EESC · USP
Escola de Engenharia de São Carlos
Universidade de São Paulo

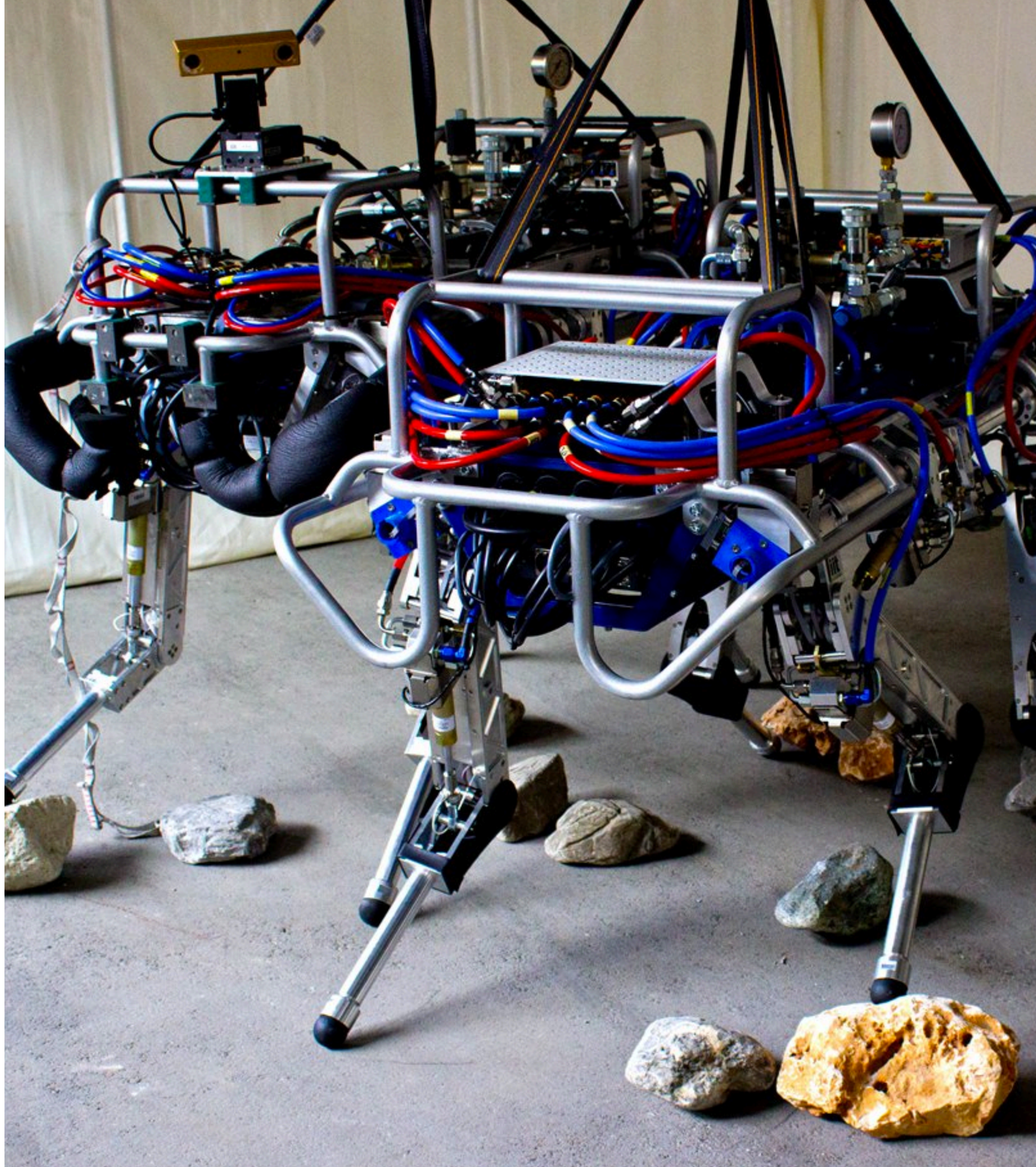
ARC Lab
Advanced Robotics Control Laboratory

SEM5950 - SEM0586
Legged Robots

Aula #10: Estabilidade e passividade de controladores de impedância

Prof. Dr. Thiago Boaventura
tboaventura@usp.br

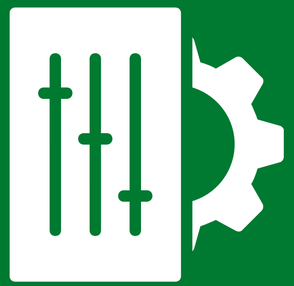
São Carlos, 09/11/20



Conteúdo

- Controlador de impedância
- Controlador de força

Revisão



- Estabilidade da interação
- Passividade
- Z-width

Estabilidade

- Take-home messages
- Bibliografia

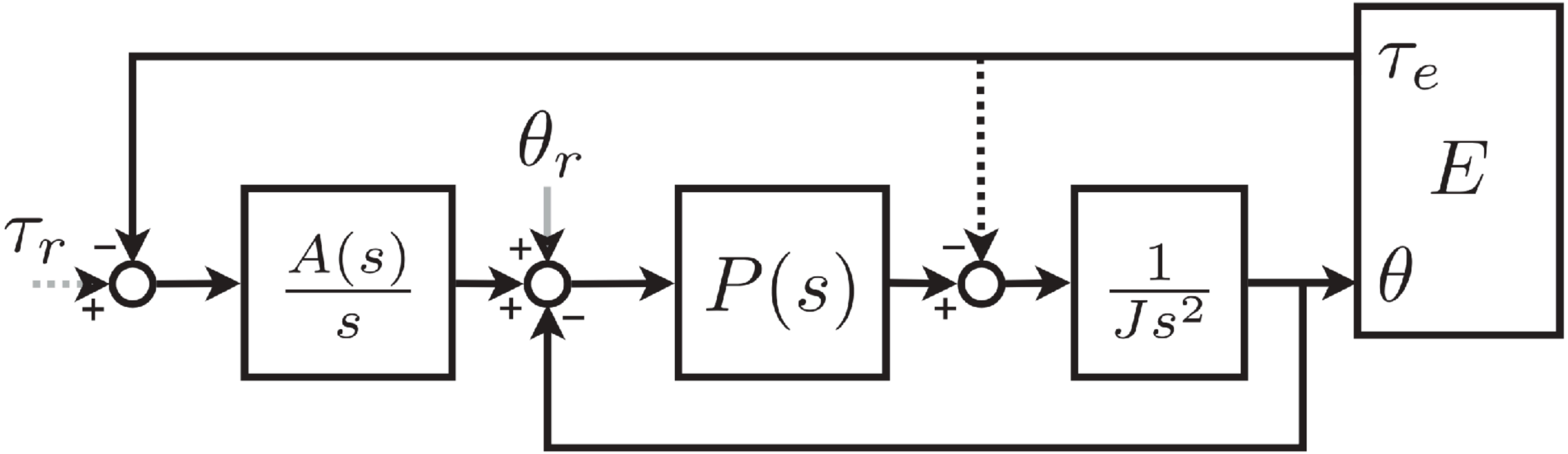
Conclusão

Conteúdo

- Controlador de impedância
- Controlador de força

Controlador de admitância

“Controlador de impedância baseado em posição”



Controlador de admitância

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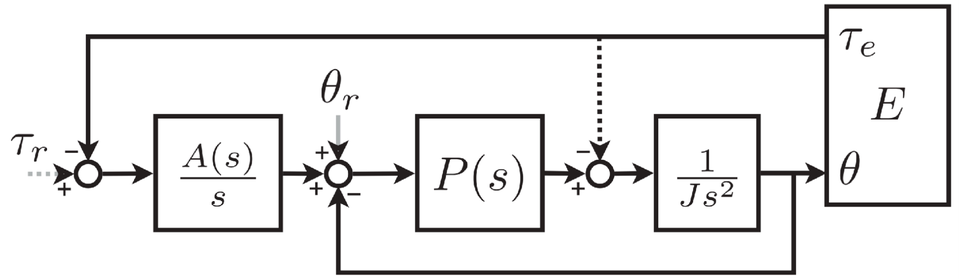

	Impedance	Admittance
Transfer function definition	$z(s) = \frac{f(s)}{v(s)}$	$a(s) = \frac{1}{z(s)} = \frac{v(s)}{f(s)}$
Spring	k/s	s/k
Mass	ms	$1/ms$
Damper	b	$1/b$
Spring-mass-damper	$ms + b + k/s$	$\frac{1}{ms+b+k/s}$

Controlador de admitância

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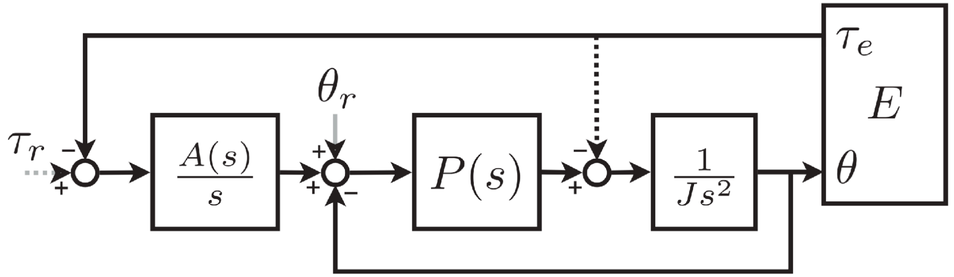

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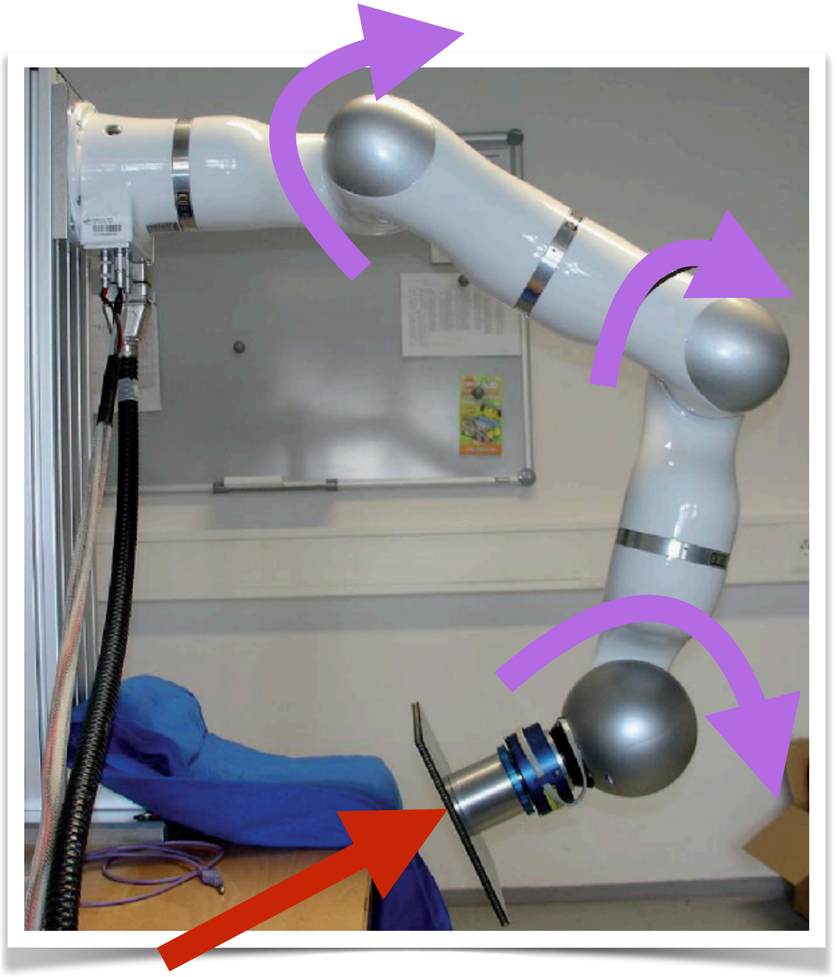
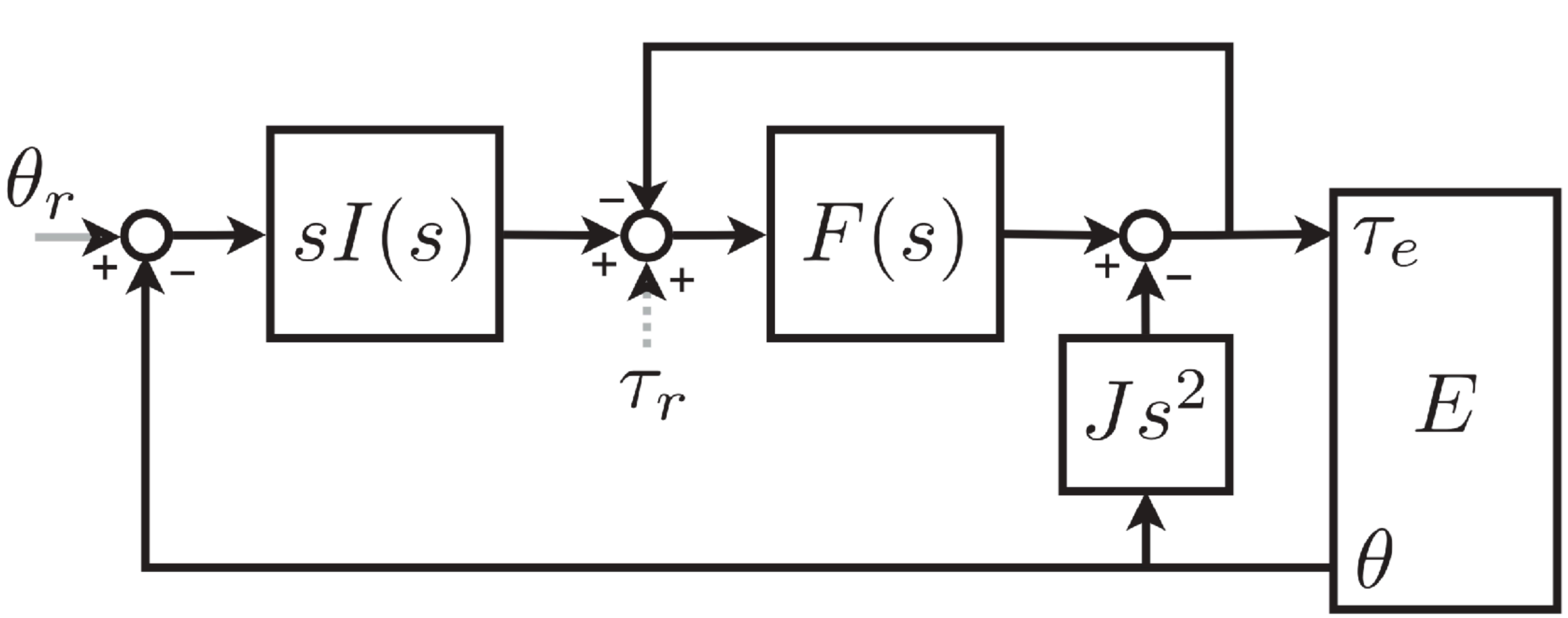


Controlador de impedância

“Controlador de impedância baseado em força”



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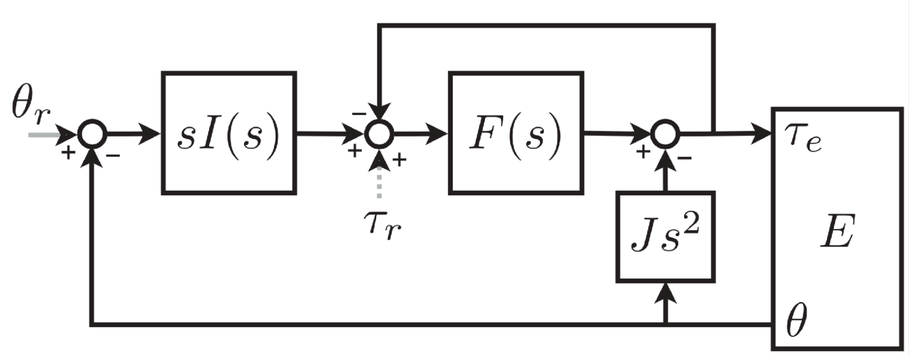

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Controlador de impedância

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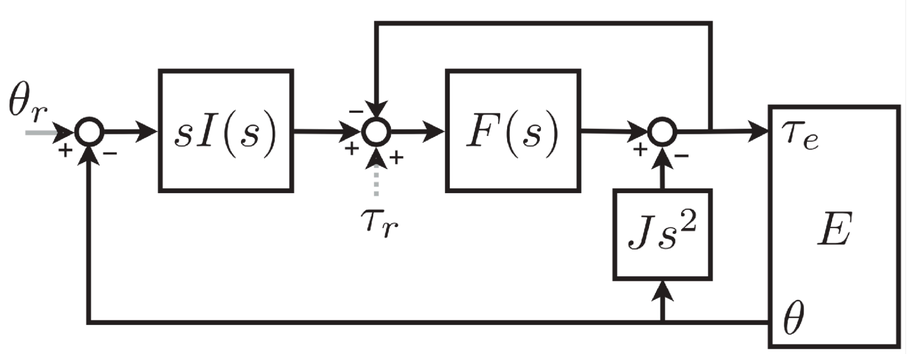

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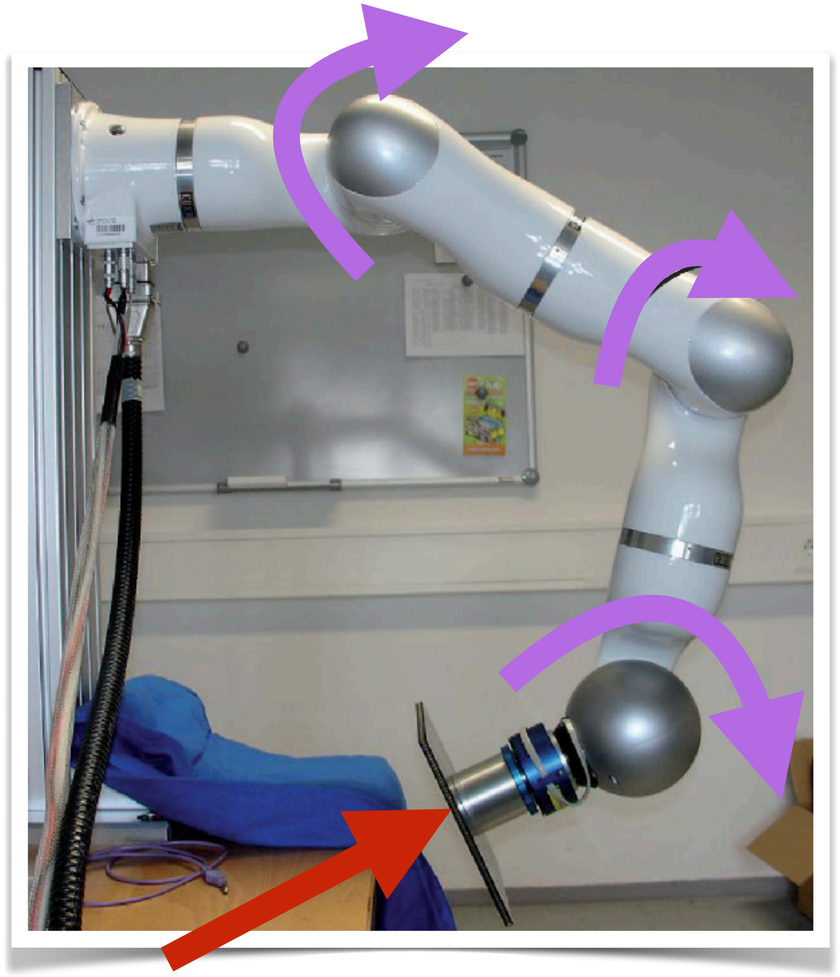

Controlador de impedância

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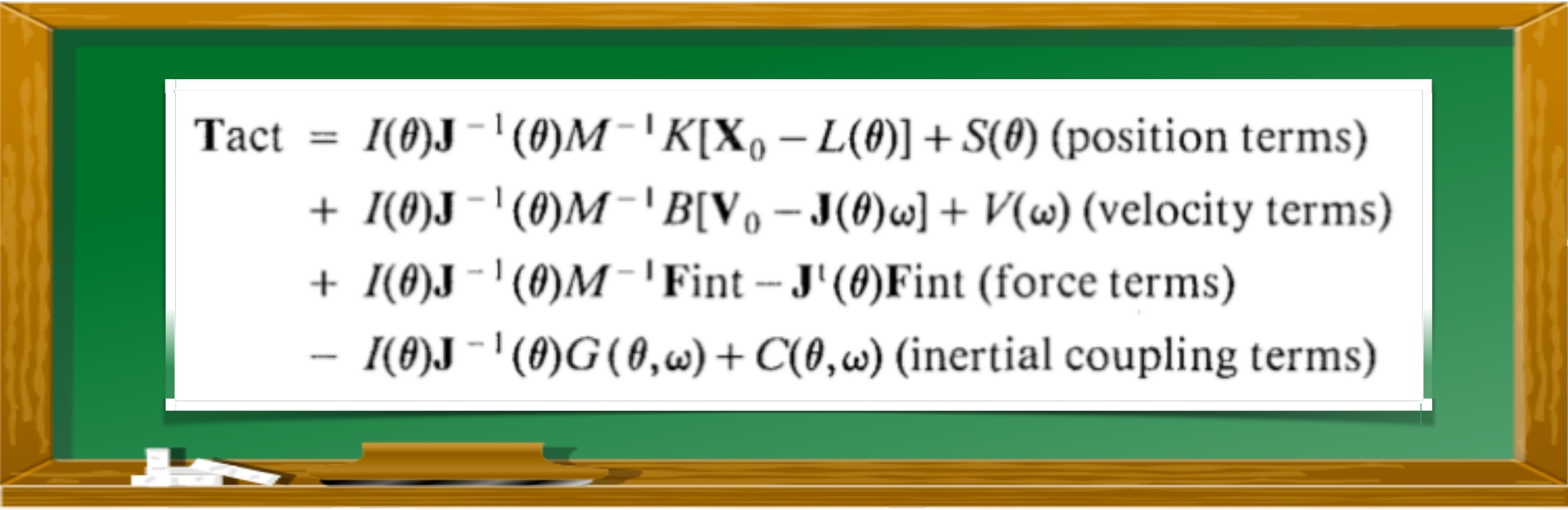
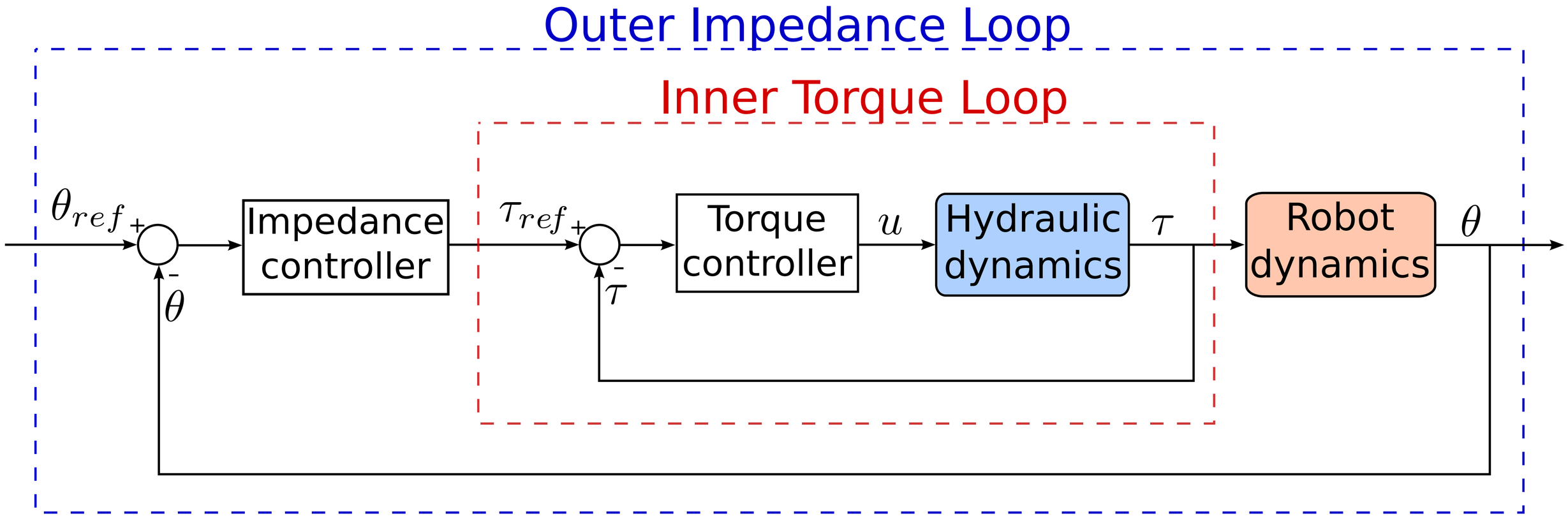
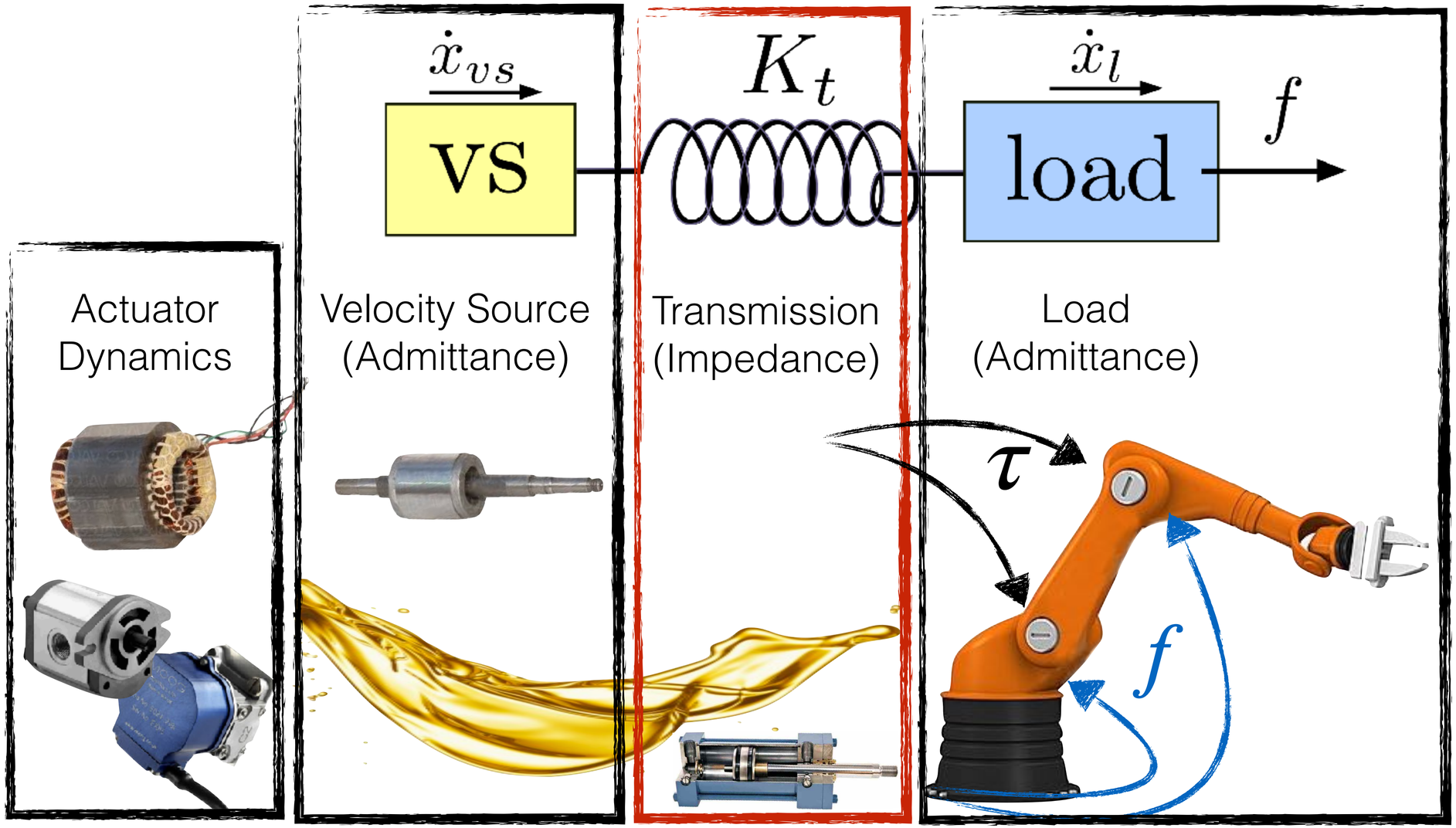


Hogan, N. (1985). Impedance control: An approach to manipulation: Part II—Implementation. Journal of dynamic systems, measurement, and control, 107(1), 8-16.

Arquitetura clássica



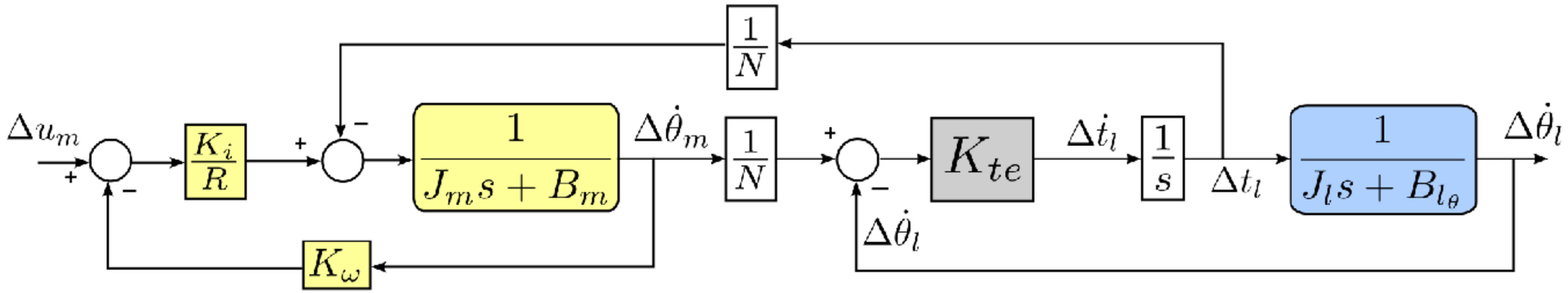
Cadeia de atuação



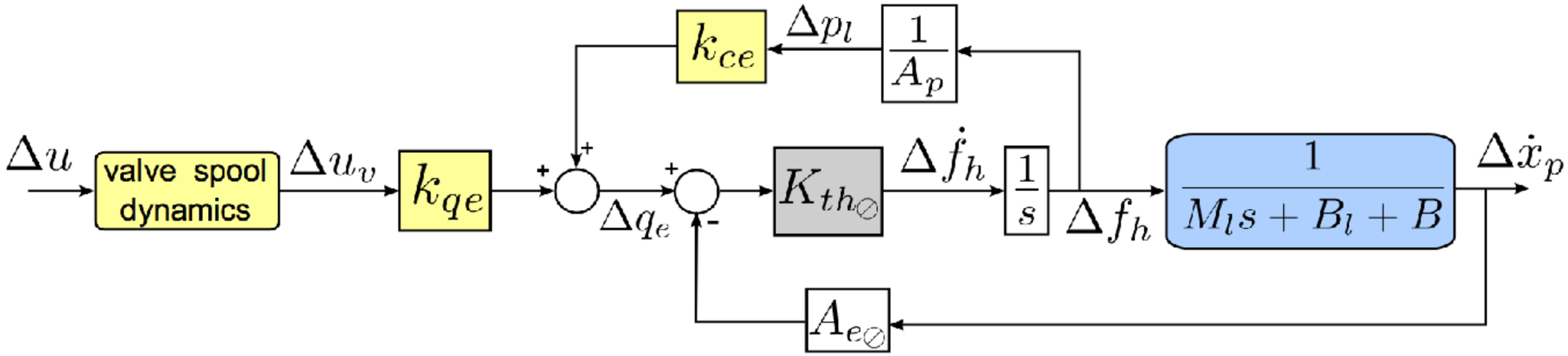
Realimentação intrínseca da velocidade

Open-loop torque/force dynamics

Electric actuation

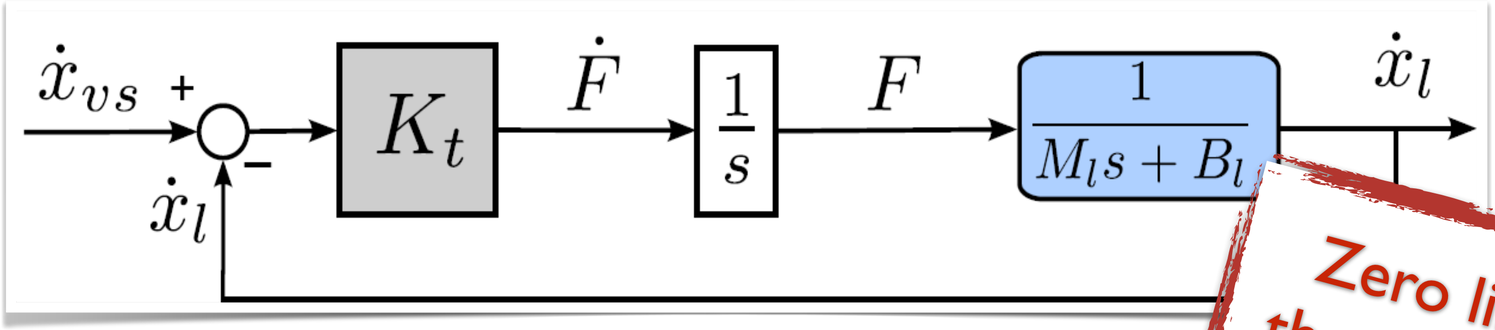


Hydraulic actuation



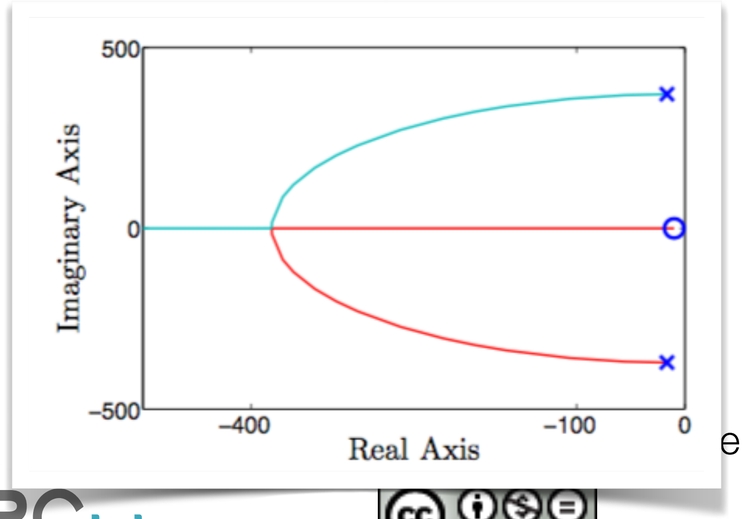
Boaventura, T., et al. On the role of load motion compensation in high-performance force control. IROS, 2012

Realimentação intrínseca da velocidade



Zero limits the response.

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

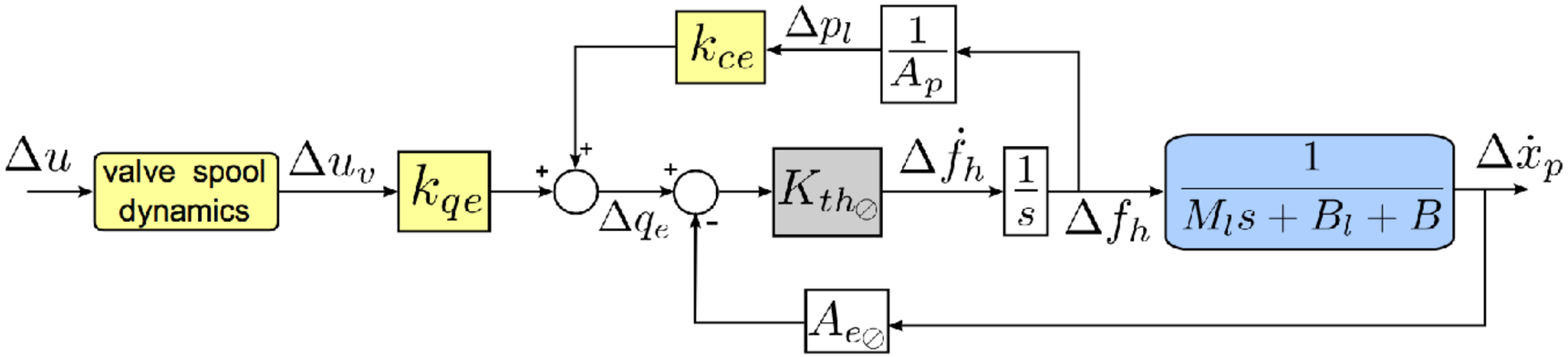


It does not depend on the actuation

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

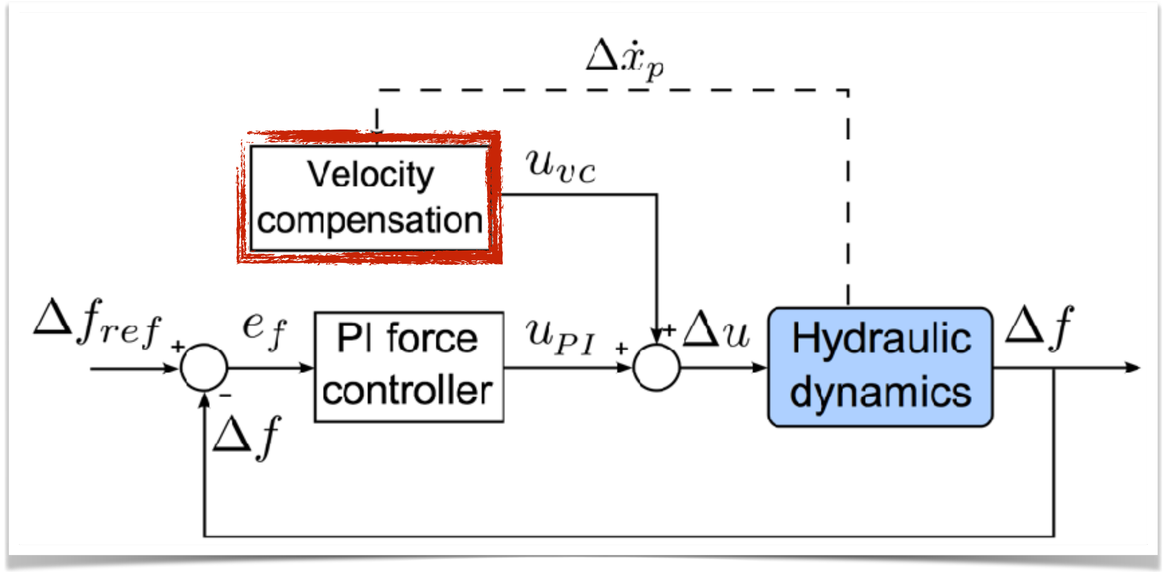
Compensação de velocidade baseada em modelo

Hydraulic actuation



Feedforward command:

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



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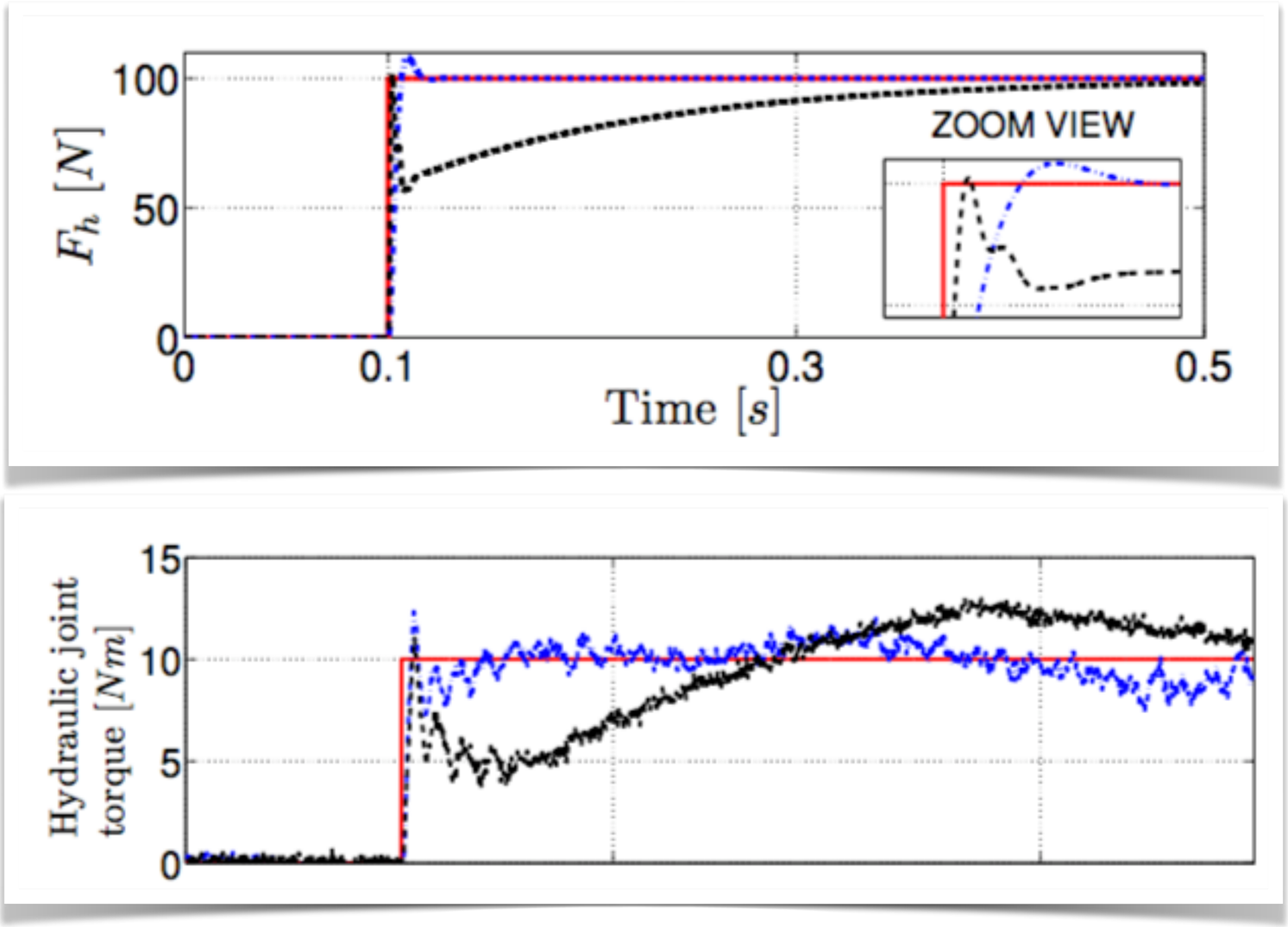
Compensação de velocidade baseada em modelo

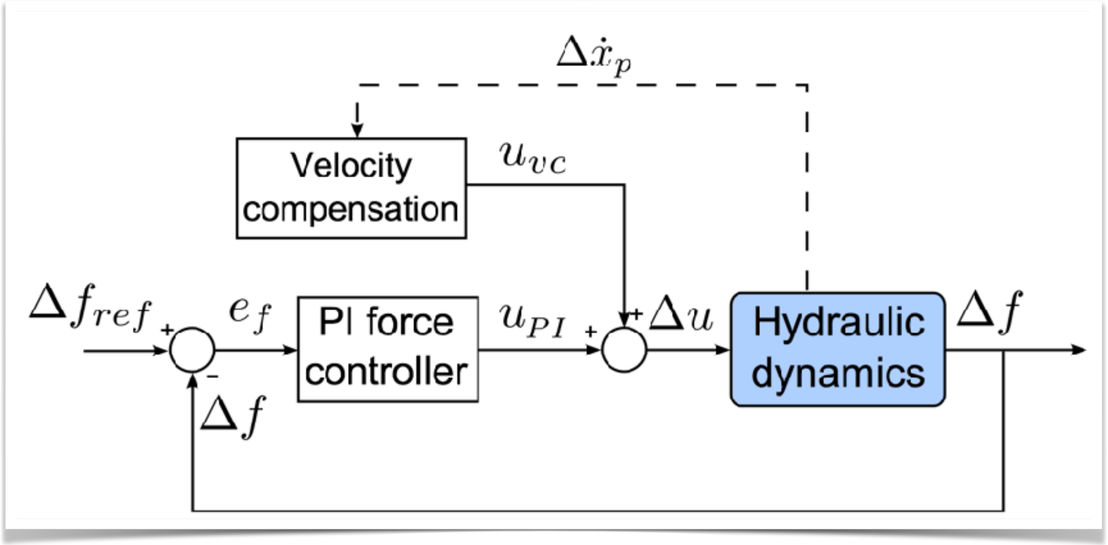


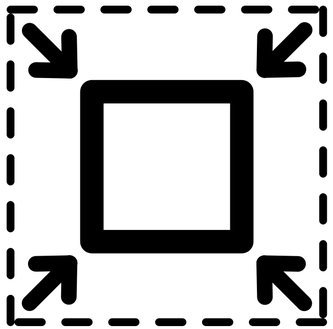
Boaventura, T., et al. On the role of load motion compensation in high-performance force control. IROS, 2012

Conteúdo

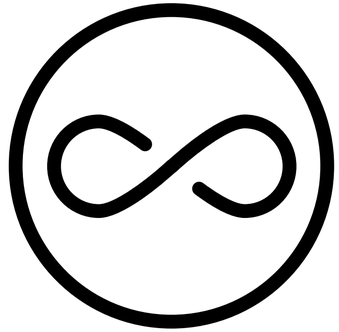
- Estabilidade da interação
- Passividade
- Z-width

Realimentação de força



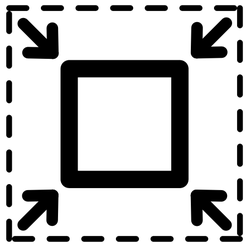


Reduzir inércia aparente



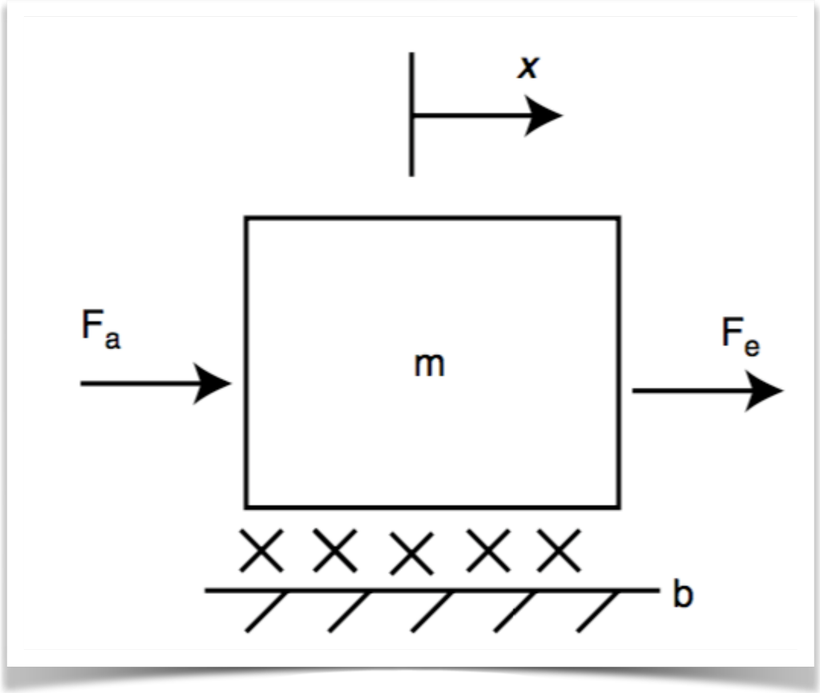
Problemas de estabilidade

Realimentação de força



Reduzir inércia aparente

$$(ms^2 + bs)X = F_a + F_e$$



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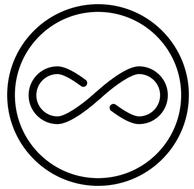

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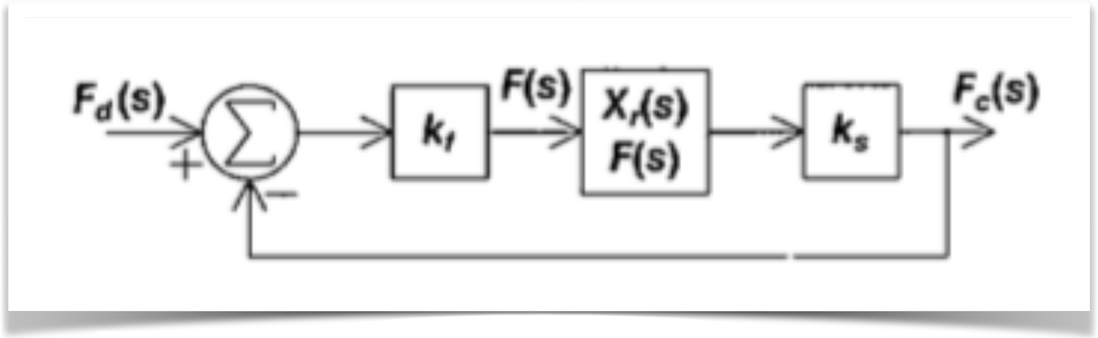
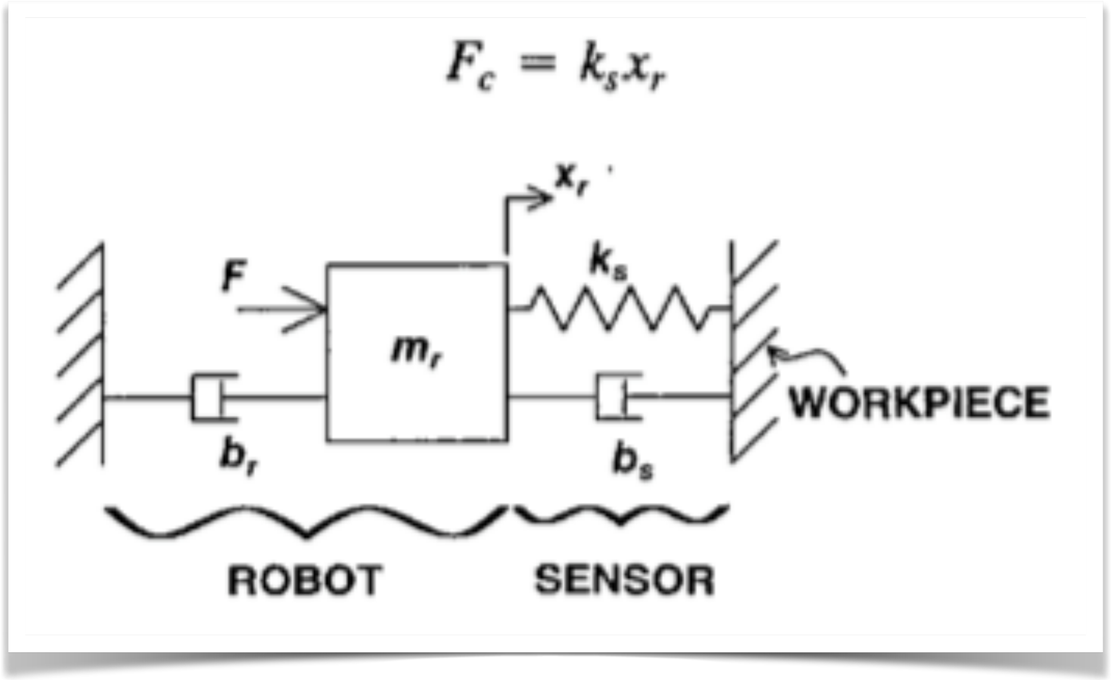
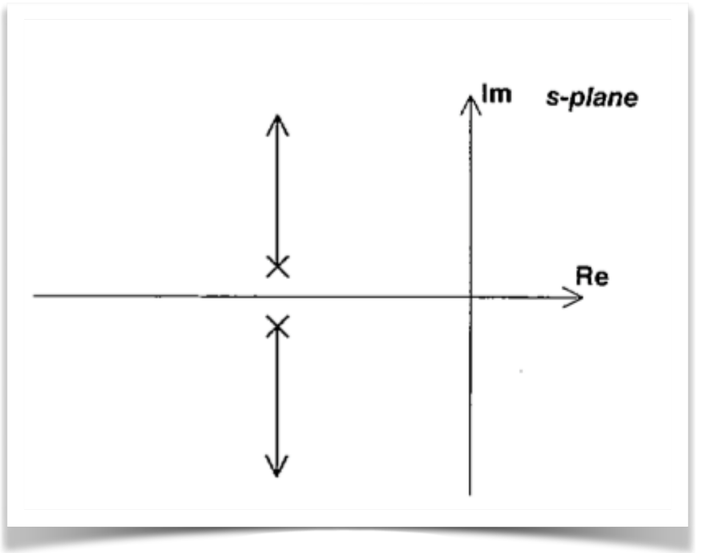


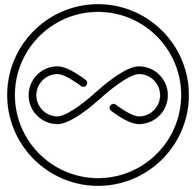
$$\frac{F_c(s)}{F_d(s)} = \frac{k_f k_s}{m_r s^2 + (b_r + b_s)s + k_s(1 + k_f)}$$





Eppinger & Seering, “Introduction to dynamic models for robot force control”,1987

Realimentação de força



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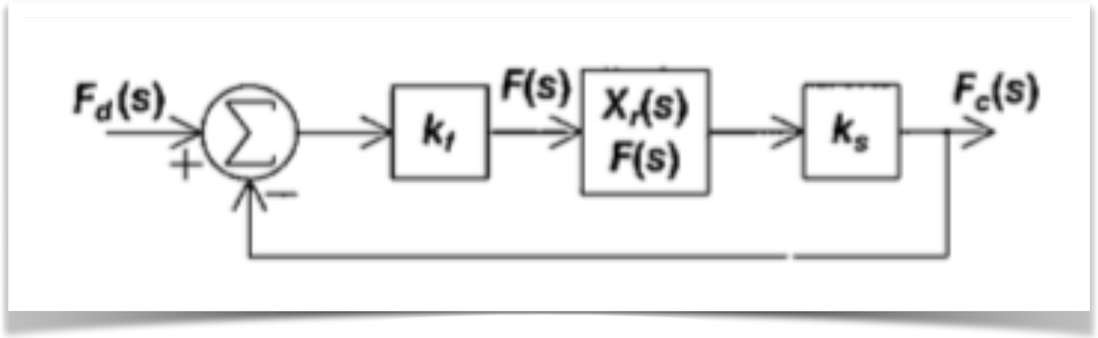

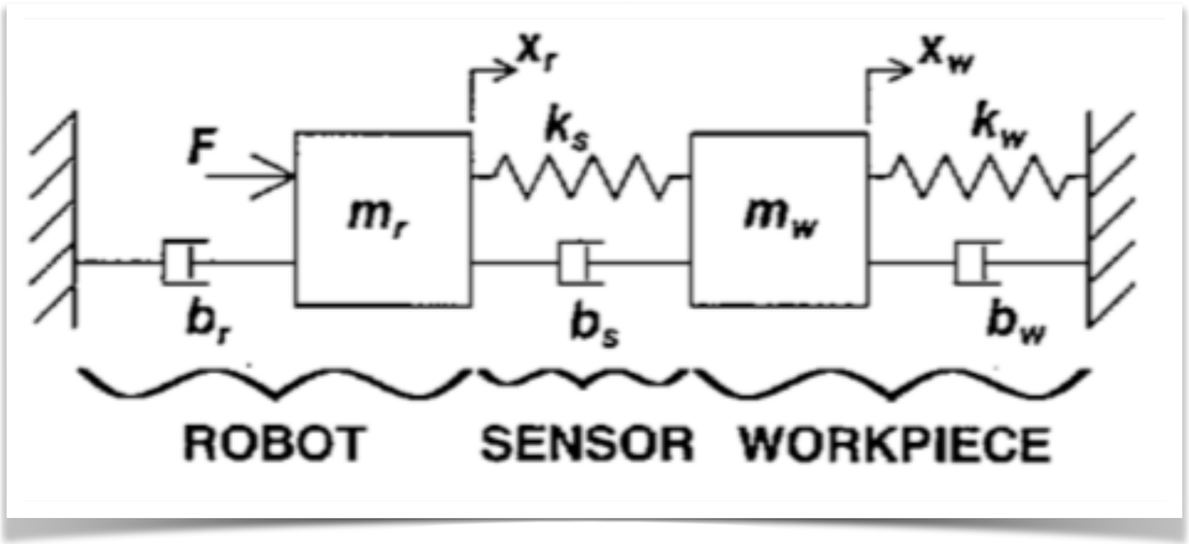

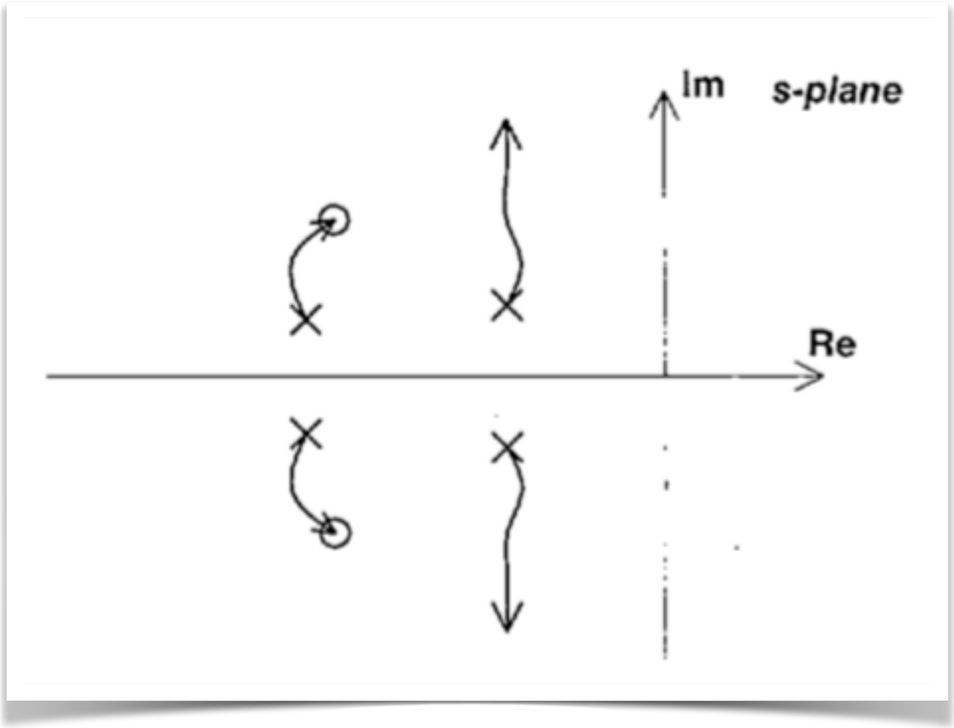

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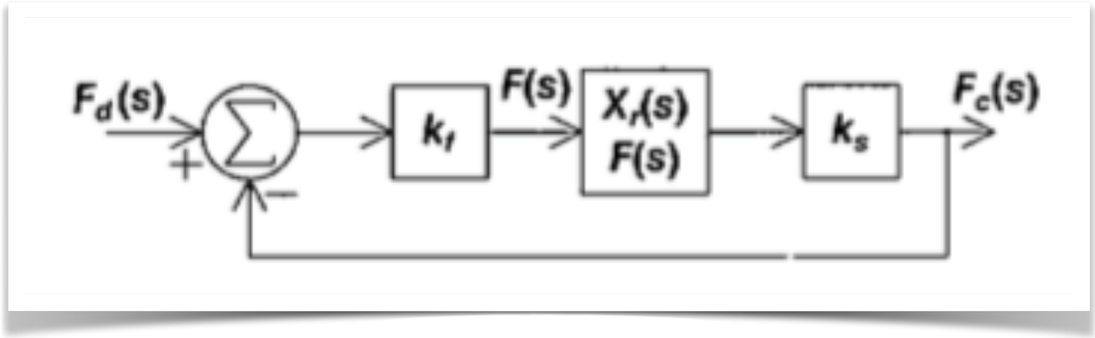
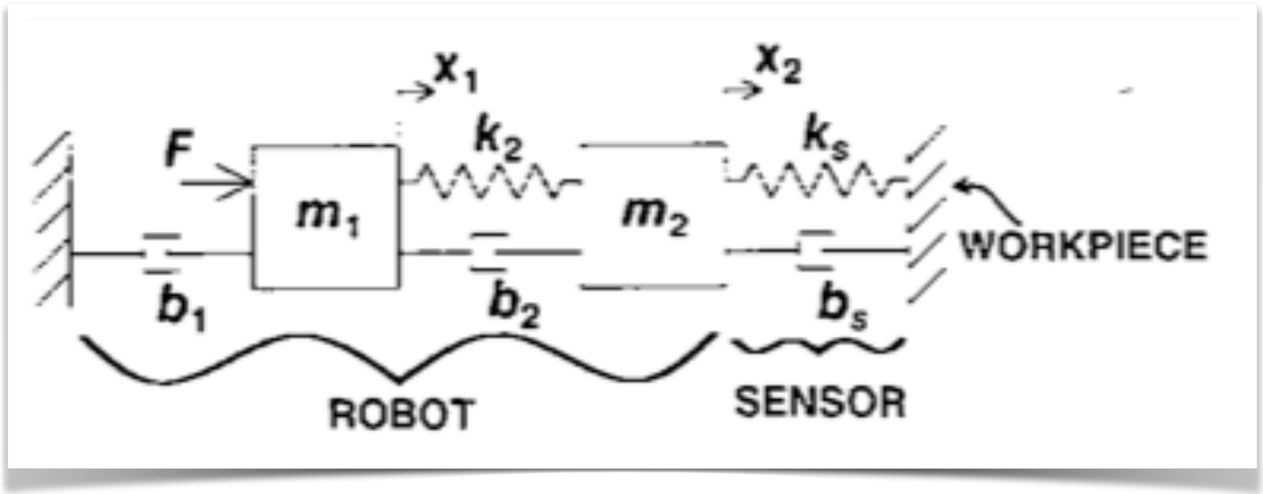
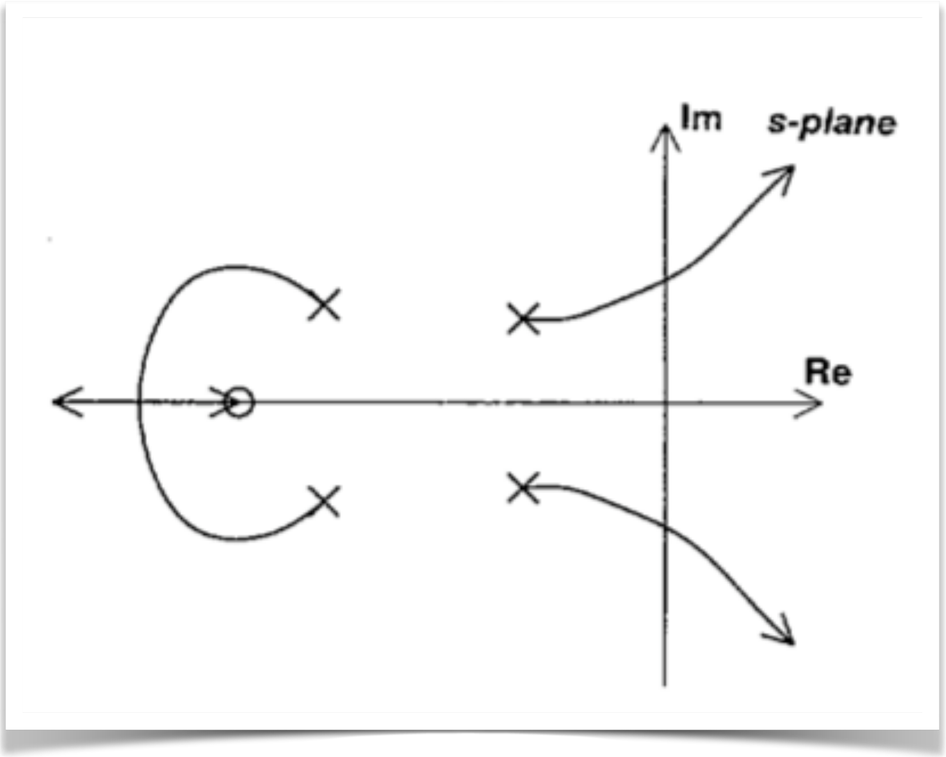
Realimentação de força

Problemas de estabilidade

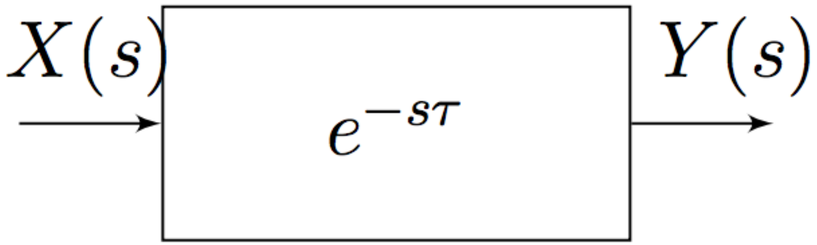






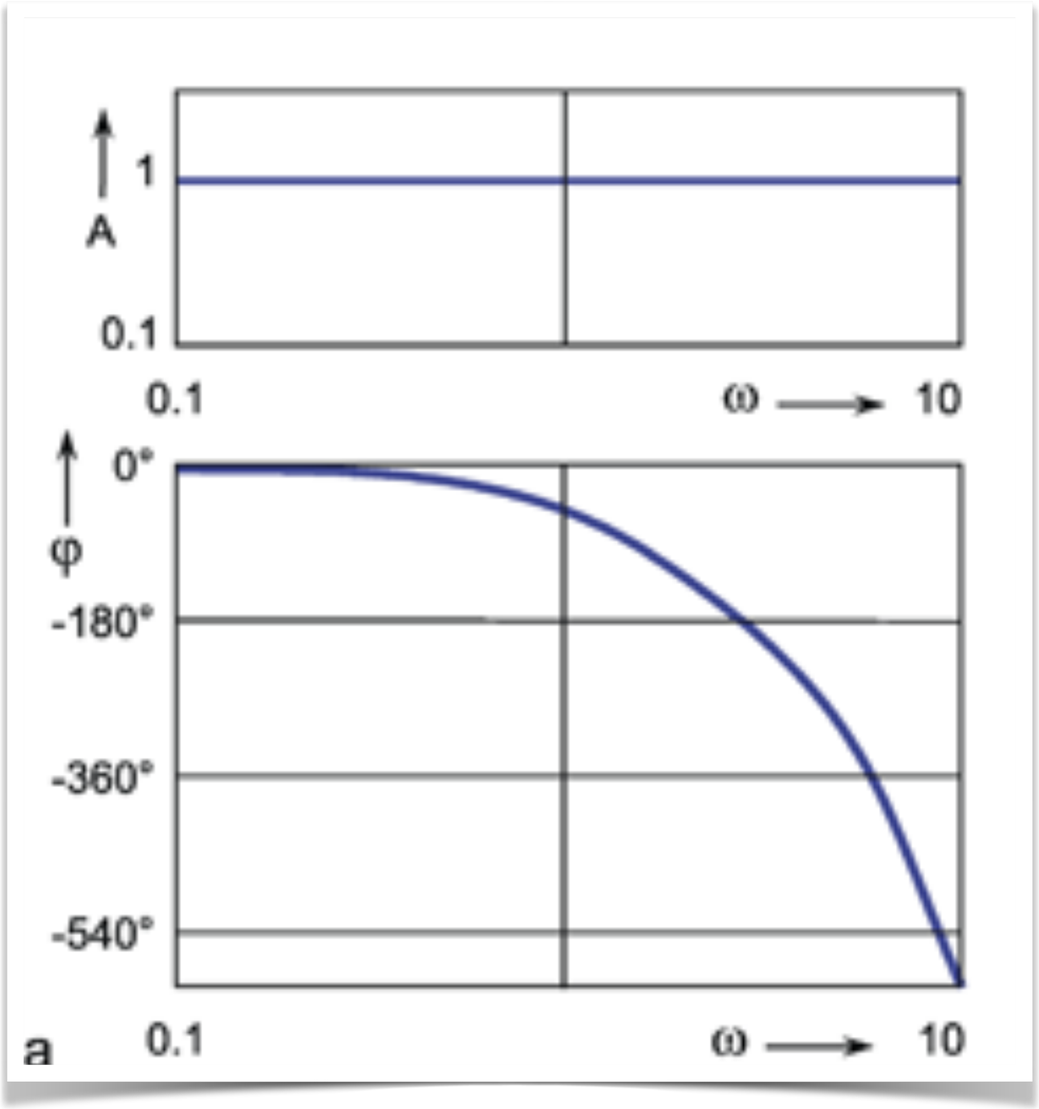
Eppinger & Seering, “Introduction to dynamic models for robot force control”,1987

Atraso no sistema



$$| e^{-i\omega\tau} | = 1$$

$$\angle e^{-i\omega t} = \omega\tau$$



Non-collocation

> **Means that the actuator and sensor are not at the same physical location, but are separated by dynamic elements.**

Colgate & Hogan, 1989

Eppinger & Seering, 1987

Conteúdo

Revisão

- Estabilidade da interação
- **Passividade**
- Z-width

Estabilidade

Conclusão

Reafirmação do principio de conservação de energia

Um sistema passivo não pode armazenar mais energia do que a que foi fornecida exteriormente

Passividade

$$\Sigma : \begin{cases} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{cases}$$

$$\underbrace{H[x(t)] - H[x(0)]}_{stored\ \ energy} \leq \underbrace{\int_0^t u^\top(s)h(x(s))ds}_{supplied\ energy}$$

Passividade de sistemas lineares

$$y(s) = h(s)u(s)$$

Teorema de Parseval:

$$\int_0^T y(t)u(t)dt = \int_{-\infty}^{\infty} y(t)u_T(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} y(j\omega)u_T^*(j\omega)d\omega$$

$$\mathbf{Re}[h(j\omega)] \geq 0 \text{ for all } \omega$$

Lozano, Rogelio, et al. Dissipative systems analysis and control: theory and applications. Springer Science & Business Media, 2013.

Passividade de sistemas lineares

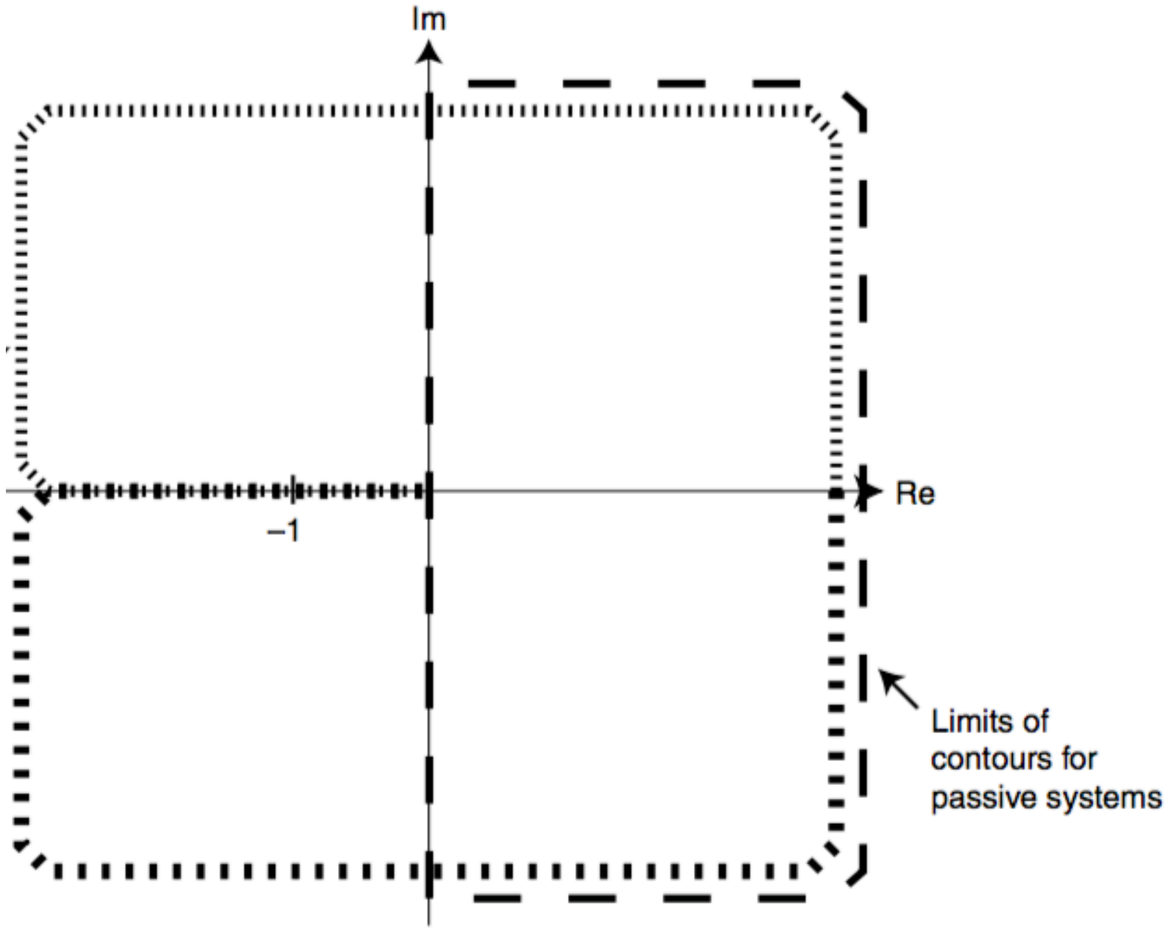
$$y(s) = h(s)u(s)$$

Condições para passividade:

1. Z(s) é estável
2. $\mathrm{Re}[Z(i\omega)] \geq 0 \; \forall \omega \in \mathbb{R}^+$

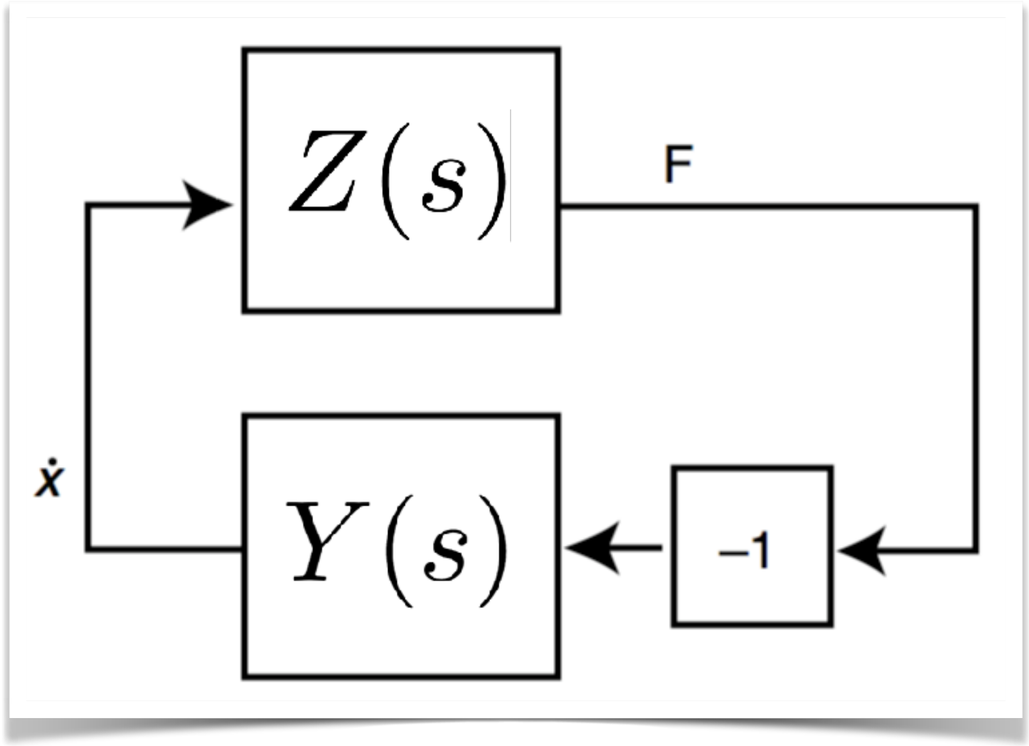
Passividade de sistemas lineares

2. $\mathrm{Re}[Z(i\omega)] \geq 0 \; \forall \omega \in \mathbb{R}^+$

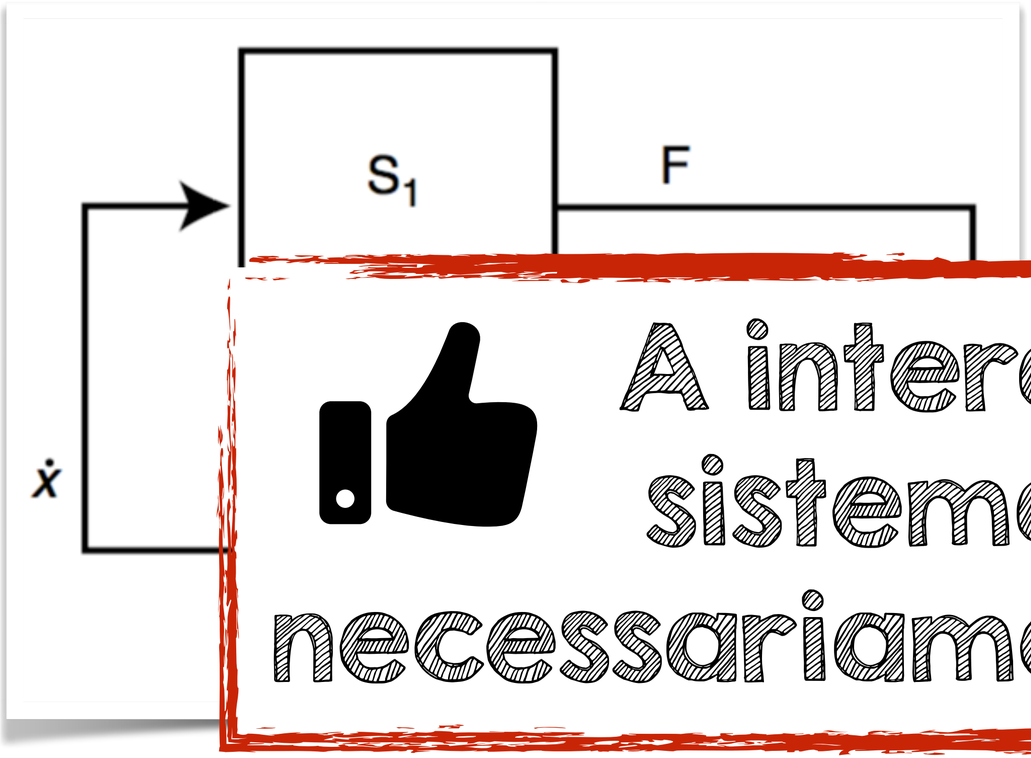


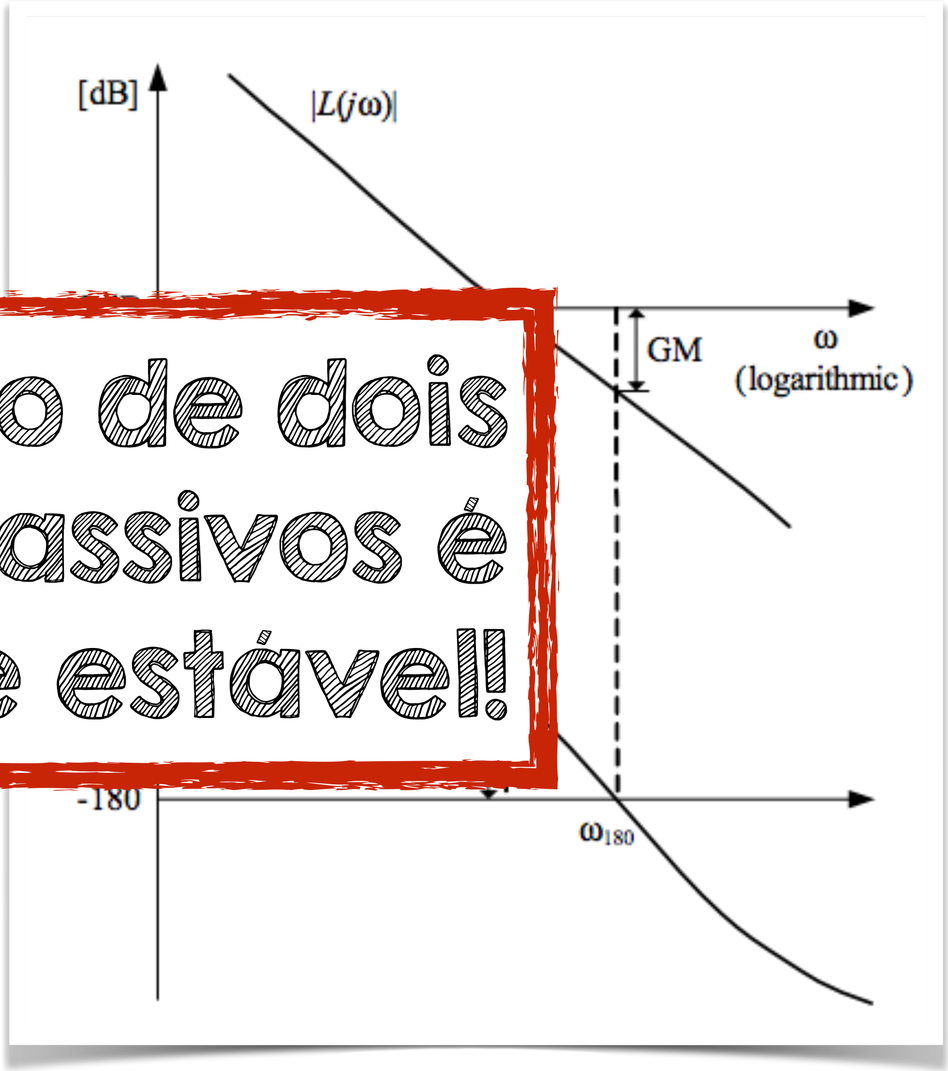
$$|\angle h(j\omega)| \leq 90°$$

Estabilidade acoplada via passividade



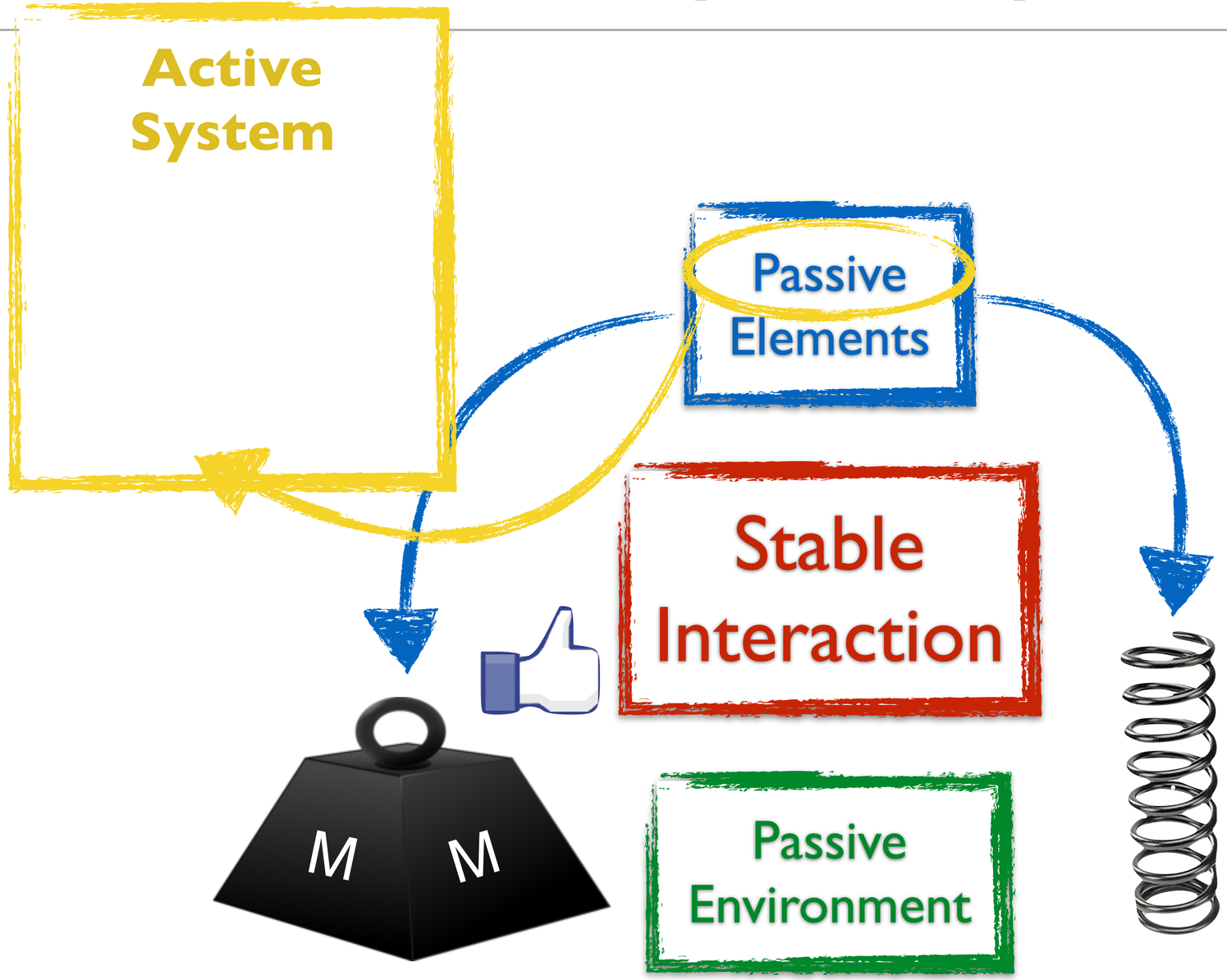
Estabilidade acoplada via passividade



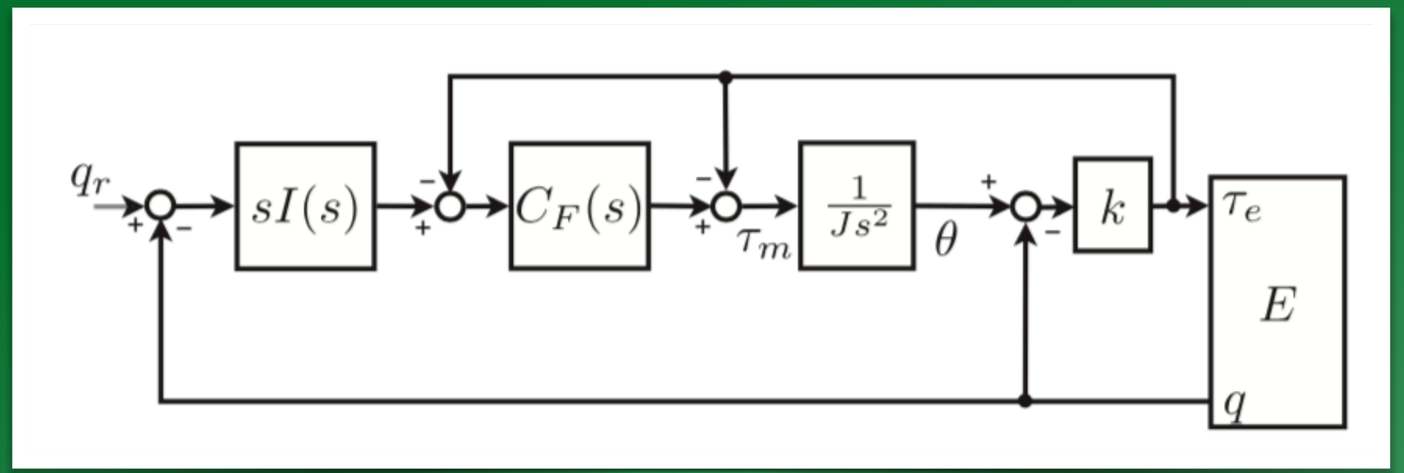


A interação de dois sistemas passivos é necessariamente estável!

Estabilidade acoplada via passividade



Estabilidade acoplada via passividade



$$C_F(s) = P + sD$$

$$-\tau_e = \frac{C_F(s)I(s) + Js}{C_F(s) + \frac{J}{k}s^2 + 1}\,\dot{q}$$

Conteúdo

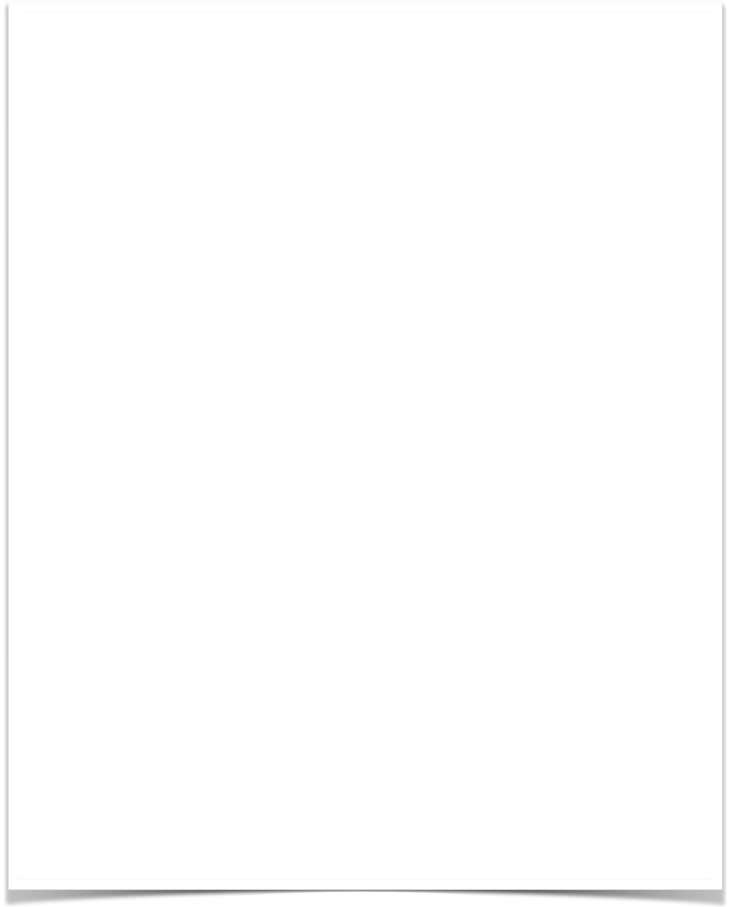
Revisão

- Estabilidade da interação
- Passividade
- Z-width

Estabilidade

Conclusão

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”]

Z-Width

- Sampling time
- Friction
- Filters
- Torque loop gains
- Actuator bandwidth

Passive range

Stable, but not passive range

Unstable range

Boaventura, T., et al. Stability and performance of the compliance controller of the quadruped robot HyQ. IROS, 2013

Z-Width

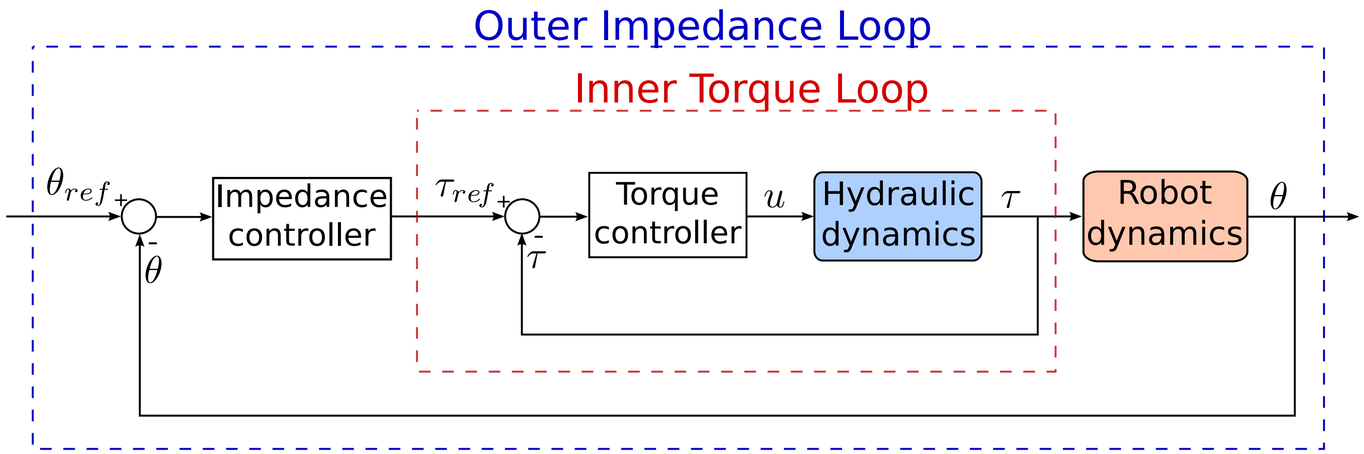
$$\frac{\Delta f(s)}{\Delta u(s)} = \left(\frac{1}{\frac{1}{\omega_v^2}s^2 + \frac{2D_v}{\omega_v}s + 1} \right) \left(\frac{K_{u_v}(M_l s + B_l)}{(s - K_{f_h})(M_l s + B_l + B) - K_{\dot{x}_p}} \right)$$

$$\omega_v = 2\pi F_v$$

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

Boaventura, 2013

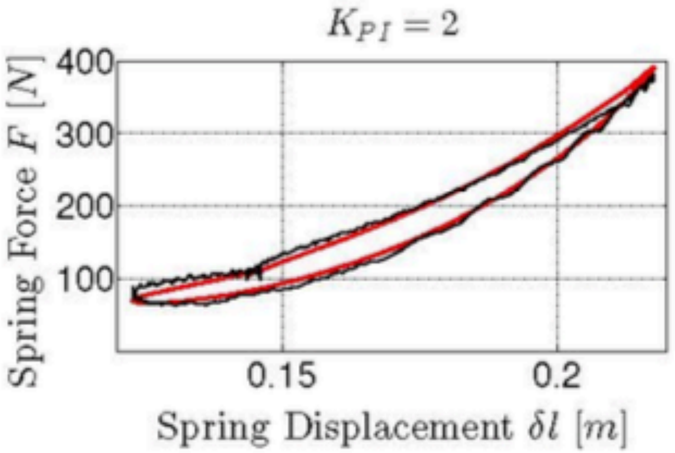
Z-Width

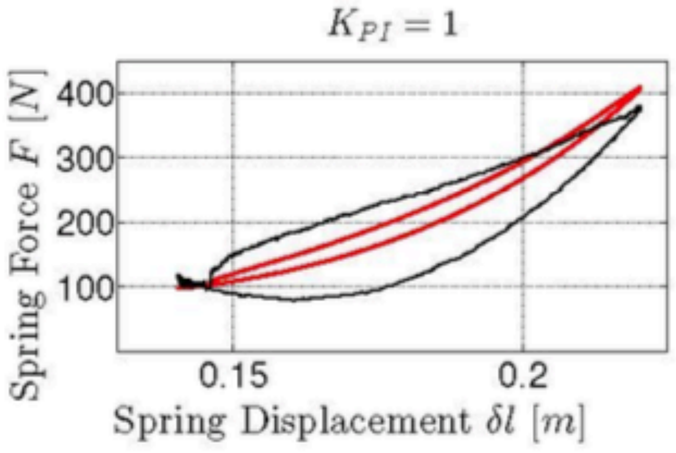


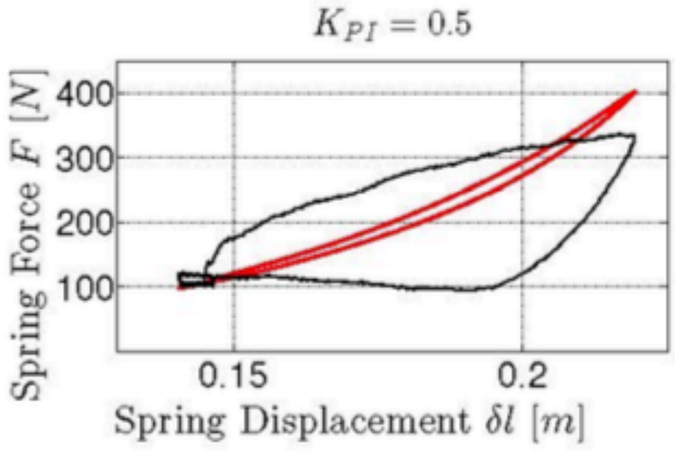
$$C = K_{PI} \frac{0.03838\,(z - 0.9953)}{z - 1}$$

Boaventura, T., et al. Stability and performance of the compliance controller of the quadruped robot HyQ. IROS, 2013

Z-Width

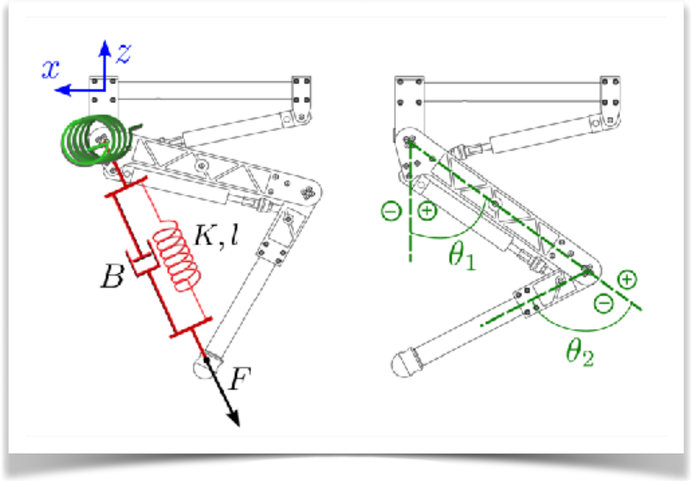


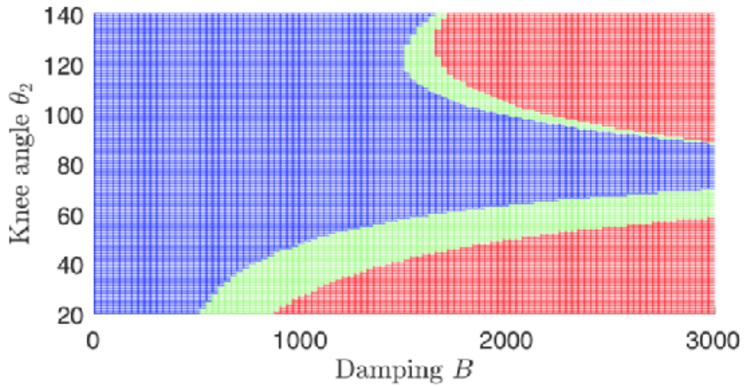




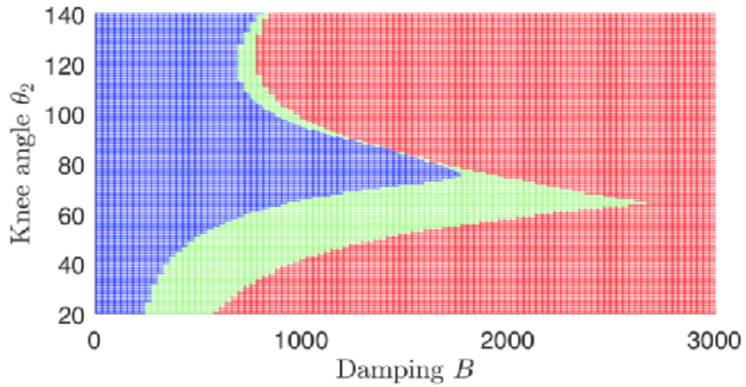
Boaventura, T., et al. Stability and performance of the compliance controller of the quadruped robot HyQ. IROS, 2013

Z-Width

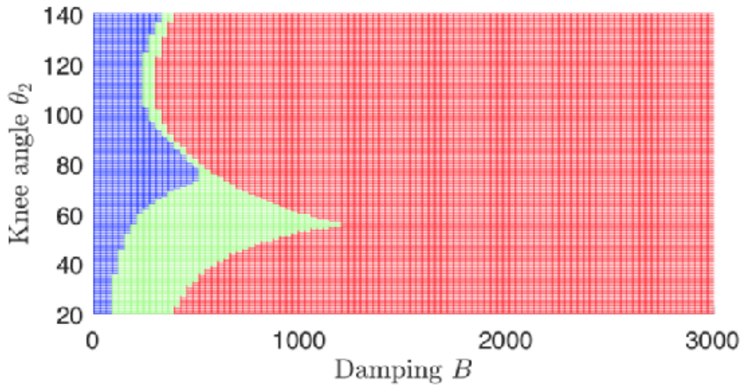




(a) $K_{PI} = 0.5$



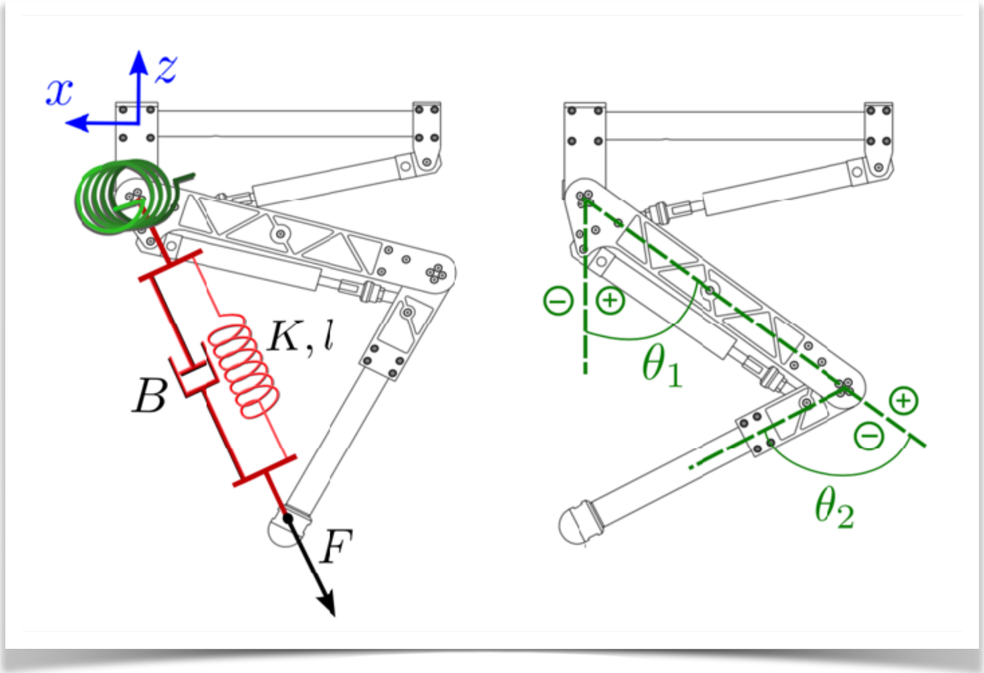
(b) $K_{PI} = 1.0$

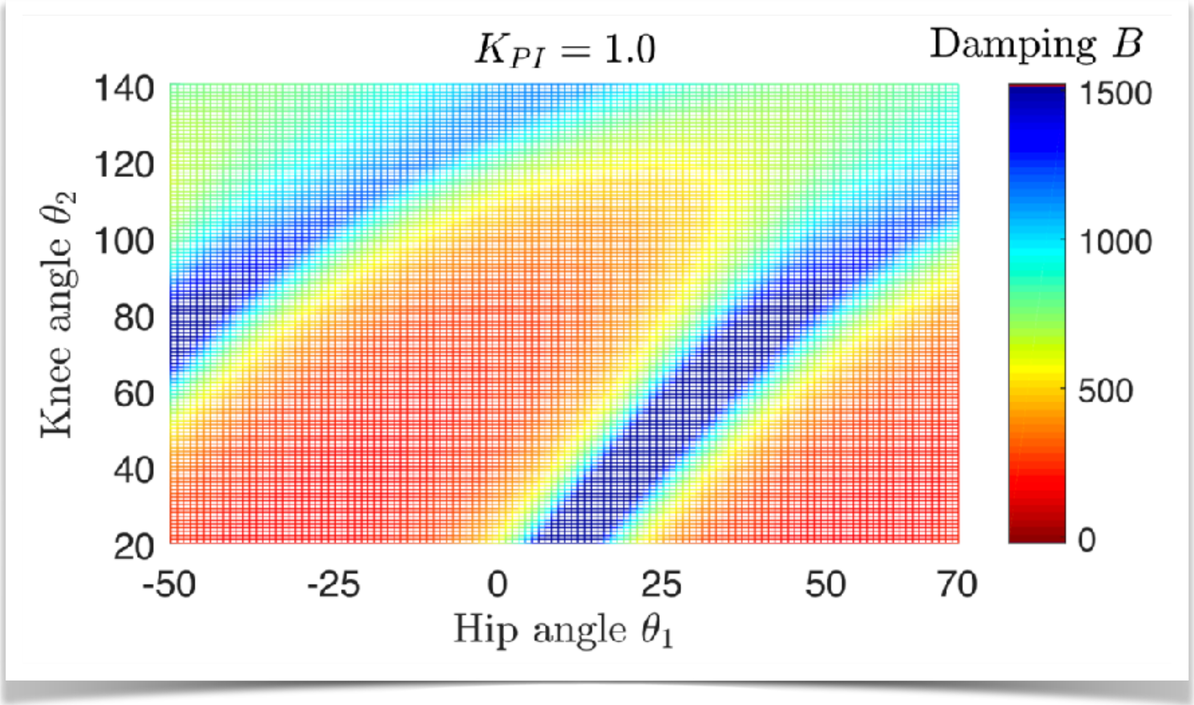


(c) $K_{PI} = 2.0$

Higa, F. Y. G., et al. Joint kinematic configuration influence on the passivity of an impedance-controlled robotic leg. ICRA, 2019

Z-Width





Higa, F. Y. G., et al. Joint kinematic configuration influence on the passivity of an impedance-controlled robotic leg. ICRA, 2019

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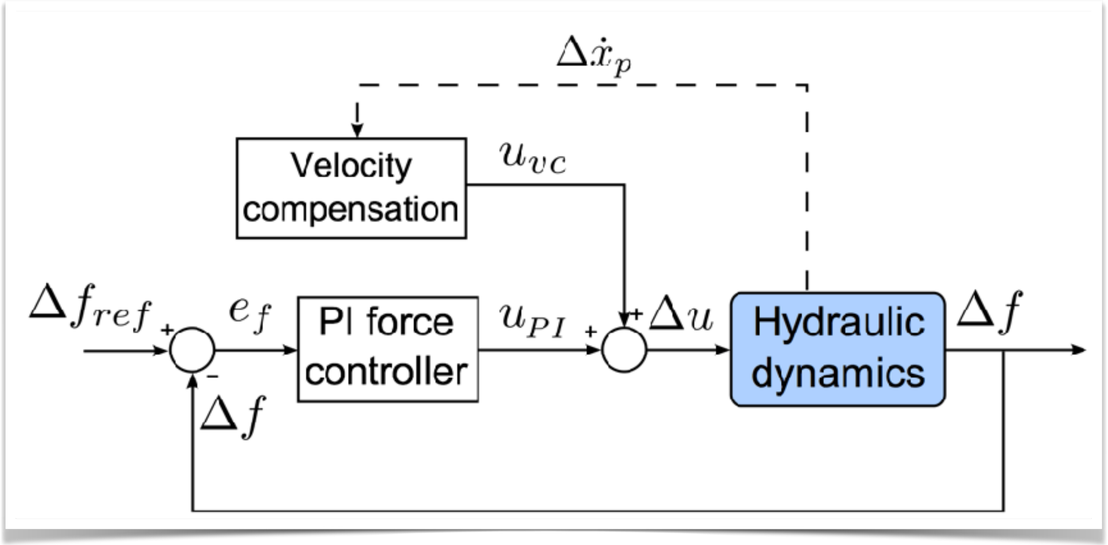
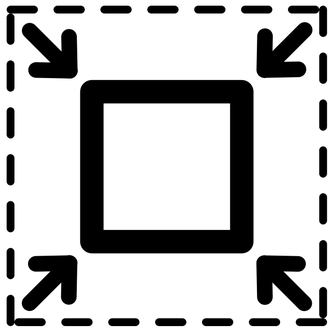
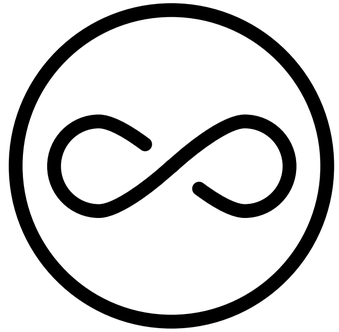
Conclusão

Take-home messages



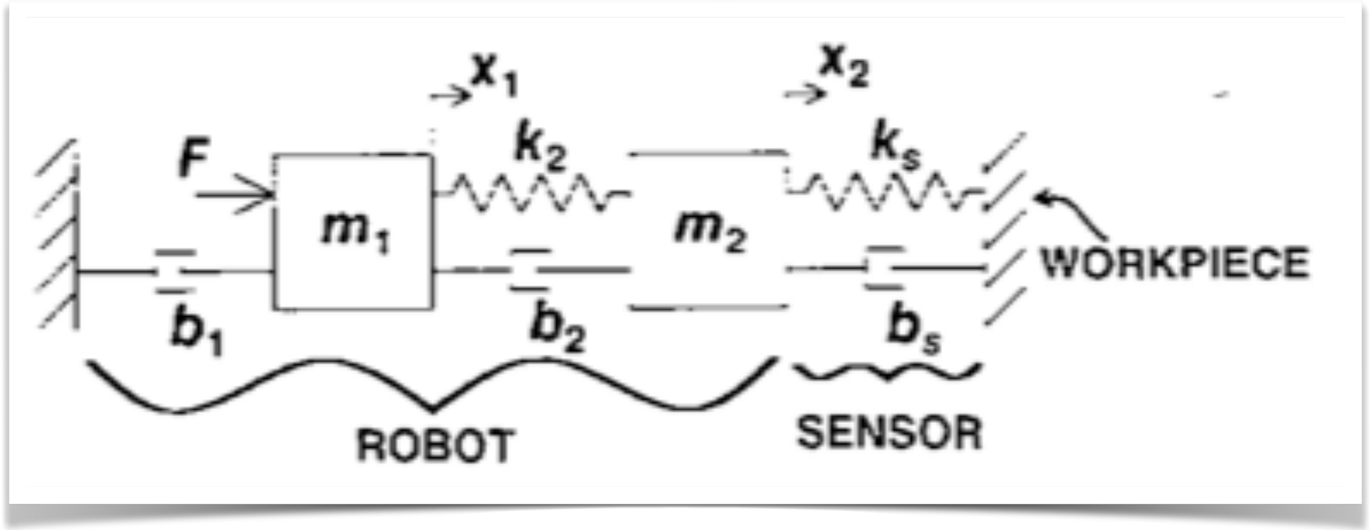


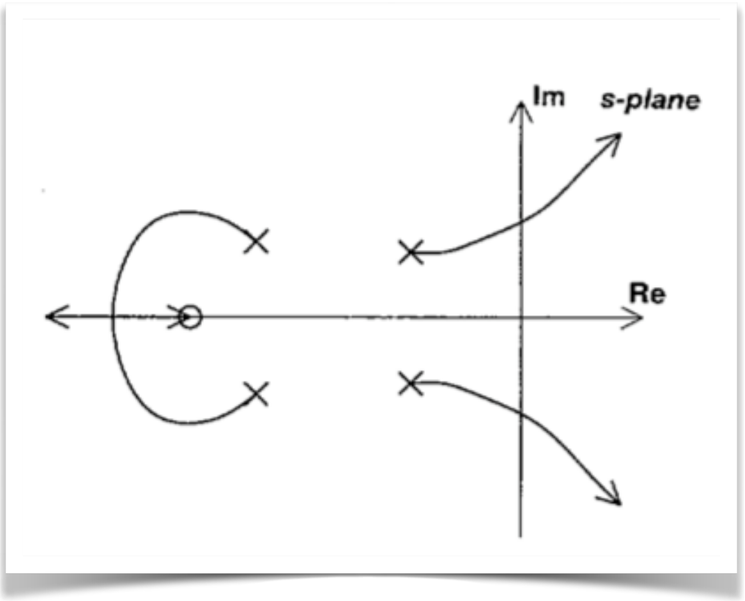
Reduzir inércia aparente



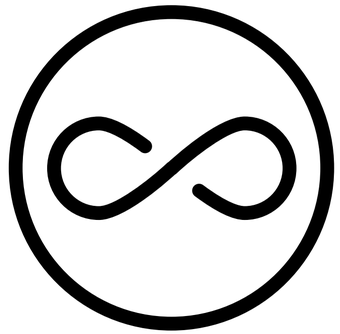
Problemas de estabilidade

Take-home messages



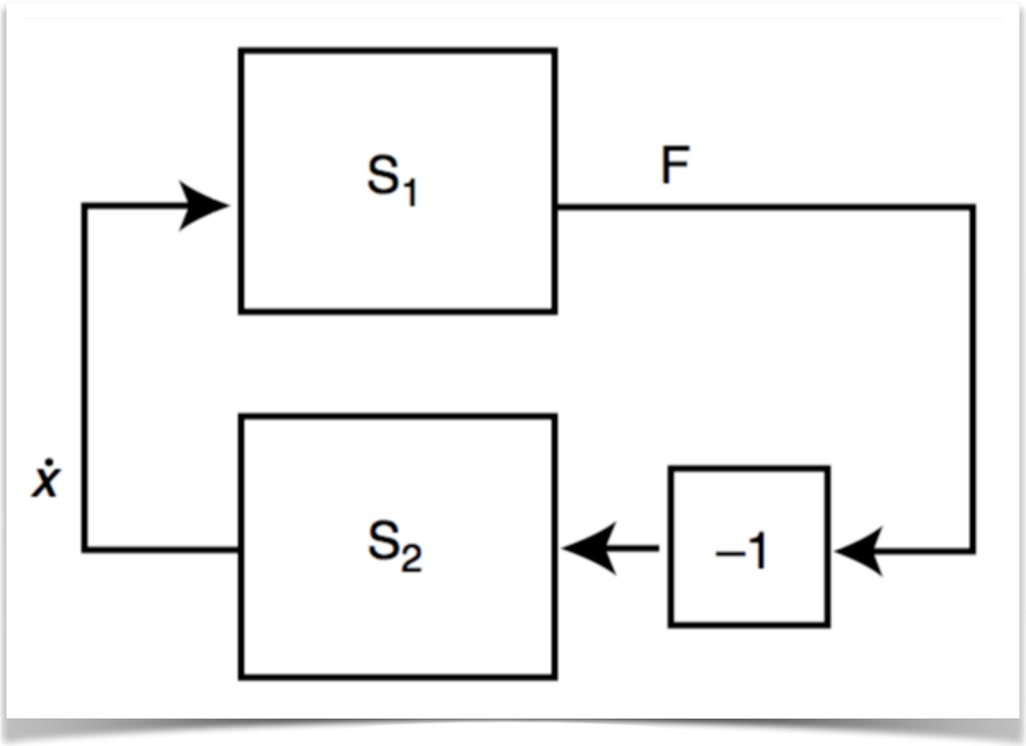


Non-collocation



Problemas de estabilidade

Take-home messages



Take-home messages

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That's all Folks!