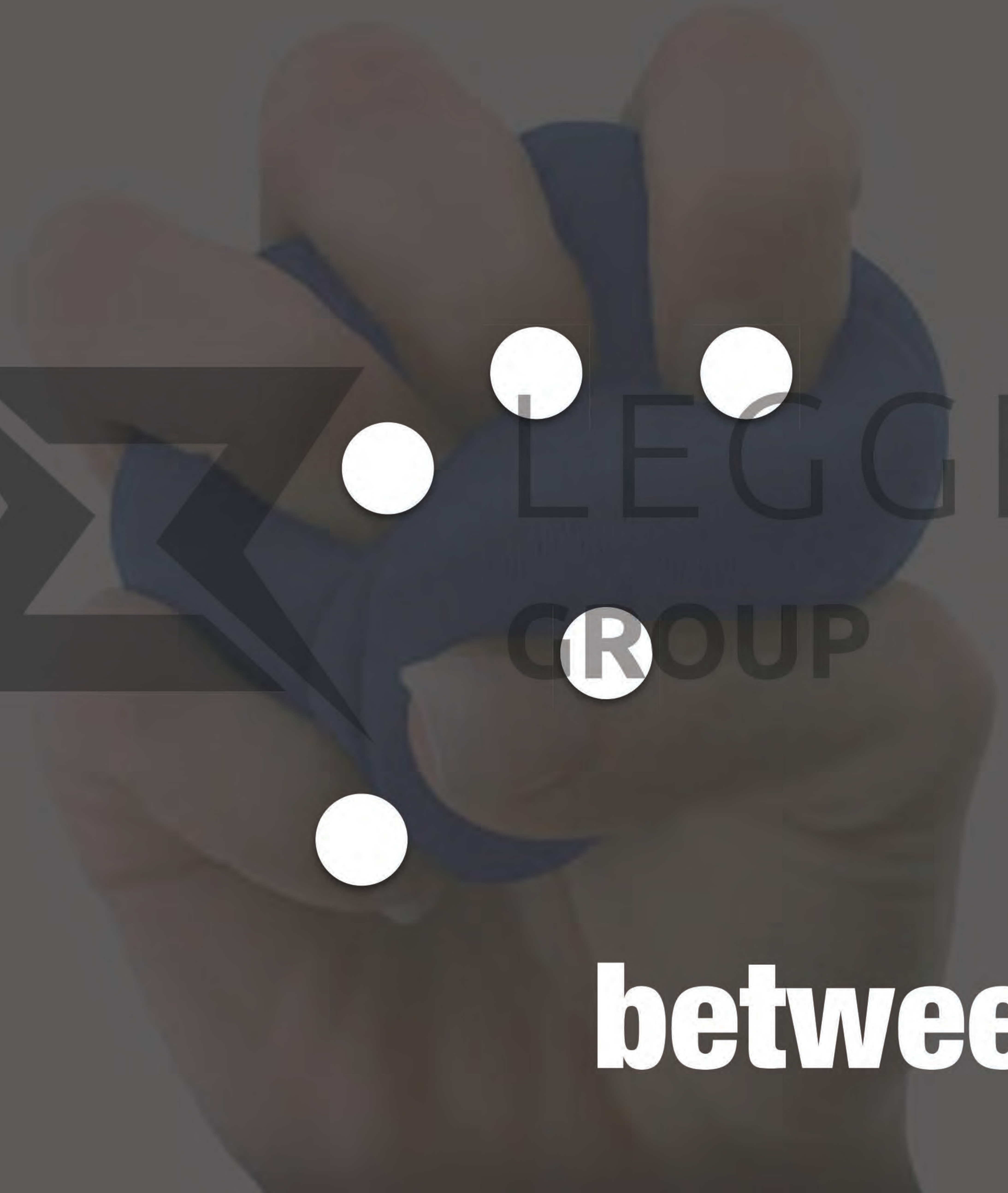
Alternative:

To control the dynamic behaviour of the interaction points



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Alternative:

To control the
dynamic behaviour
of the interaction points

i.e.

the RELATION
between force and motion

interaction control

basic principle

impedance control

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Impedance Control

Establish a **dynamic relation** between **force** and **position**

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$$F = M\ddot{x} + B\dot{x} + Kx$$

Inertia — **Damping** — **Stiffness**

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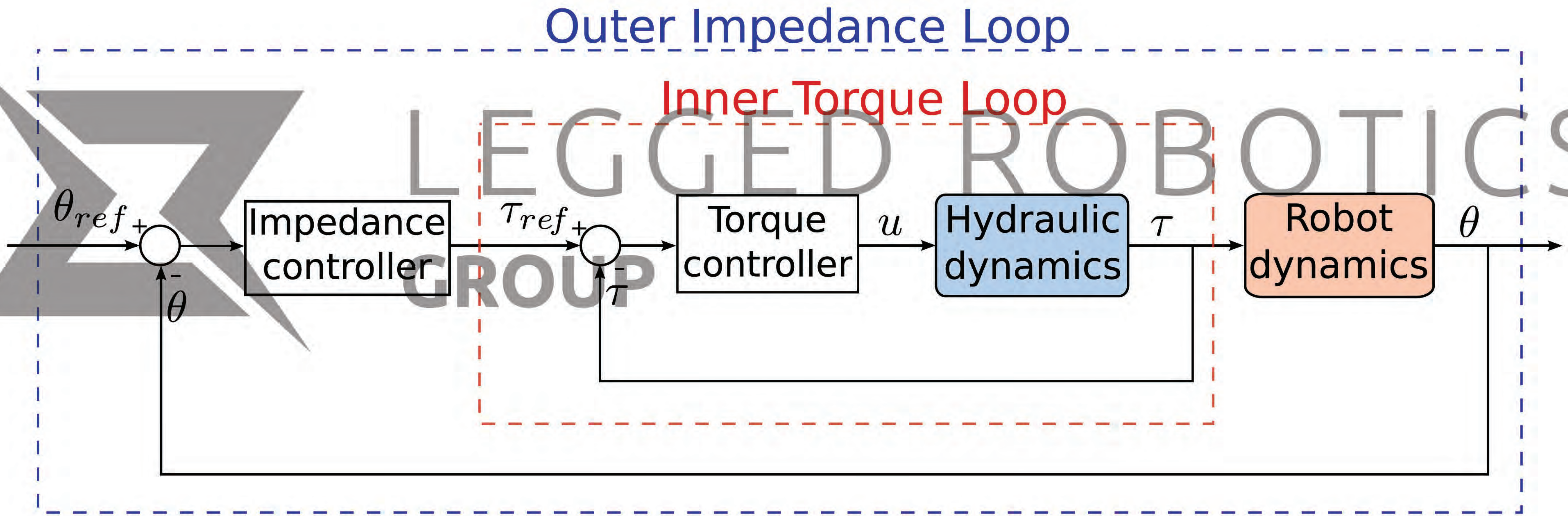
Classic Architecture



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Mimicking passive leg
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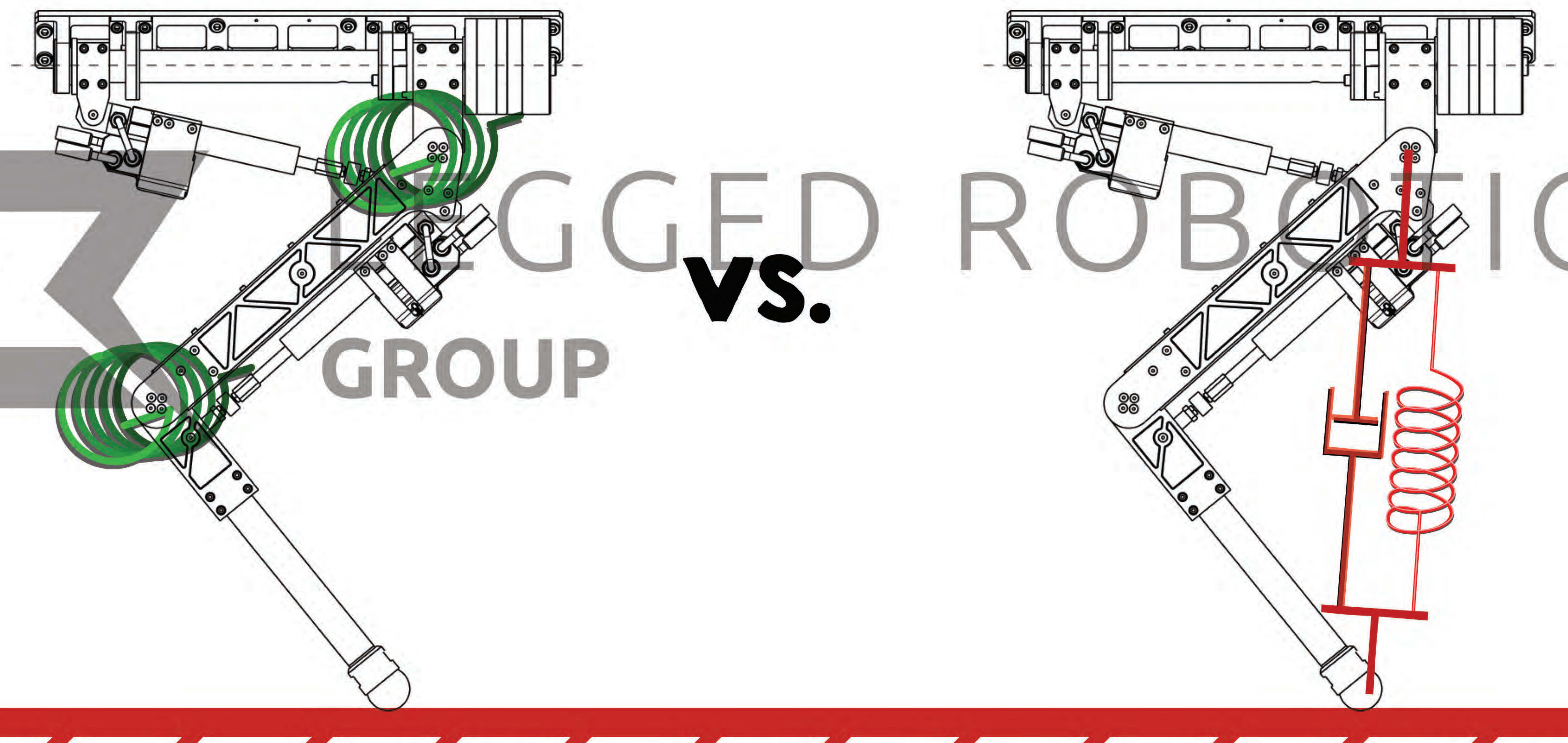
0 0
$\tau = K\theta + B\dot{\theta}$
Joint space
ETH Zürich
iit ADVR

Joint space vs. Task space



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Virtual springs:
Rotational spring at hip
Linear spring in leg
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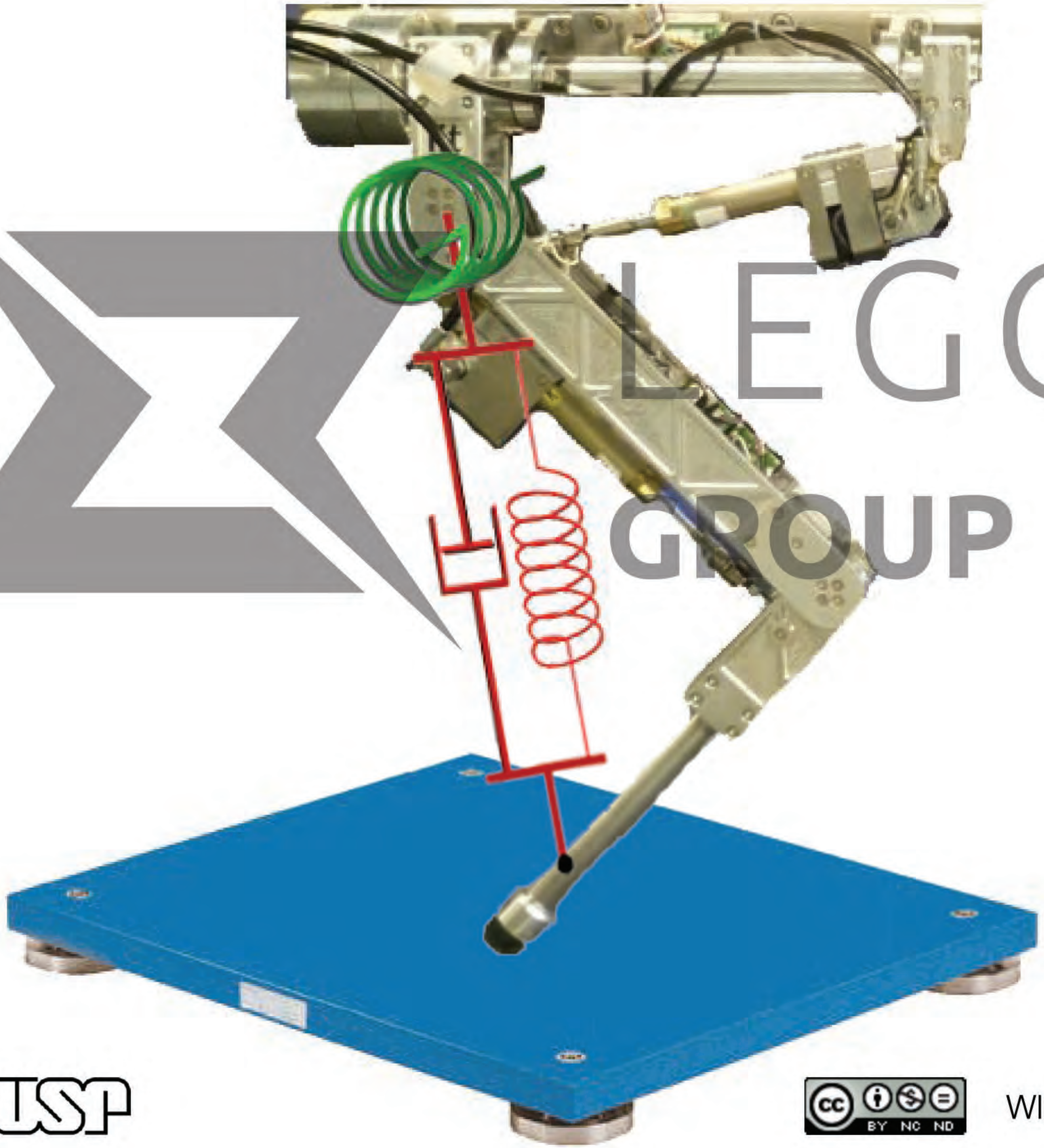
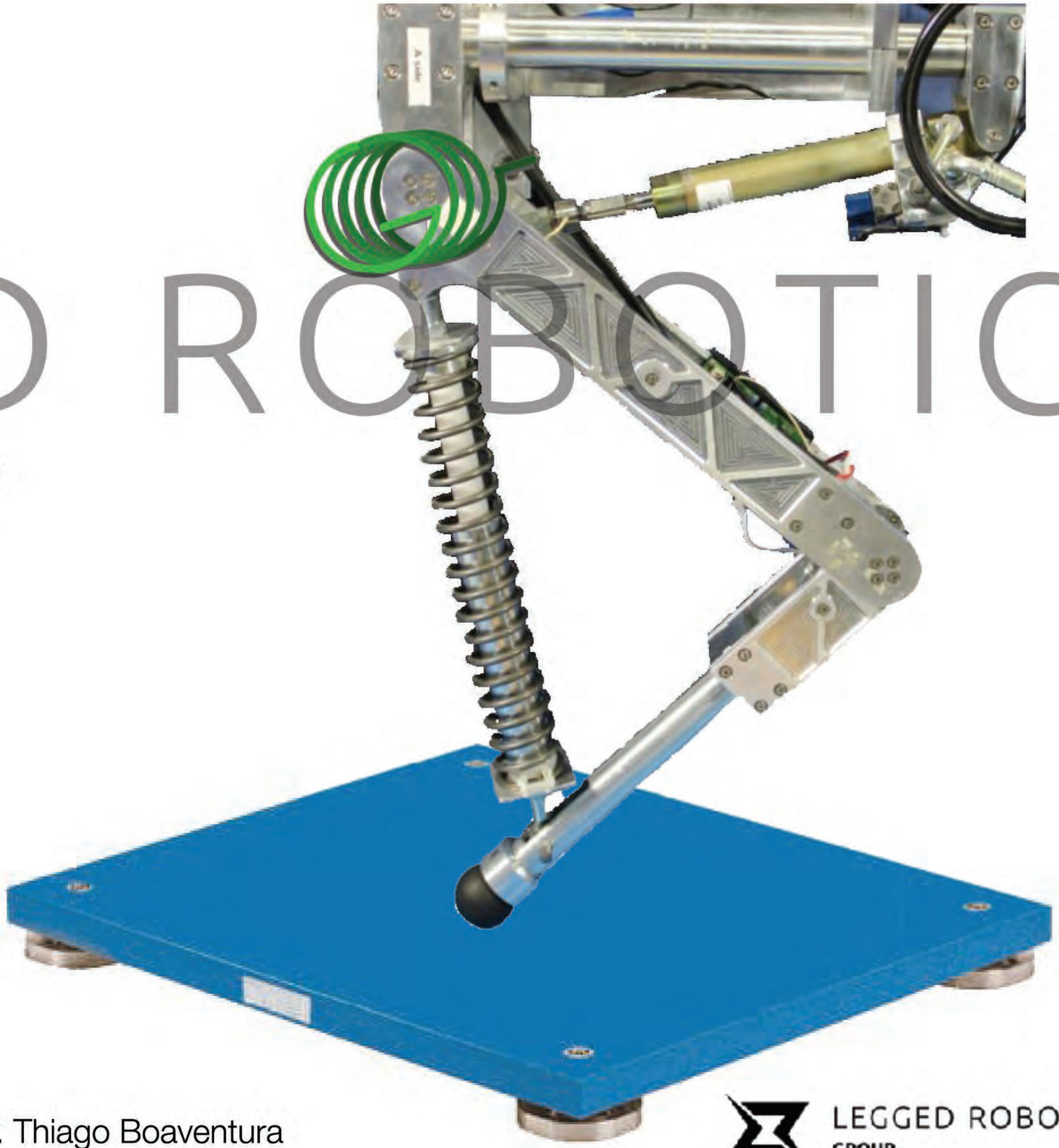
ADVR

Active impedance
(task space)



vs.

Passive impedance



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Active Impedance vs. Passive Impedance
Drop test – Speed 1/16

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ETH Zürich

iit ADVR


iit
ADVR
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Approaches to control the robot impedance

joint control	kinematic configuration	contact points

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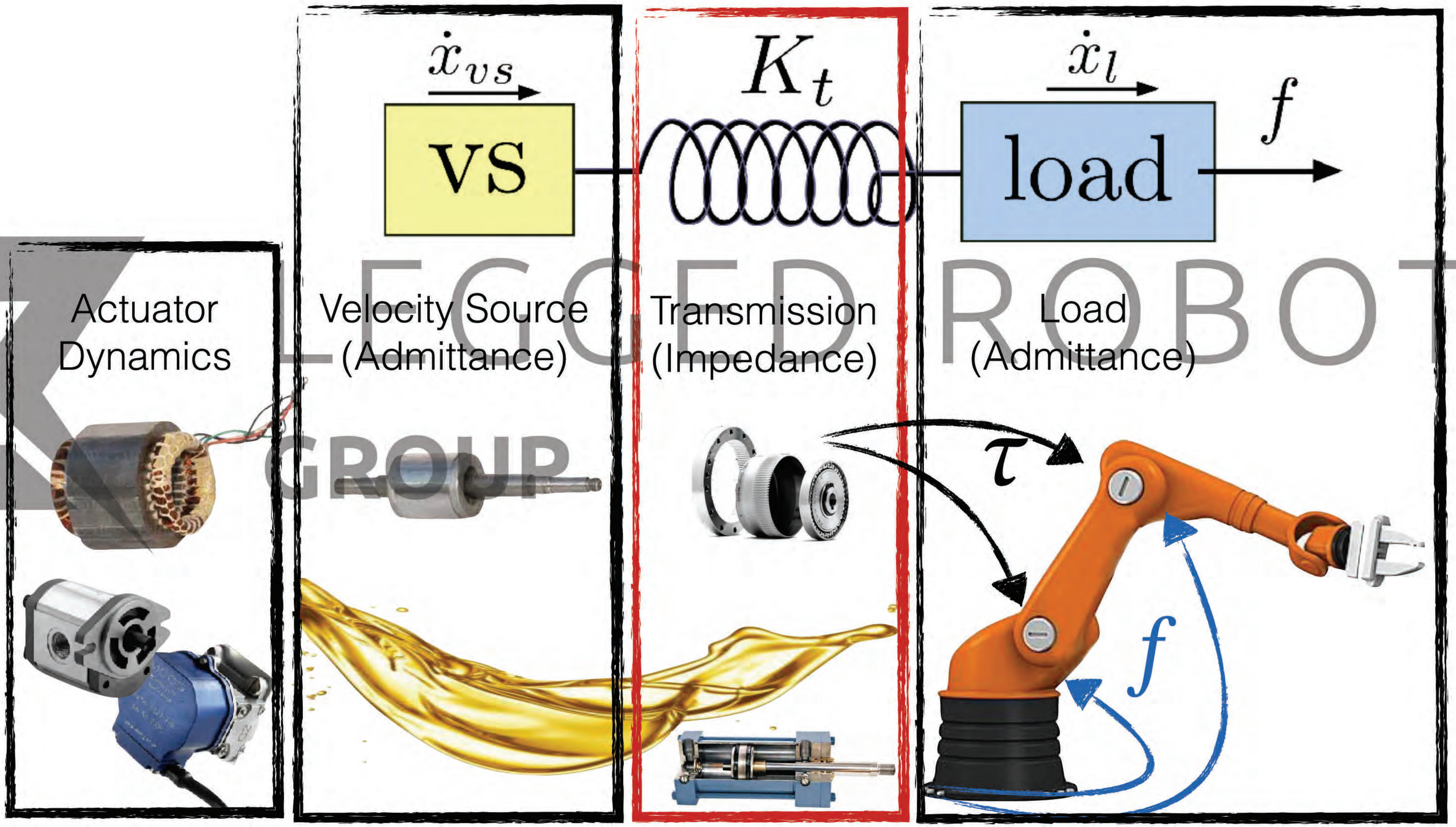
Actuation Chain



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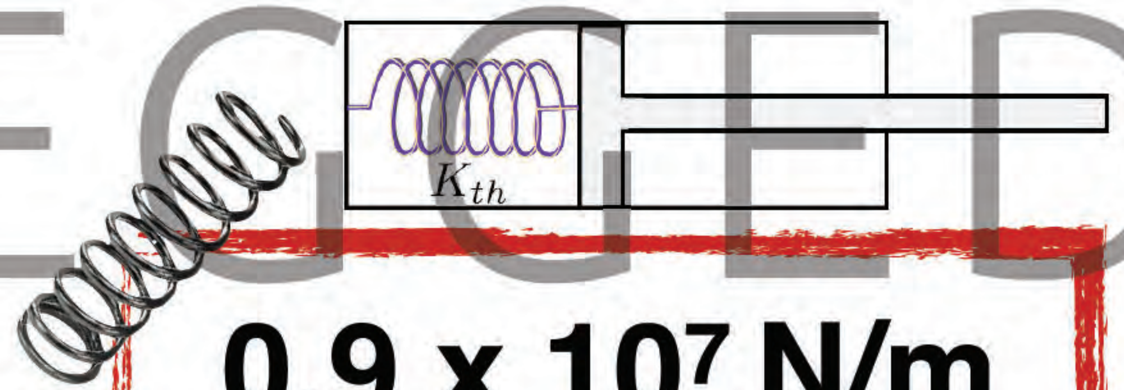
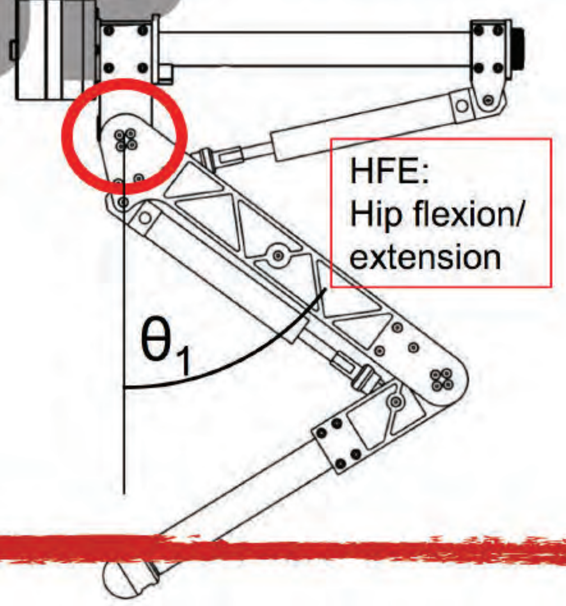
Transmission stiffness

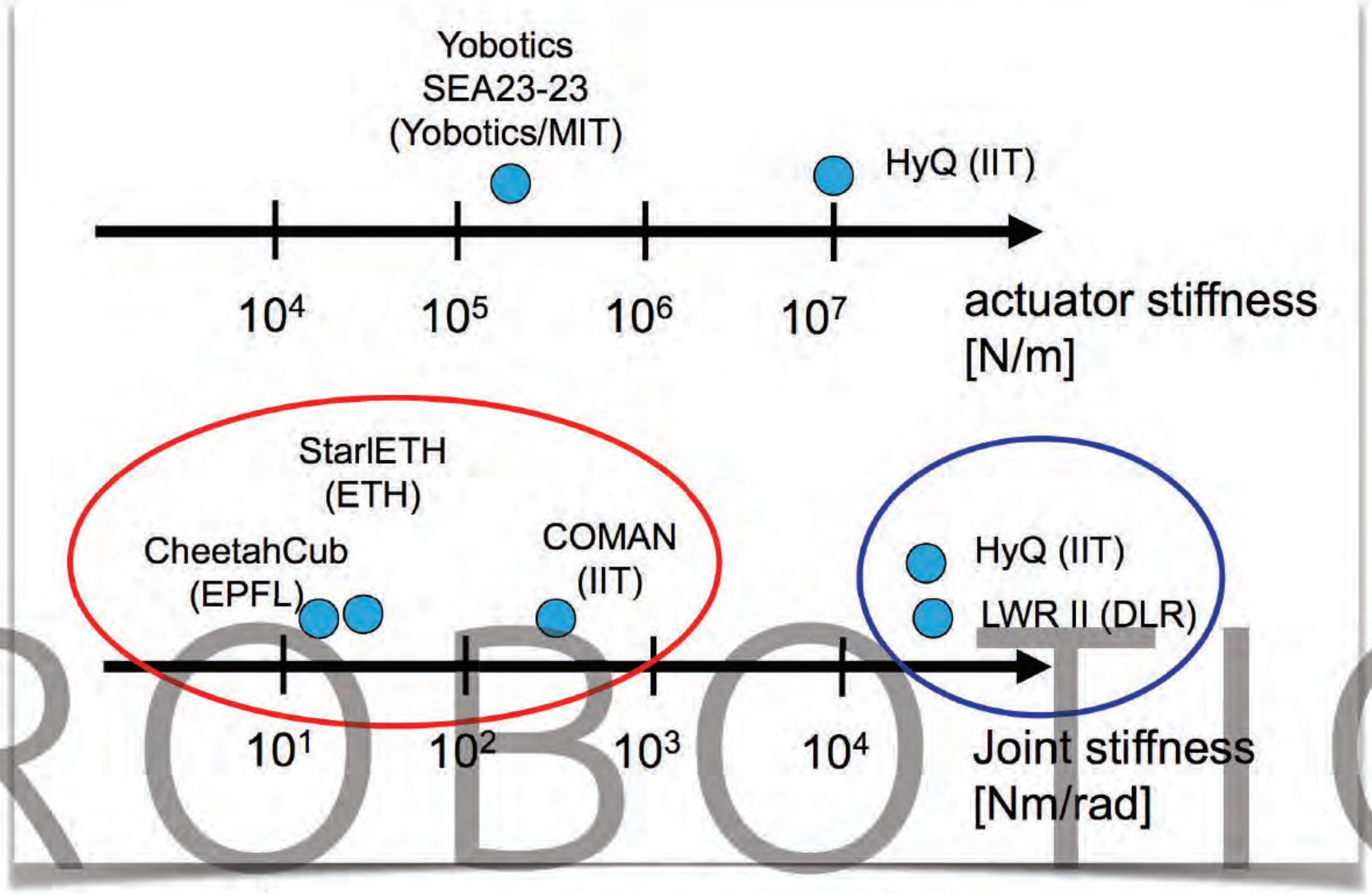
2.7 x 10⁴ Nm/rad

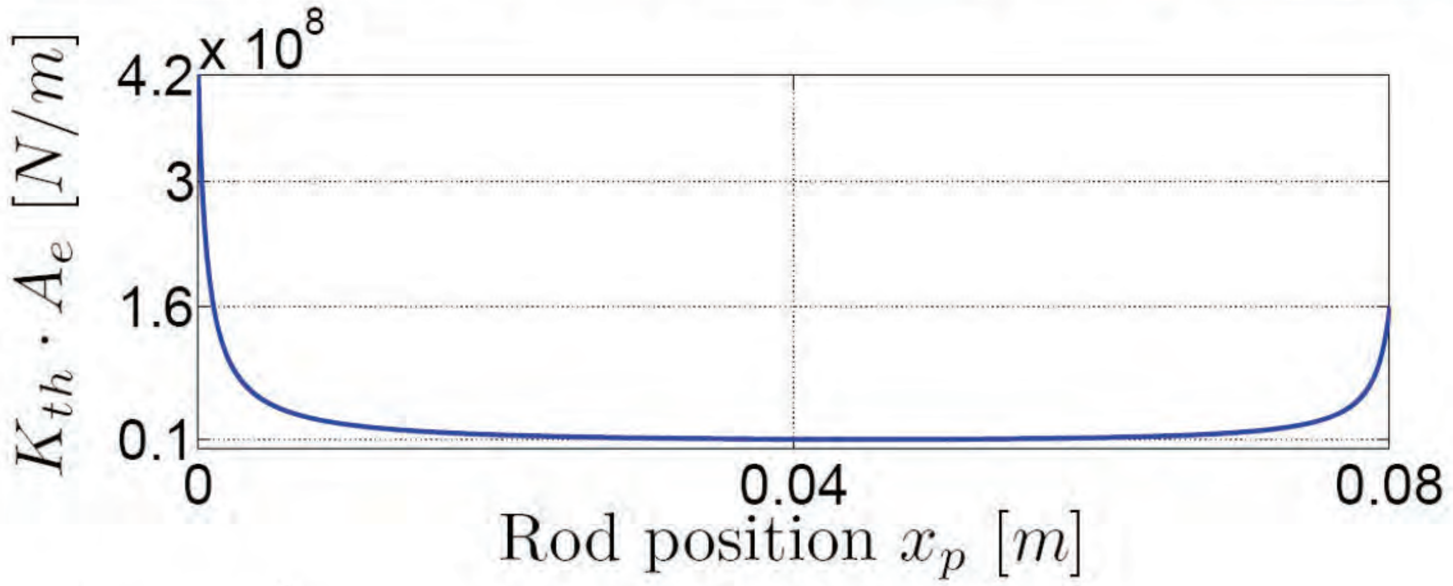


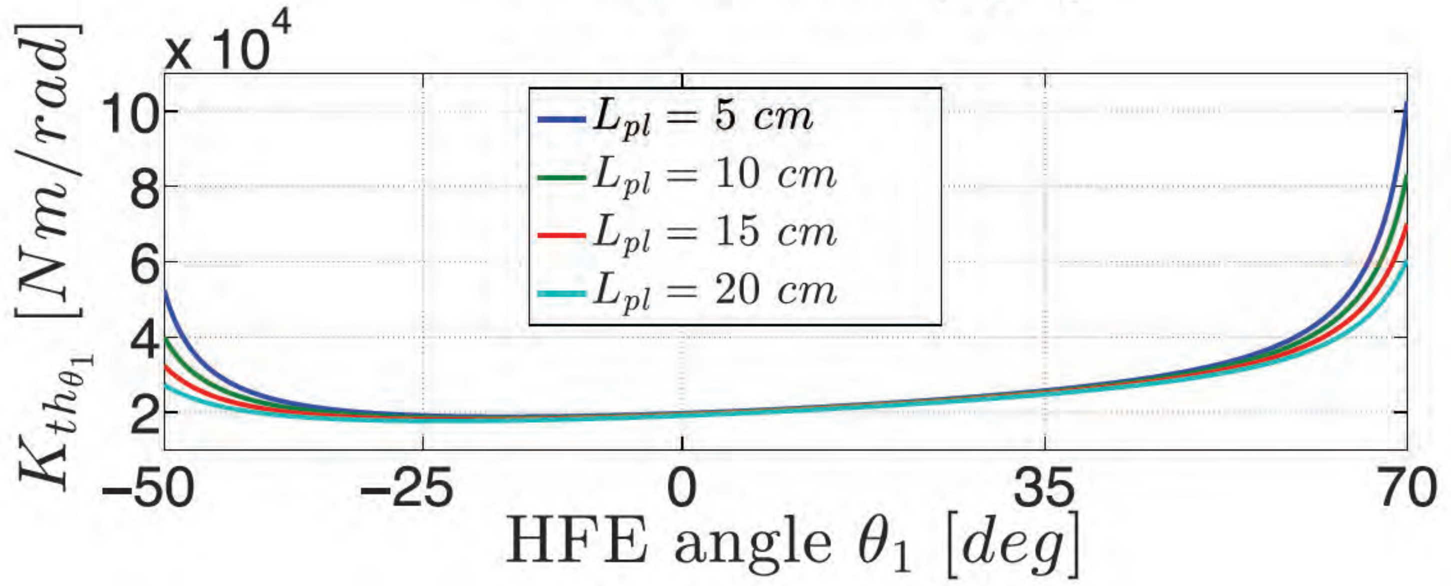
0.9 x 10⁷ N/m



2.1 x 10⁴ Nm/rad







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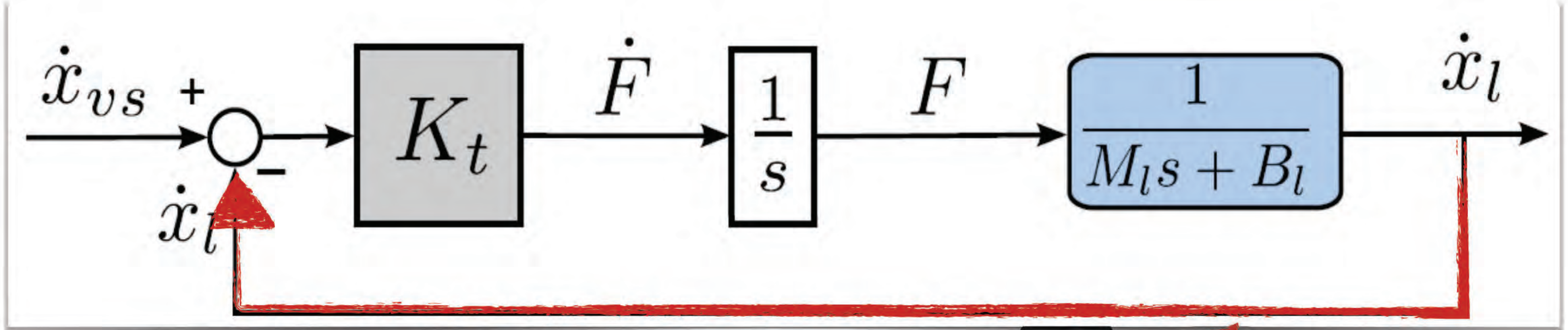
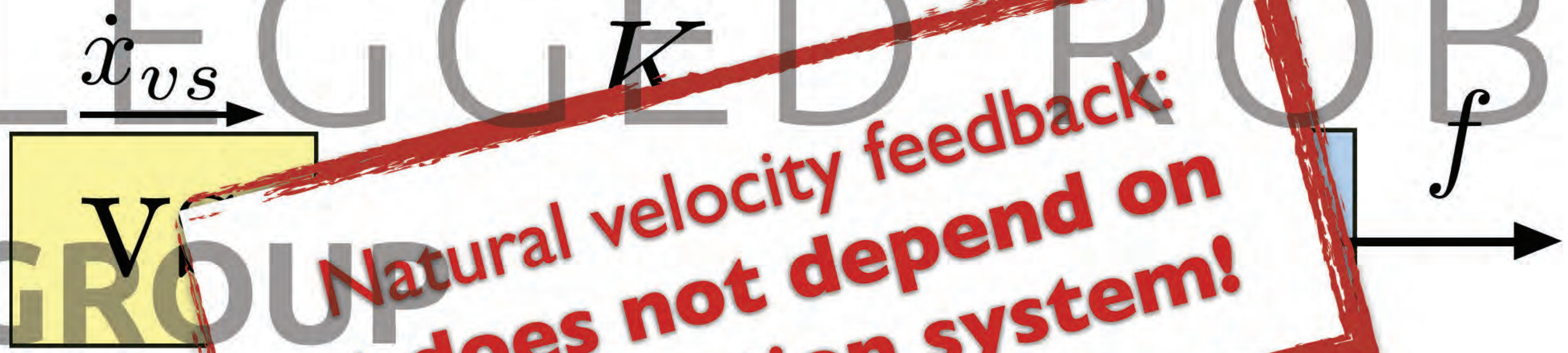
Intrinsic Velocity Feedback





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Natural velocity feedback: **it does not depend on the actuation system!**

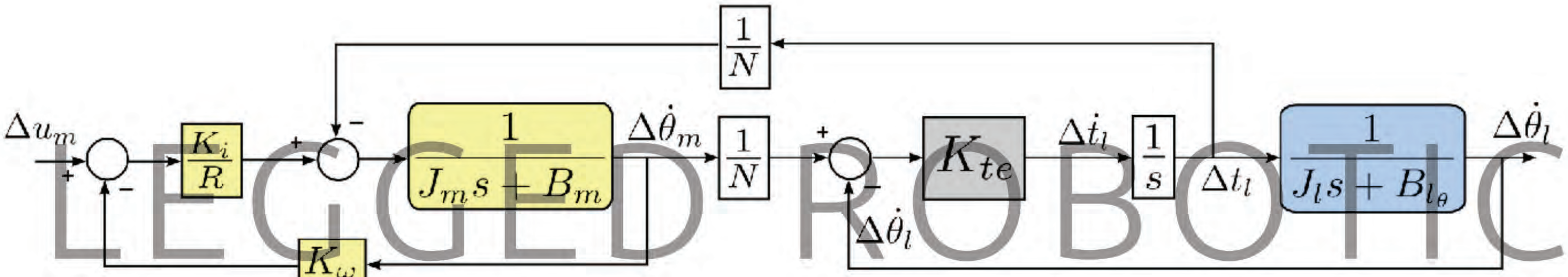
$$\dot{f} = K_t\left(\dot{x}_{vs} - \dot{x}_l\right)$$

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

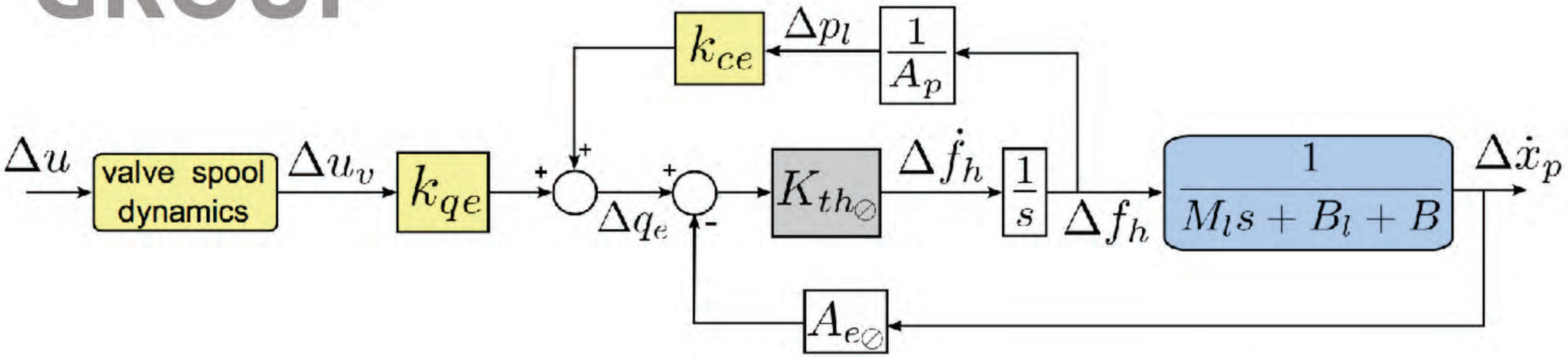
Intrinsic Velocity Feedback

Open-loop torque/force dynamics

Electric actuation



Hydraulic actuation



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

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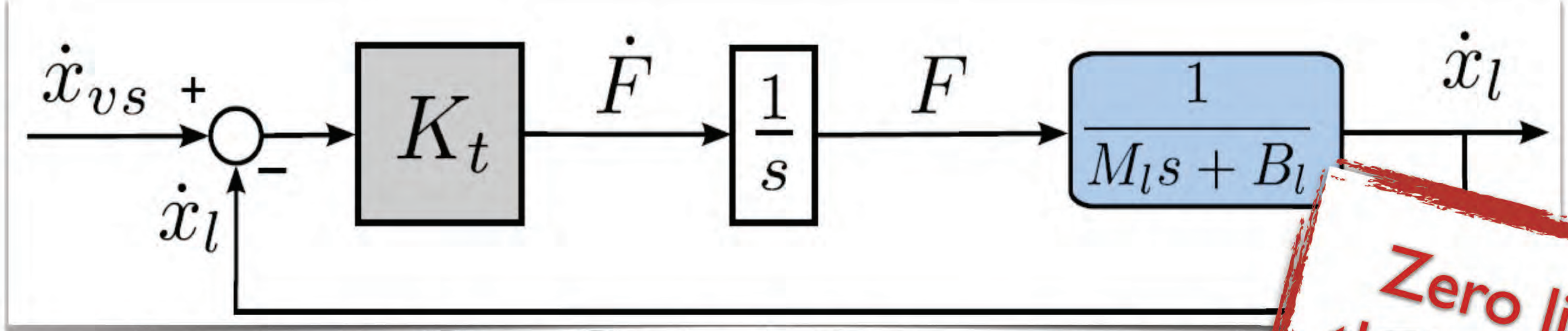
Intrinsic Velocity Feedback



Zero limits the response.

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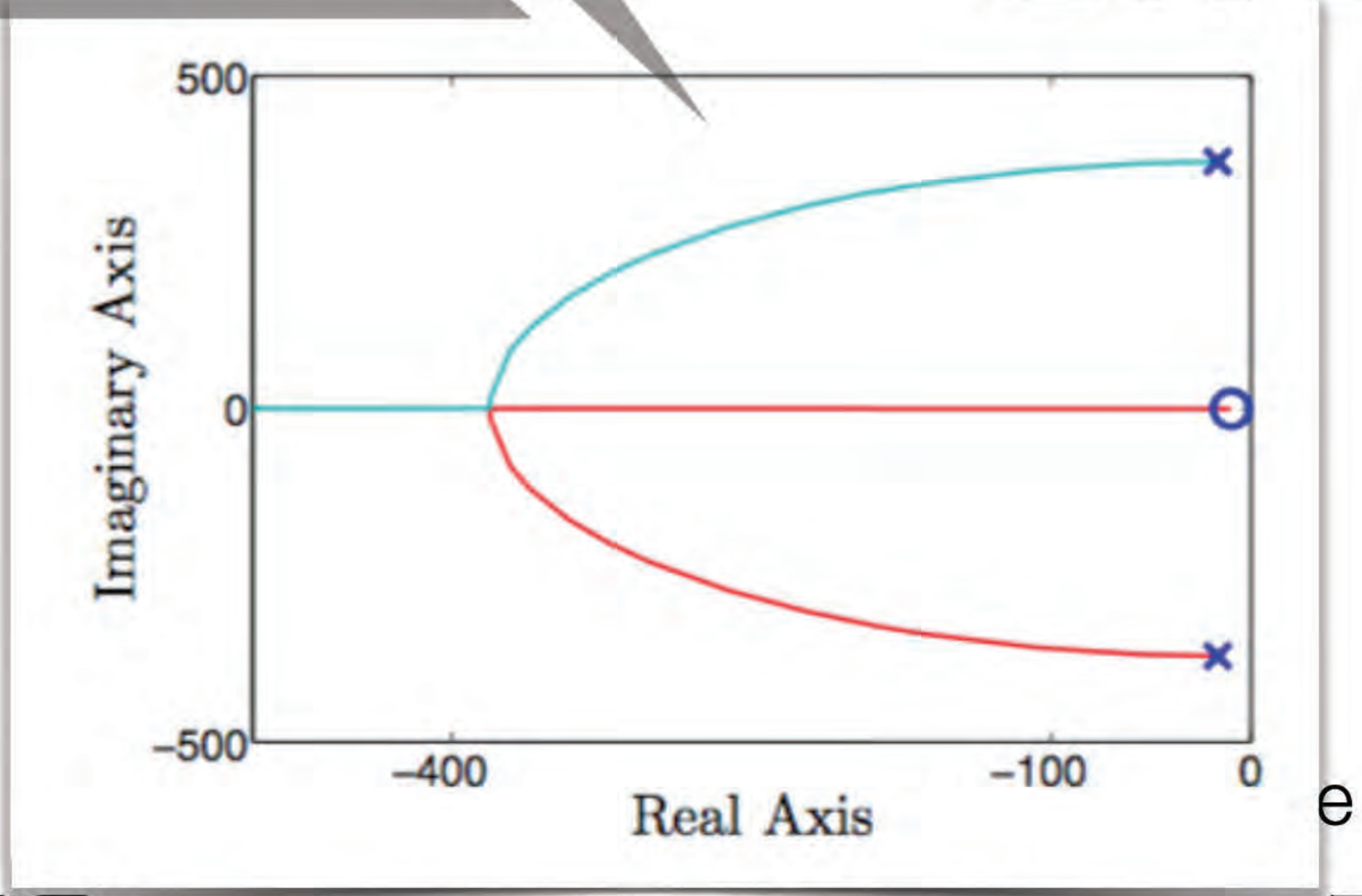
$$\frac{f(s)}{\dot{x}_{vs}(s)} = \frac{K_t\,(M_l s + B_l)}{s\,(M_l s + B_l) + K_t}$$



It does not depend on the actuation

e of load motion compensation in high-performance force control. IROS, 2012

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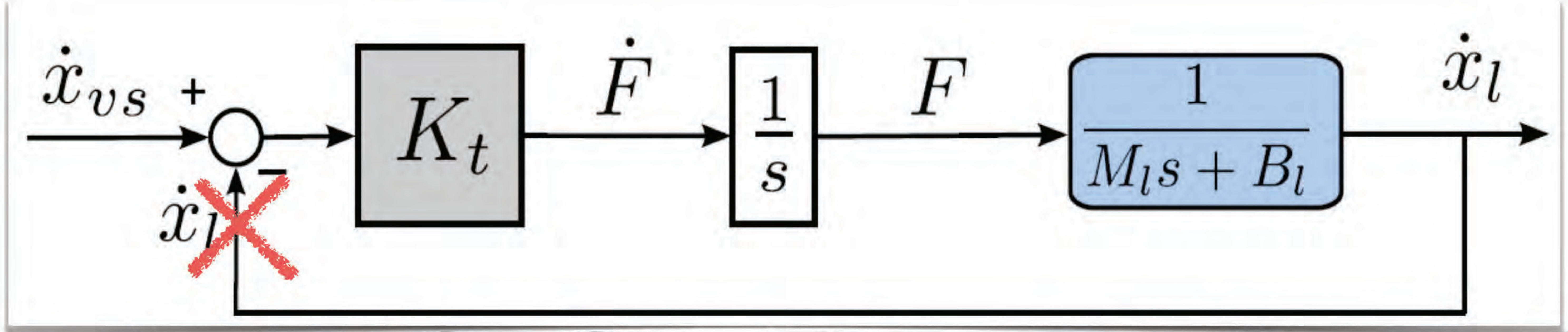
Model-based velocity compensation



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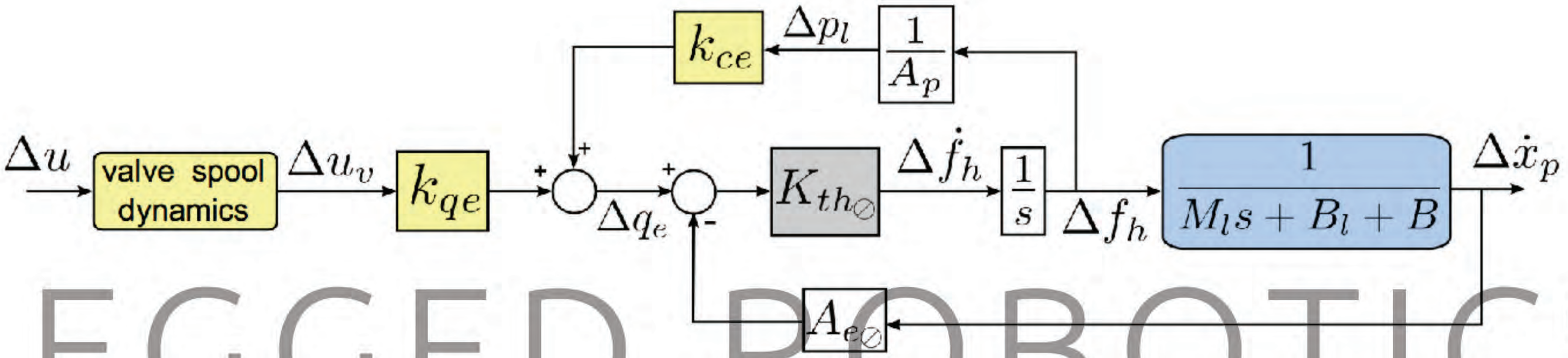
$$\frac{f(s)}{\dot{x}_{vs}(s)} = \frac{K_t\,(M_l s + B_l)}{s\,(M_l s + B_l) + K_t} = \frac{K_t}{s}$$

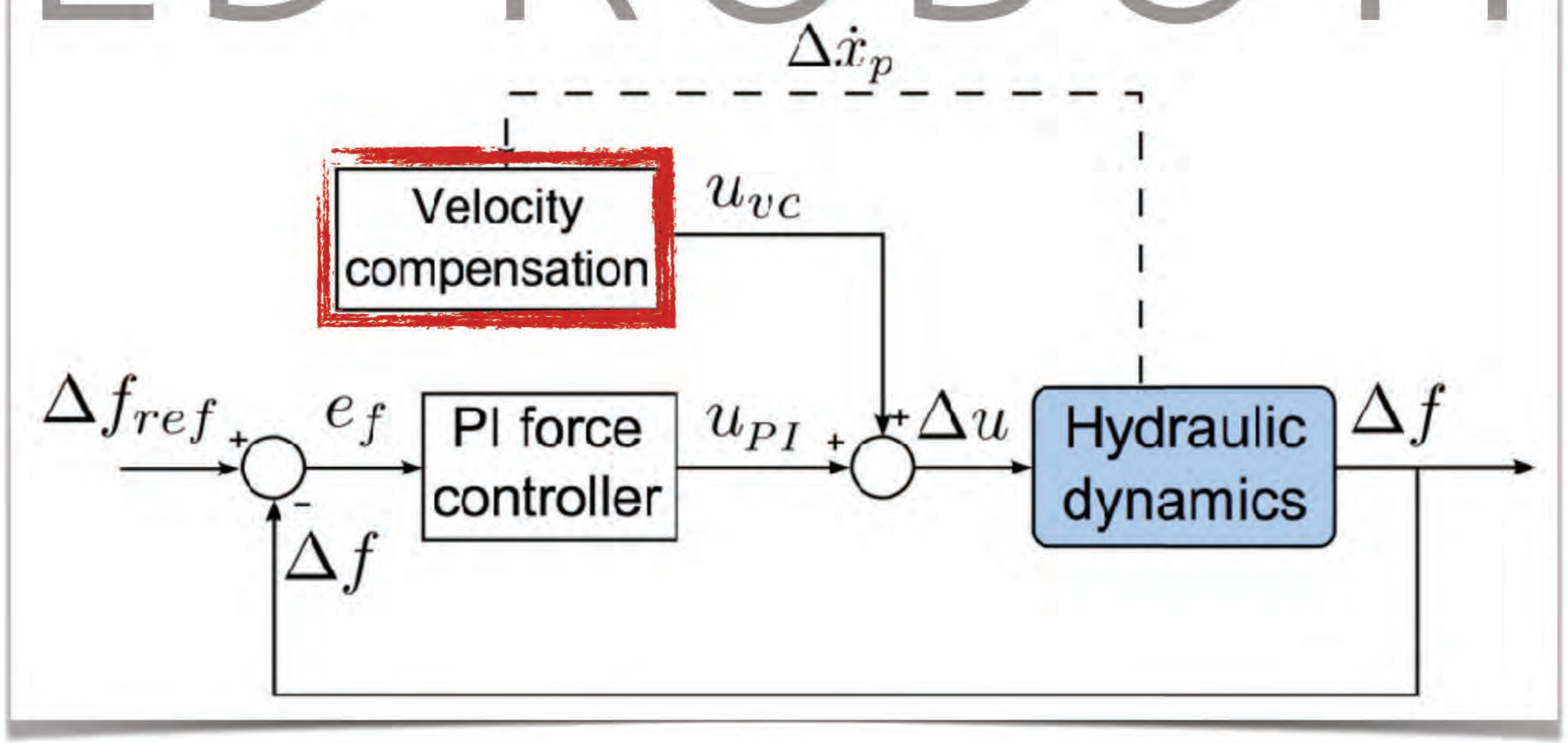
$$\dot{x}_{ex} = \dot{x}_l$$

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

Model-based velocity compensation

Hydraulic actuation





Feedforward command:

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

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

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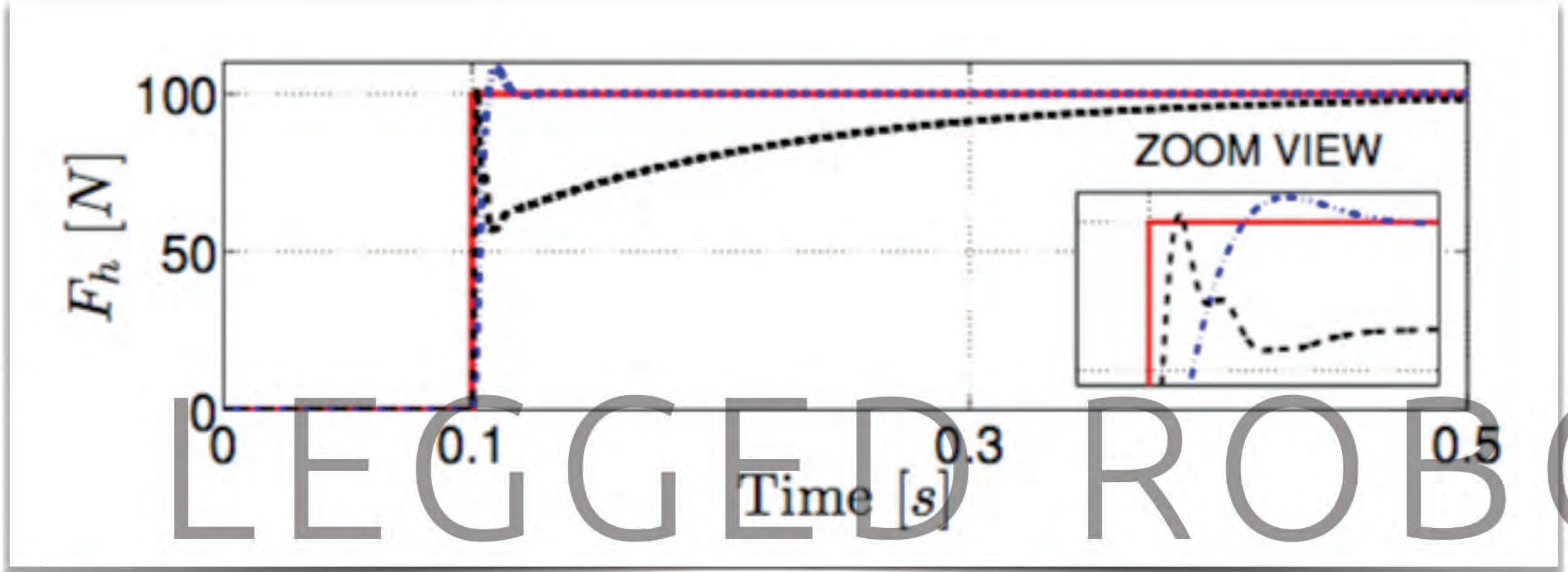
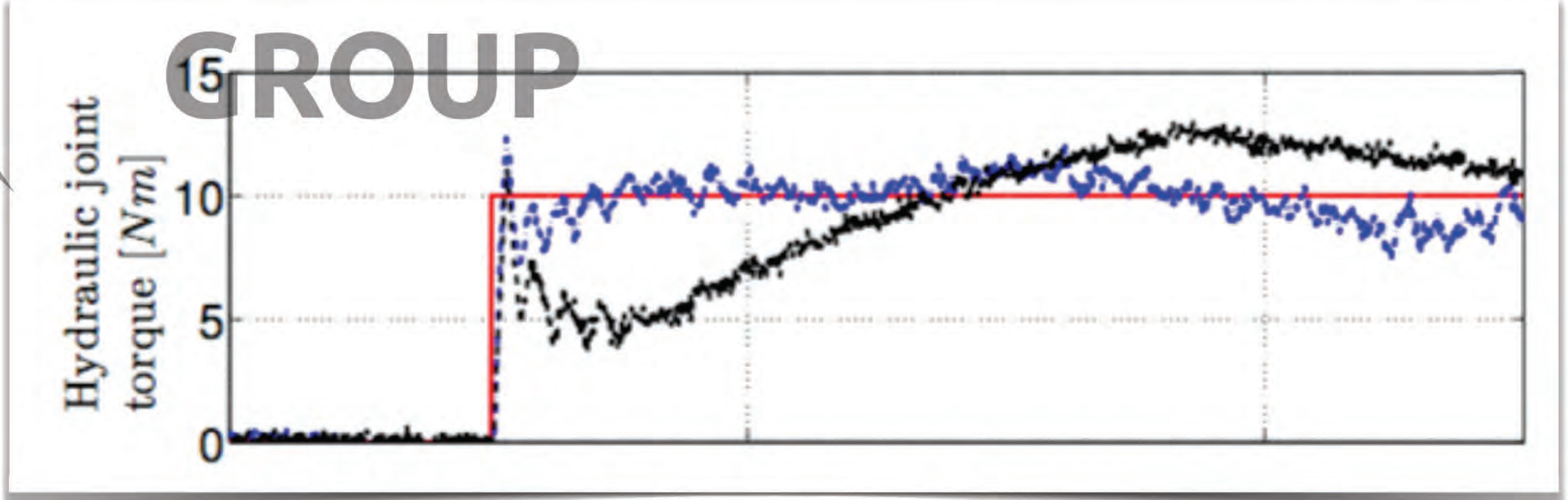
Model-based velocity compensation





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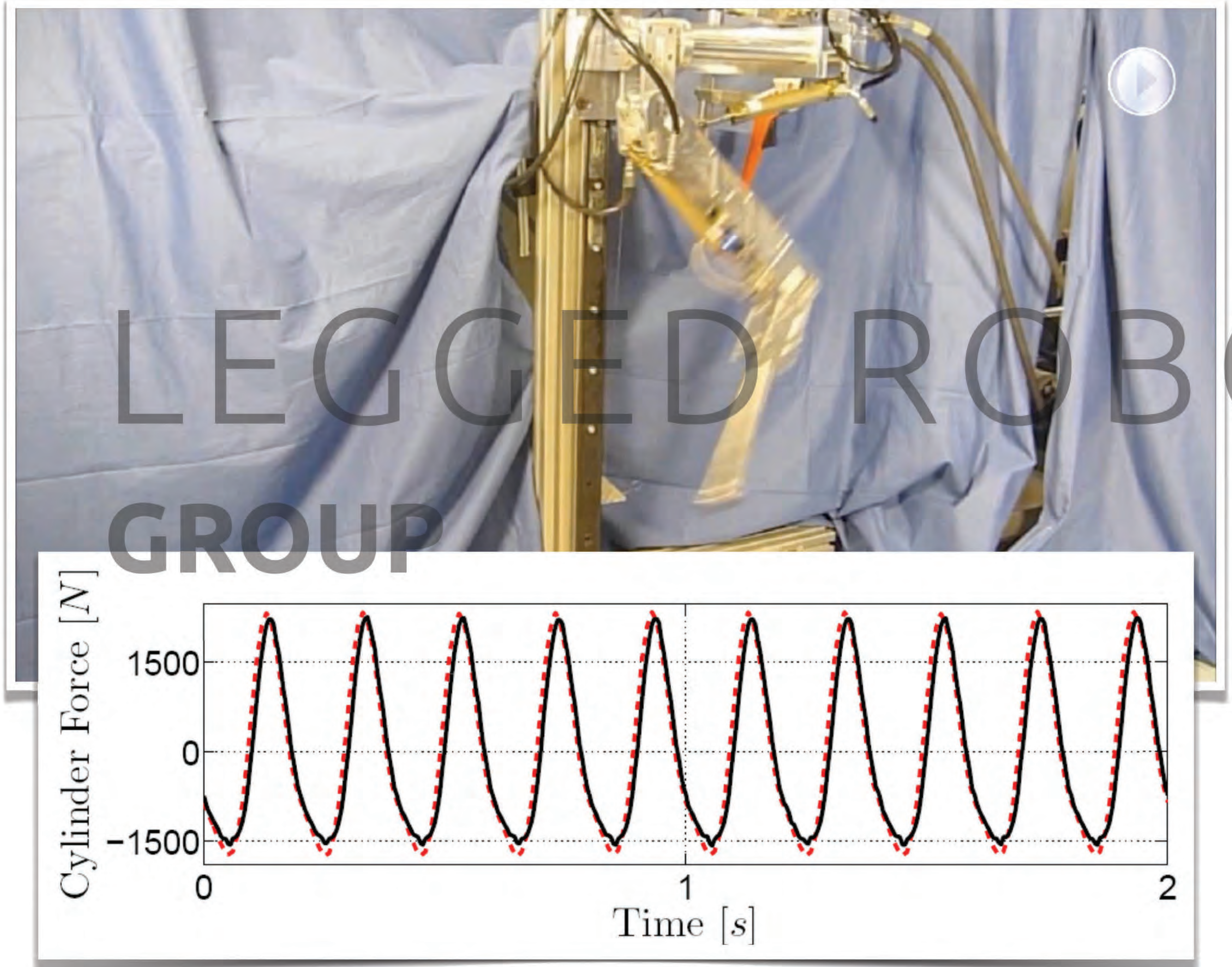
Boaventura, T., et al. On the role of load motion compensation in high-performance force control. IROS, 2012

Model-based velocity compensation



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Model-based velocity compensation

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Take-home message

controlling
impedance is not
controlling **force**…

… neither controlling
position…

but their **relation**.

Talk on "Interaction Control for Contact Robotics" by Neville Hogan

https://www.youtube.com/watch?v=GjKy3EFs3g8
https://www.youtube.com/watch?v=Dkc1LkTDXXk&t=2693s

Hogan, N. (1985). Impedance control: An approach to manipulation: Part II—Implementation. Journal of dynamic systems, measurement, and control

Hogan N, Buerger S. P. Impedance and interaction control. Robotics and automation handbook. 2005;1

Calanca, A., et al. (2016). A review of algorithms for compliant control of stiff and fixed-compliance robots. IEEE/ASME Transactions on Mechatronics

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

Ott, C., Mukherjee, R., & Nakamura, Y. (2010). Unified impedance and admittance control. ICRA, 2010, pp. 554-561.

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That's all Folks!