Interaction Control

Introduction to interaction control methods

Joint Space Impedance Control

Task Space Impedance Control

PHYSICAL INTERACTION MOTIVATIONS

Applications

- robots that interact with humans (assistive robotics)
- surface interaction tasks (polishing, deburring)
- MOBILE / LEGGED robots
- WEARABLE robots (EXOSKELETONS)

objectives

- avoid applying too large forces (fragile objects)
- control interaction force (eg. balancing, brushing)

PASSIVE METHODS

physical springs are introduced between the robot and the environment, to control force (e.g. SEA)

⊕ more stable control

ACTIVE METHODS

use feed-back control techniques

① Direct force control: explicit force feedback

⊖ (noisy) to directly regulate contact forces

② Indirect force control: control force and position at the same time

- COMPLIANCE CONTROL
- IMPEDANCE CONTROL

⊕ more flexible : I can change online the stiffness via software

⊖ The controller delay influences the maximum BANDWITH we can control the force.

- The most famous indirect methods are :

IMPEDANCE CONTROL : requires inner Torque loop

ADMITTANCE CONTROL : requires inner position loop

DIRECT FORCE CONTROL

IDEA:

1. measure contact force f
2. if $f < f^d \Rightarrow$ apply more force
3. if $f > f^d \Rightarrow$ apply less force

$$\boxed{f^* = f^d + K_f \underbrace{(f^d - f)}_{e_f} + \dots \text{integral}}$$

$$\tau = -J^T f^* + h$$

DYNAMICS:

$$M\ddot{q} + h = \tau + J^T f$$

at steady state:

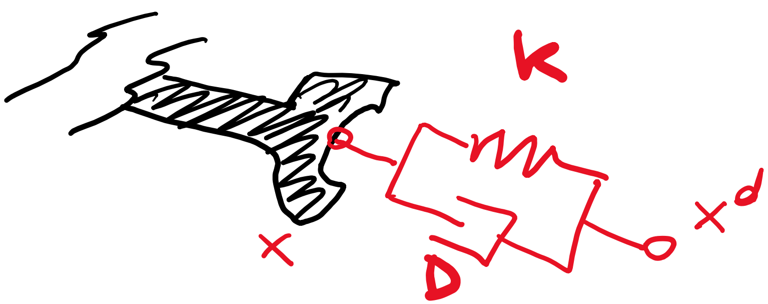
$$\cancel{g} - J^T f = -J^T f^* + \cancel{g} \Rightarrow f = f^d + K_f e_f$$

$$(1 + K_f) e_f = 0 \Rightarrow e_f = 0$$

IMPEDANCE CONTROL

IDEA: indirectly regulate forces by generating a motion that satisfy a dynamic relationship (IMPEDANCE) between force and position. (eg emulates SPRING/DAMPERS)

MECHANICAL IMPEDANCE



$$\frac{F(s)}{X(s)} = Ms^2 + Ds + K$$

(Laplace Domain)

- Mechanical impedance gives an idea on how a point of a system moves if you apply a force to it.

IMPEDANCE CONTROL IS IN THE MIDDLE...

POSITION CONTROL

control position no matter what force is applied

↑ accuracy

⊕

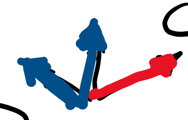
↑ force

- actuator saturation
- break mechanical parts

FORCE CONTROL

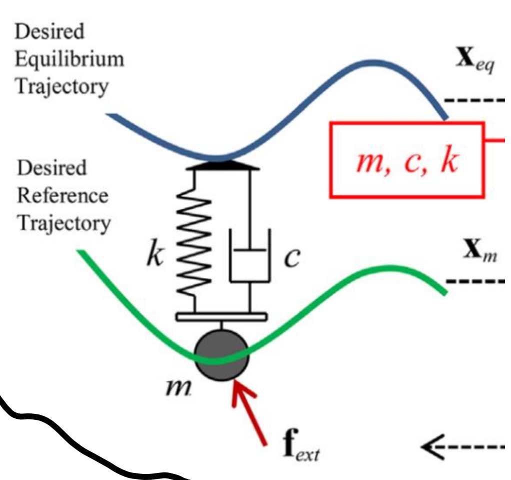
control force no matter which position is achieved

HYBRID CONTROL



FC in some direction

PC in others



IMPEDANCE CONTROL

CAUSALITY

[Hogan 1985]

ADMITTANCES

$$F \rightarrow \boxed{A} \rightarrow \dot{x}$$

$$\Downarrow$$

IMPEDANCES

$$\dot{x} \rightarrow \boxed{I} \rightarrow F$$

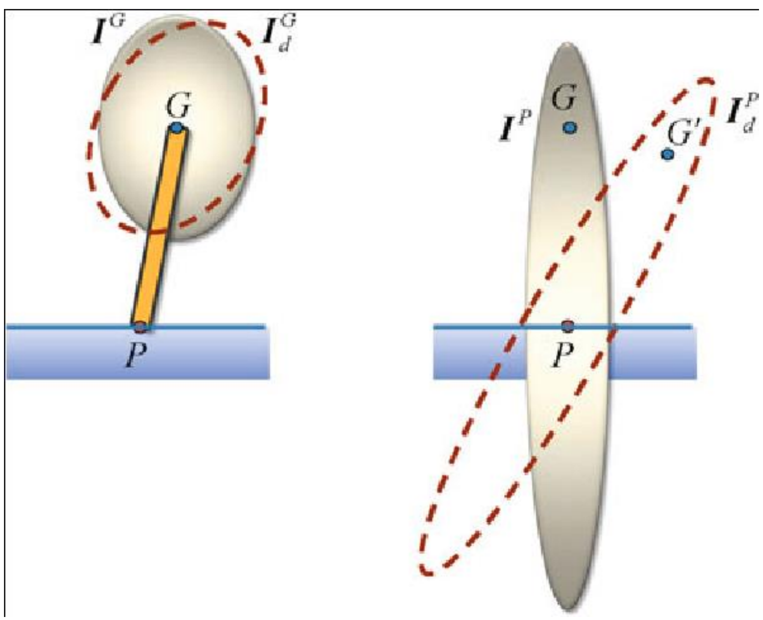
- inertial objects accept force as input and give motion as output (ADMITTANCES)

- To interact with the environment the robot must behave as an impedance (cannot connect 2 admittances together)

- Idea: control robot motion, give a "disturbance" responce for deviations from that motion, that has the form of an impedance

INERTIA SHAPING FEATURE

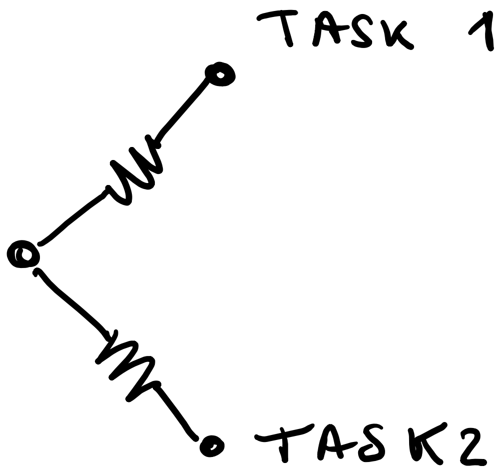
- mask the true inertia of the manipulator and (differently from OP. SP. CONTROL) impose a desired one at the END-EFFECTOR (I cannot change manipulator inertia but I can change the apparent one at the end effector)



e.g. I can make it configuration independent

SUPERIMPOSITION OF IMPEDANCES

Because the desired imperances are linear we can superimpose their effects



- each impedance can represent one task
- The behaviour will be a compromise between the tasks (if they are conflicting)

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JOINT SPACE IMPEDANCE CONTROL

Desired impedance:

$$(1) \quad M_\theta \ddot{q} + D_\theta (\dot{q}^d - \dot{q}) + K_\theta (q^d - q) = \tau_{ext}$$

Dynamics:

$$M \ddot{q} + R = \tau + J^T F_{ext}$$

- choose τ to behave as desired dynamics:

$$(1) \quad \ddot{q} = M_\theta^{-1} \Big[\tau_{ext} - D_\theta \underbrace{(\dot{q}^d - q)}_{\dot{e}} - K_\theta \underbrace{(q^d - q)}_{e} \Big]$$

$$\boxed{\tau = R - J^T F_{ext} + M M_\theta^{-1} \left[\tau_{ext} - D_\theta \dot{e} - K_\theta e \right]}$$

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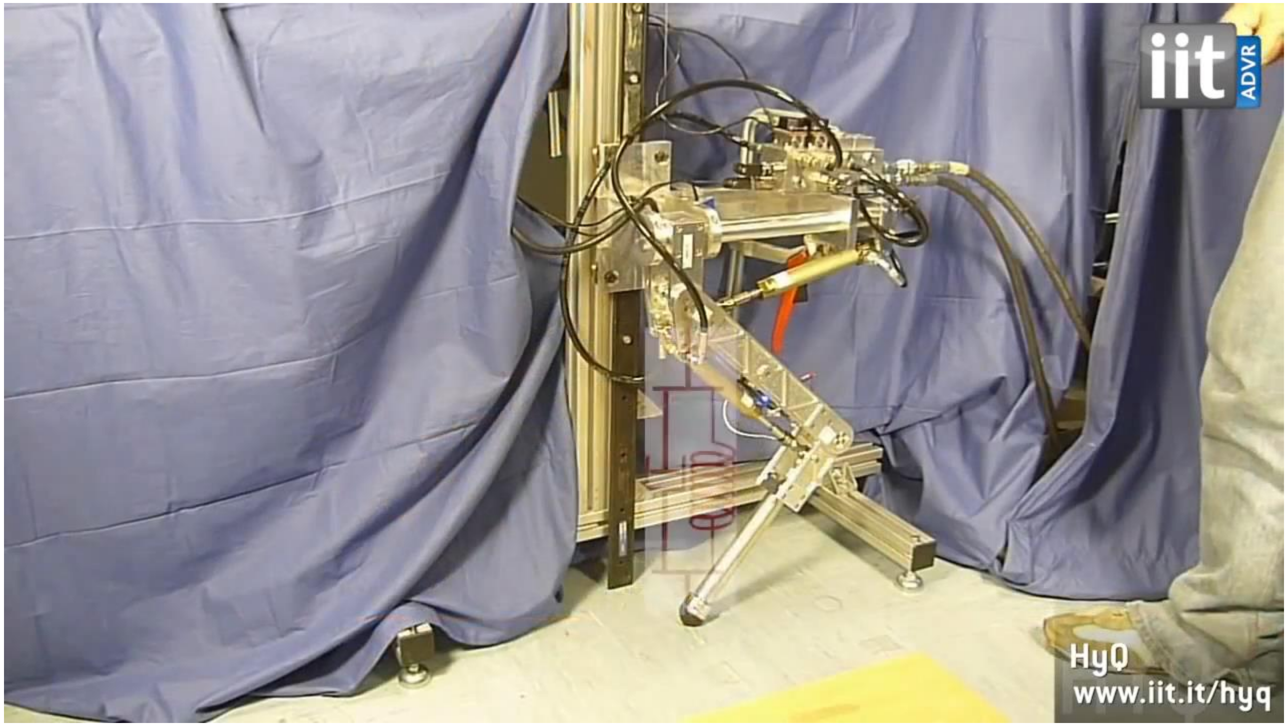
TASK SPACE IMPEDANCE CONTROL

Desired impedance:

(1) $$M_x \ddot{x} + K_x (x^d - x) + D_x (\dot{x}^d - \dot{x}) \doteq F_{ext}$$

↳ desired inertia at end-effector



Dynamics:

$$(2)\quad M\ddot{q} + h = \tau + J^T F_{ext}$$

$$\boxed{\tau = M\ddot{q}^d + h - J^T F_{ext}}$$

where:

$$(1) \longrightarrow \ddot{x}^d = M_x^{-1}\left[F_{ext} - K_x(x^d - x) - D_x(\dot{x}^d - \dot{x})\right]$$

$$\ddot{q}^d = J^{-1}(\ddot{x}^d - \dot{J}\dot{q}) = J^{-1}\ddot{x}^d - J^{-1}\dot{J}\dot{q}$$

$$(3)\quad \boxed{\begin{aligned}\tau = {} & M J^{-1} M_x^{-1}\left(F_{ext} - K_x(x^d - x) - D_x(\dot{x}^d - \dot{x})\right) \\ & - M J^{-1}\dot{J}\dot{q} + h - J^T F_{ext}\end{aligned}}$$

⊖ exact cancellation is impossible

⊖ $M J^{-1} M_x^{-1}$ big torques if M_x is small

⊖ requires torque sensor at the joints and force sensor at the end-effector to measure F_{ext}

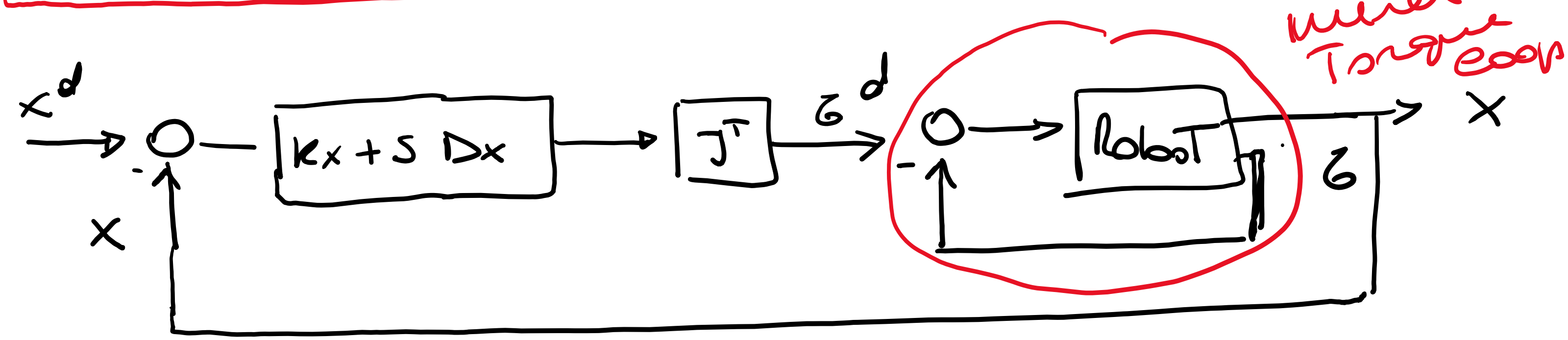
⊕ plugging (3) into (2) we cancel the robot dynamics enforcing the desired one:

$$\ddot{x} = \ddot{x}^d \rightarrow \boxed{M_x \ddot{x} = F_{ext} - K_x(x^d - x) - D_x(\dot{x}^d - \dot{x})}$$

PERFECT IMPEDANCE EMULATION

⇒ because of ⊖ is not so used in practice and only K_x, D_x terms are used:

$$\boxed{\tau = J^T \left[K_x (x^d - x) + D_x (\dot{x}^d - \dot{x}) \right]} \quad (4)$$



(4)

- equivalent to a PD control in task space
- no need of contact force sensor
- ok if inertias are small
- passive if $K_x > 0$, $D_x > 0$

$\Downarrow$

stable when interacting with possive environments

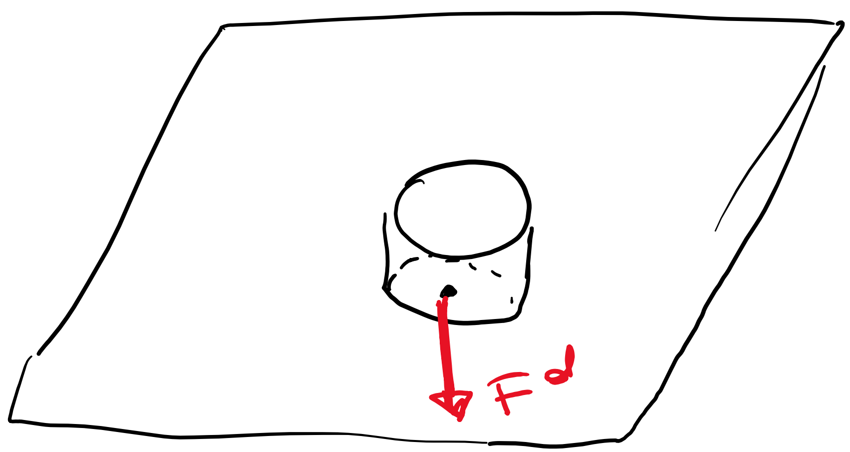
ADDING DESIRED FORCE

Desired impedance:

$$M_x \ddot{x} + K_x (x^d - x) + D_x (\dot{x}^d - \dot{x}) = F^d - F_{ext}$$

EXAMPLES:

Deburring, cleaning



DIFFERENCE WITH PD CONTROL

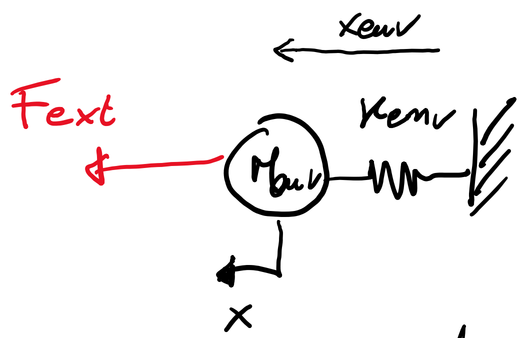
PD CONTROL	VS	IMPEDANCE CONTROL
∘ control position	⟷	∘ control relationship BW position and force
∘ k_p, k_d have no physical meaning $u = k_p e + k_d \dot{e}$ u = valve opening / voltage	⟷	∘ K, D have physical meaning of stiffness / damping
∘ There is no inner loop	⟷	∘ There is a torque inner loop
∘ do not care about disturbances	⟷	∘ gives a controlled responce to a disturbance from environment

makes the robot appear as a physical system

STABILITY IN CONTACT WITH ENVIRONMENT

⓪

stability depends both on impedance parameters and on dynamics of environment



ENVIRONMENT DYNAMICS

$$M_{env}\ddot{x} = -k(x_{env} - x) + F_{ext}$$

$$M_x\ddot{x} + K_x(x^d - x) + D_x(\dot{x}^d - \dot{x}) = F_{ext}$$

CLOSED LOOP DYNAMICS!

$$(M_x + M_e)\ddot{x} + D_x\dot{x} + (K_x + K_{env})x = K_x x^d + K_{env}x_{env} + D_x\dot{x}^d$$

↳ is asymptotically stable if

M_x, D_x, K_x are chosen POSITIVE DEFINITE

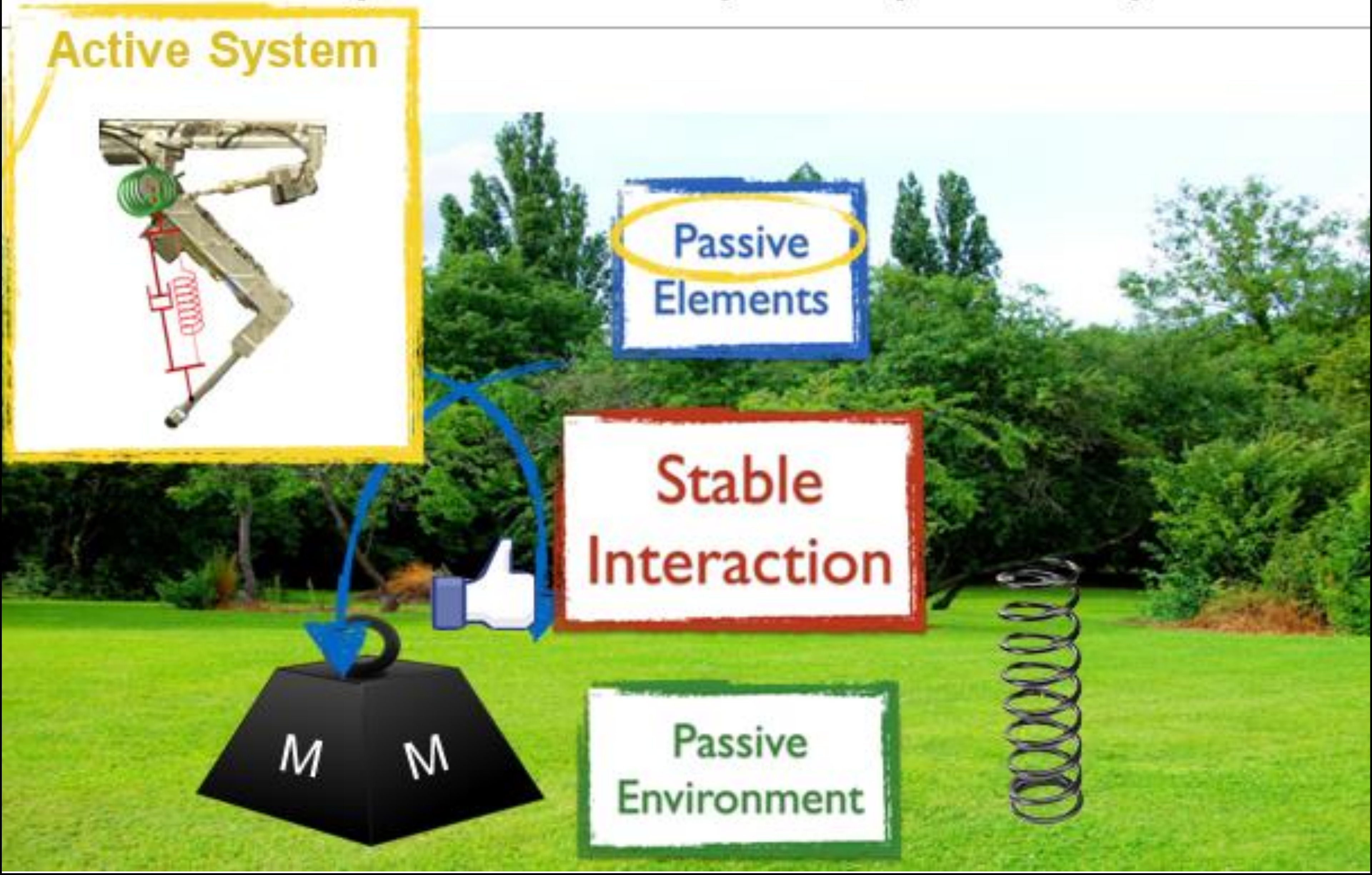
Passivity

Restatement of the

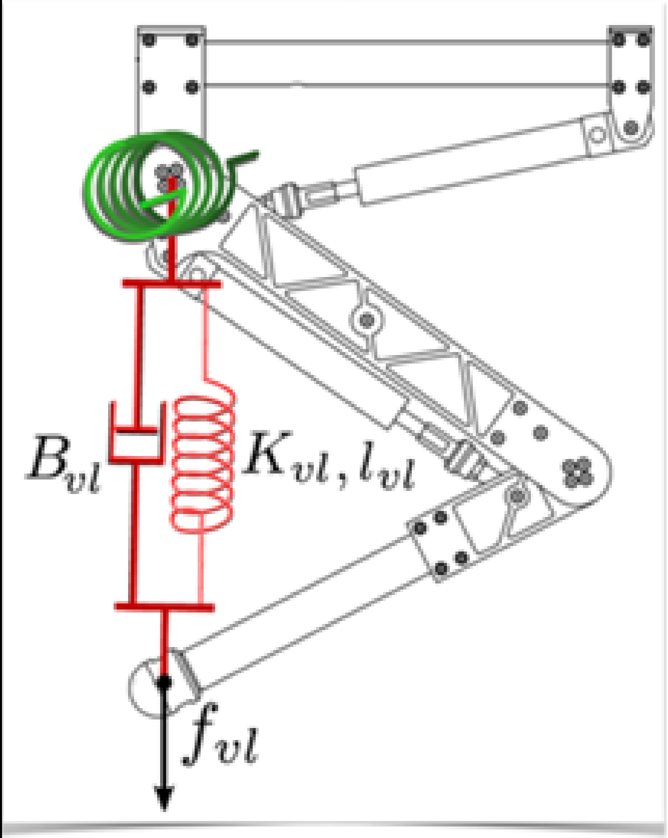
energy conservation principle

A passive system cannot store more energy than is supplied to it from the outside

Coupled stability via passivity



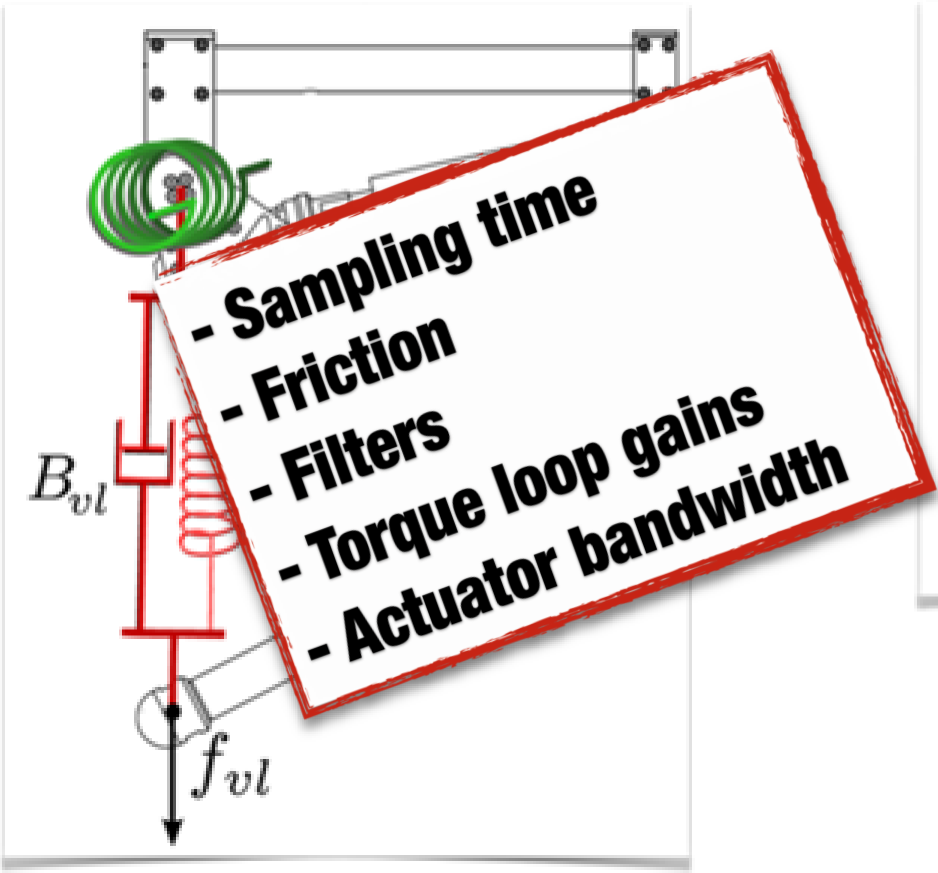
Z-Width

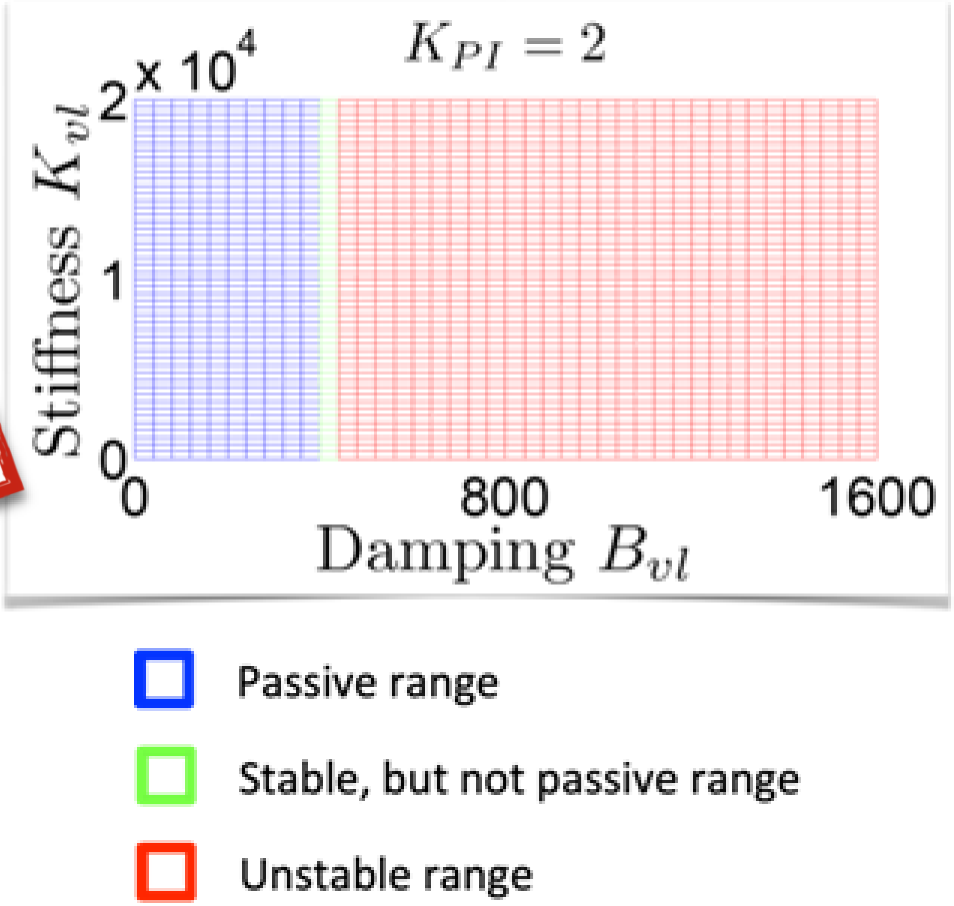


Range of stiffness and damping that keeps the system passive

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

Z-Width





[Boaventura et al. IROS, 2013]
[Focchi, PhD Thesis, 2013]

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