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Scuola Superiore
Sant'Anna

PERCRO Perceptual
Robotics Laboratory

Exoskeletons & Physical Human-Robot Interaction Controls

Seminar

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Human-Robot Interaction Area
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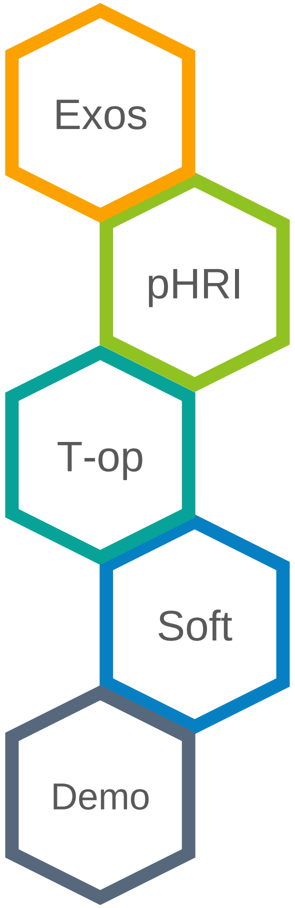
May 6, 2019

Outline



01 **Exoskeletons**

- Applications
- Interactions
- Mechanical aspects

02 **P-HRI Controls**

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- Force Control
- Interaction with a Virtual Environment

03 **Passivity and Teleoperation**

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- Time Domain Passivity Approach
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Exosuit Demo

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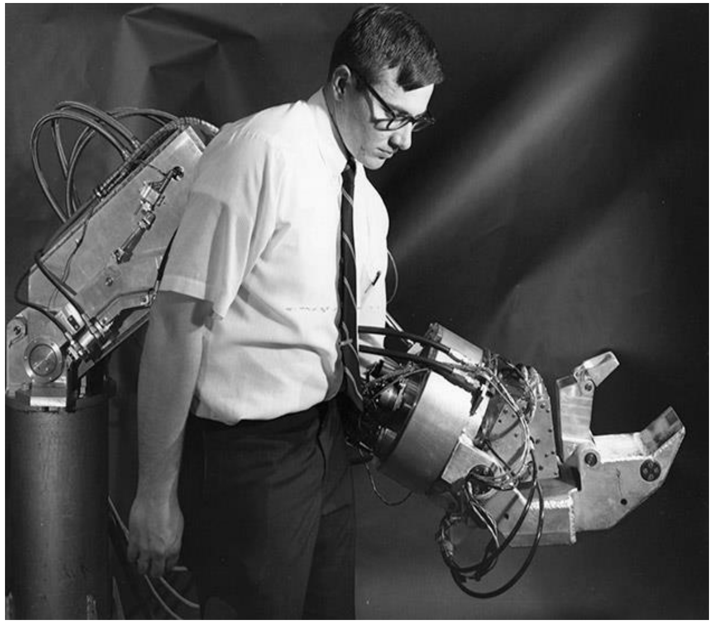
Exoskeletons

Exo…what?



Hardiman, Mosher, 1965

Exoskeleton is a robot that can be worn and behaves like an external skeleton.
It transmits forces to the wearer through its structure.
Exoskeletons try to replicate human body kinematics.

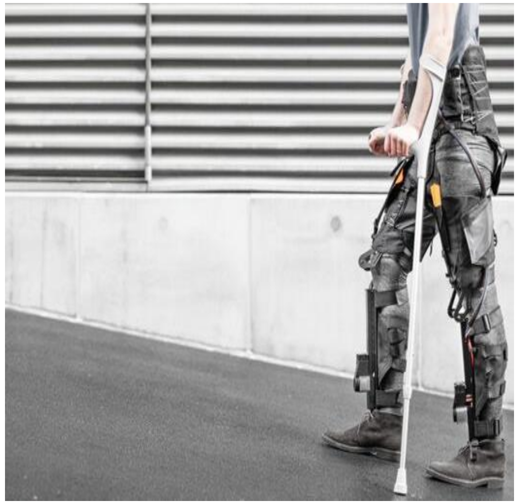
Applications

- Healthcare
  - Rehabilitation (post-stroke and spinal cord injury patients);
  - Assistance;

ALEx, Percro, Pisa

Lopes, Twente Univ.

Elbow Exosuit,
Heidelberg University & Percro



Maxx, ETH

Applications

- Healthcare
  - Rehabilitation (Post-stroke and spinal cord injury patients);
  - Assistance;

- Industrial/Military/Rescue
  - Power Augmentation
  - Assistance
  - Remote Operation

Body Extender, Percro

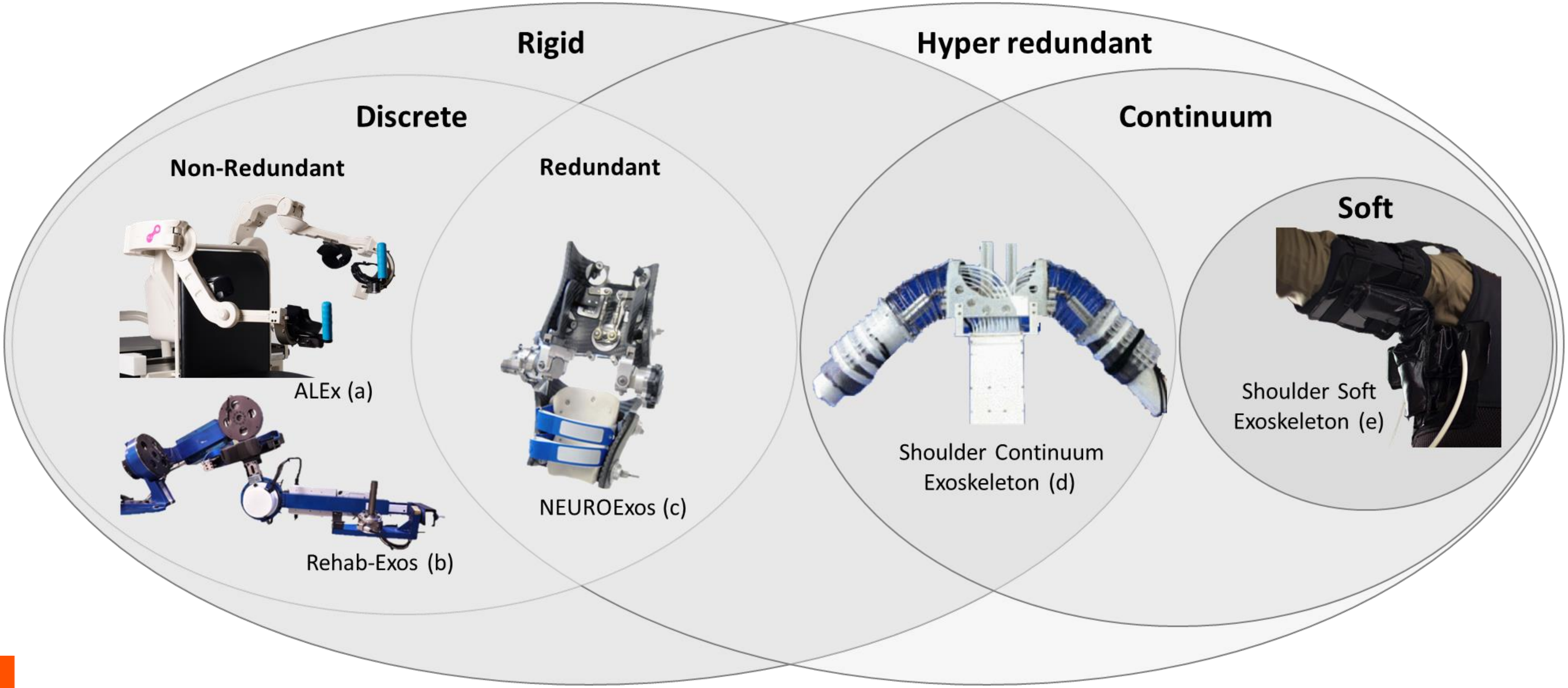
MATE, Comau (Passive)

H-Wex, Hyundai

Applications and Interactions

Rehabilitation	→	Robot interacts with user and virtual environment
Remote Operation	→	Robot interacts with user and real remote environment
Assistance	→	Robot interacts with user

Mechanical aspects: from Rigid to Soft



Rigid

Discrete

Non-Redundant

ALEx (a)

Rehab-Exos (b)

Redundant

NEUROExos (c)

Hyper redundant

Continuum

Shoulder Continuum Exoskeleton (d)

Soft

Shoulder Soft Exoskeleton (e)

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From Rigid to Soft

- Introducing compliance in the actuation stage
  - Series elastic actuators (SEA)[1];
  - Variable stiffness actuators (VSA)[2];
  - Variable impedance actuators (VIA)[3];
  - Soft materials → safe and gentle interaction[4].

[1] G. A. Pratt and M. M. Williamson, “Series elastic actuators”, IEEE/RSJ International Conference on, 1995

[2] G. Tonietti, R. Schiavi, and A. Bicchi, “Design and control of a variable stiffness actuator for safe and fast physical human/robot interaction”, in Robotics and Automation, ICRA, 2005

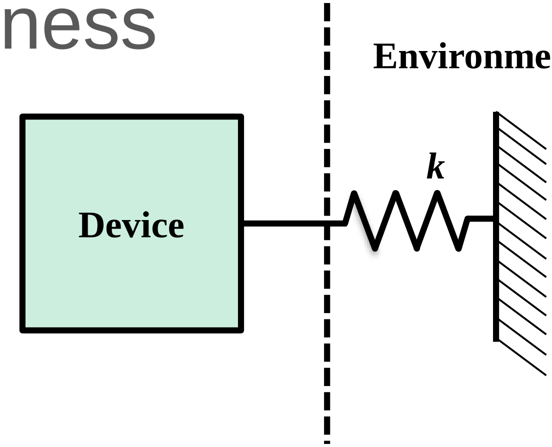
[3] B. Vanderborght, A. Albu-Schäffer, A. Bicchi, E. Burdet, D. G. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh et al., “Variable impedance actuators: A review”, Robotics and autonomous systems, 2013.

[4] A. T. Asbeck, S. M. De Rossi, I. Galiana, Y. Ding, and C. J. Walsh, “Stronger, smarter, softer: next-generation wearable robots”, IEEE Robotics & Automation Magazine, 2014.

P-HRI Controls

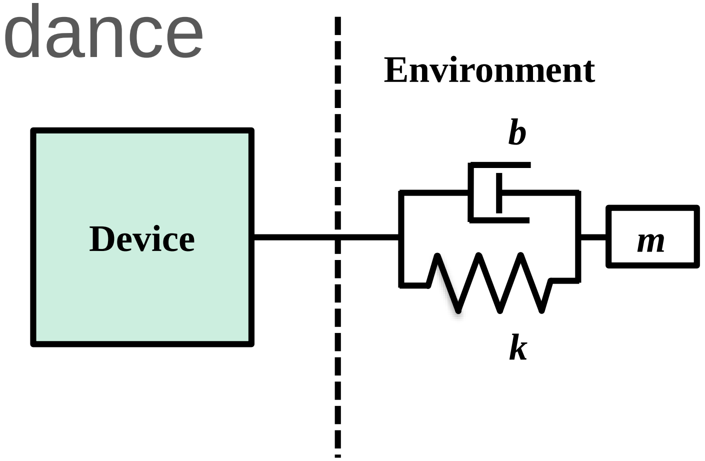
Theoretical tools

Stiffness



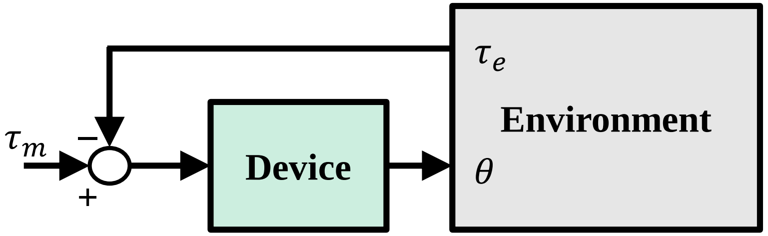
$$f_e = g(x, \dot{x}, \ddot{x}) \qquad k = \frac{\partial g(x, \dot{x}, \ddot{x})}{\partial x}\Big|_{x_0}$$

Impedance

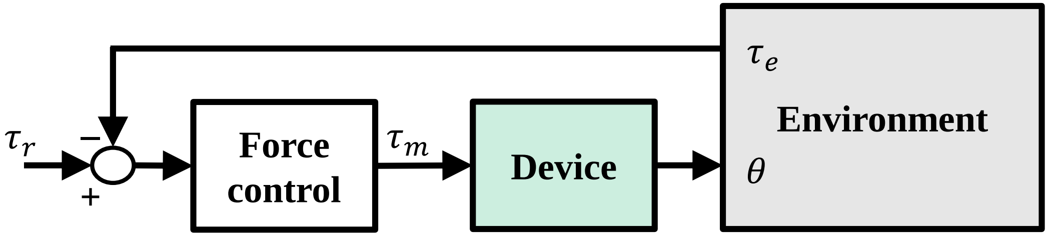


$$Z(s) = \frac{F_e(s)}{JX(s)}$$

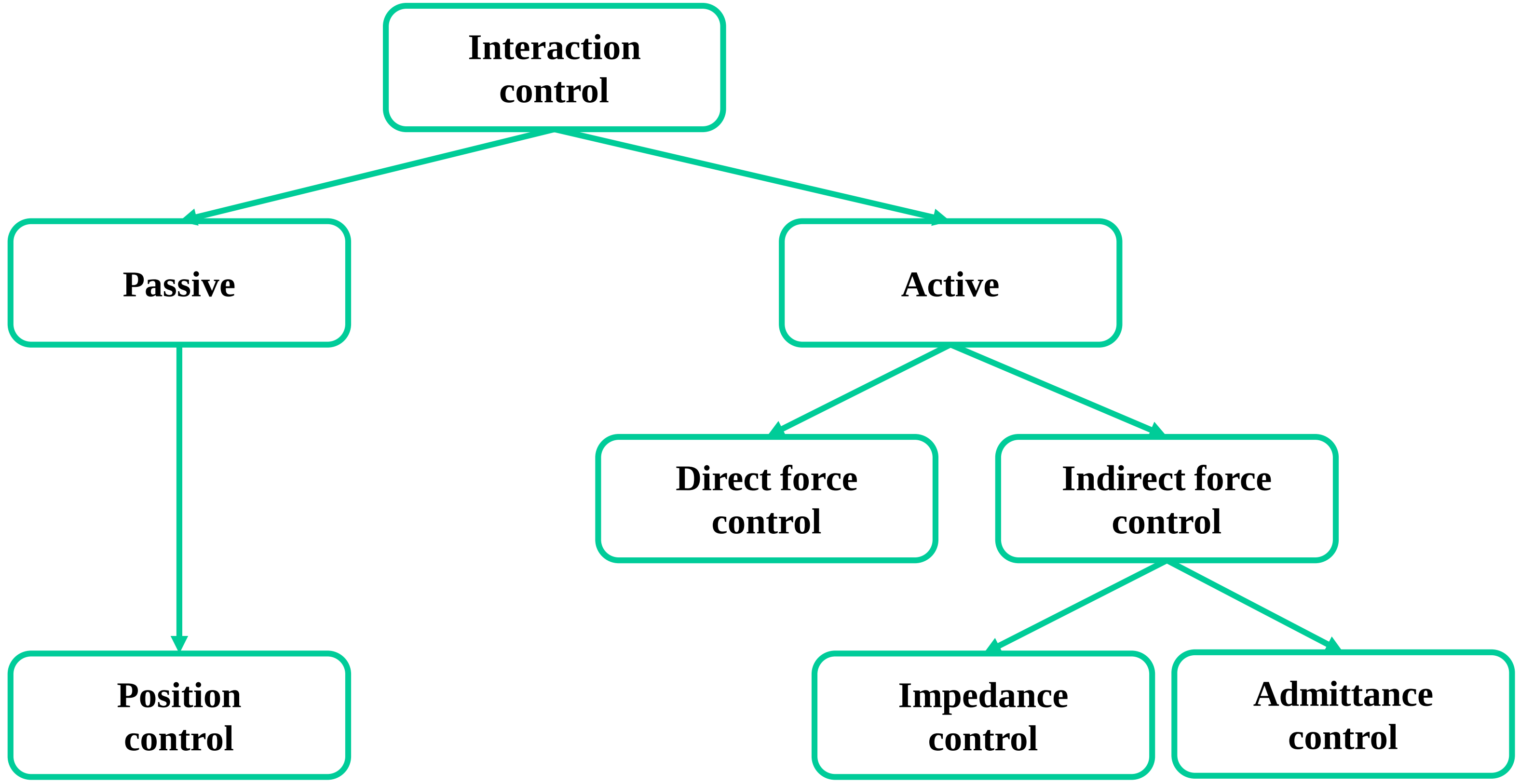
Back-drivability



Non Back-drivability



Interaction Control Taxonomy[5]



Interaction control

Passive

Active

Direct force control

Indirect force control

Position control

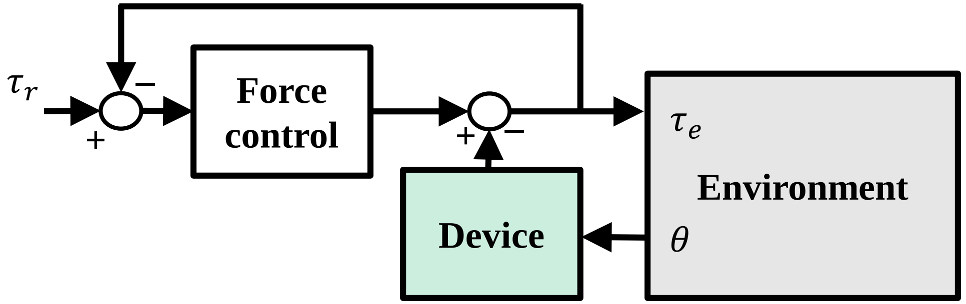
Impedance control

Admittance control

[5] A. Calanca, R. Muradore, and P. Fiorini, "A review of algorithms for compliant control of stiff and fixed-compliance robots", IEEE/ASME Transactions on Mechatronics, 2016.

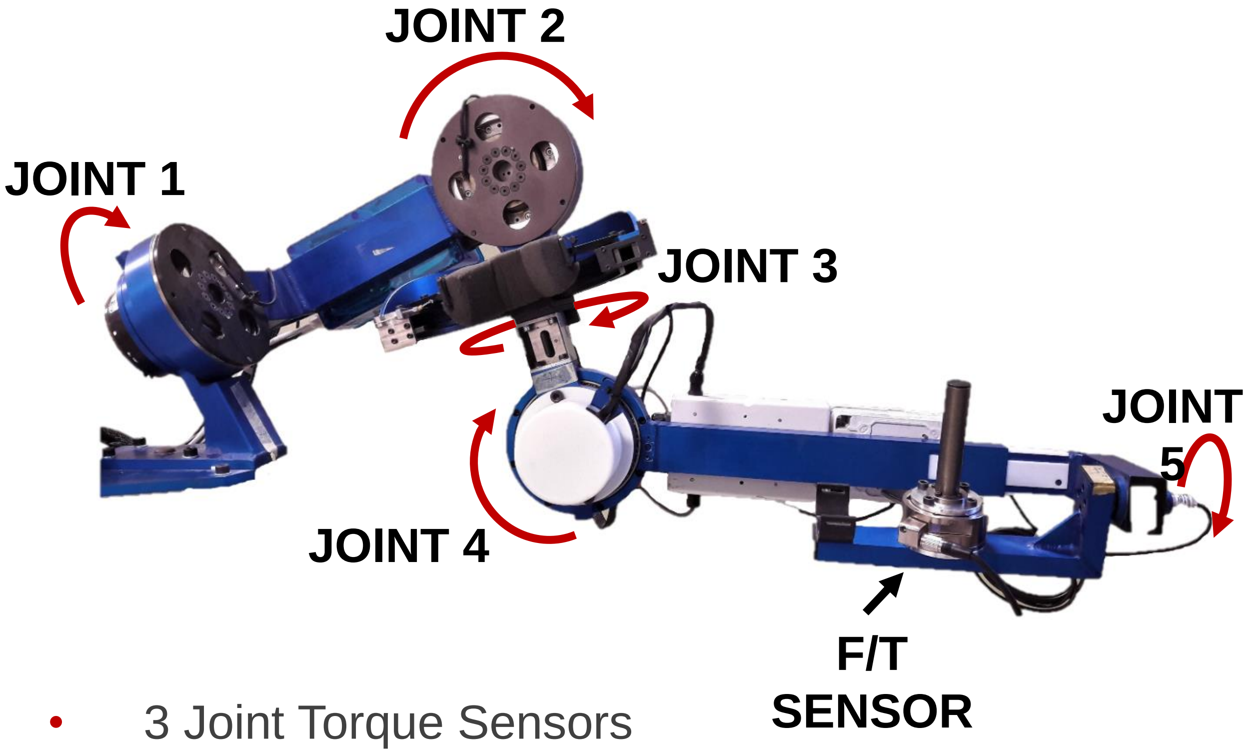
Interaction Controls

Direct Force/Torque Control



- Serial Kinematics
- 5 DOF: 4 Actuated
- Transmission Ratio (1:100) → Not backdrivable

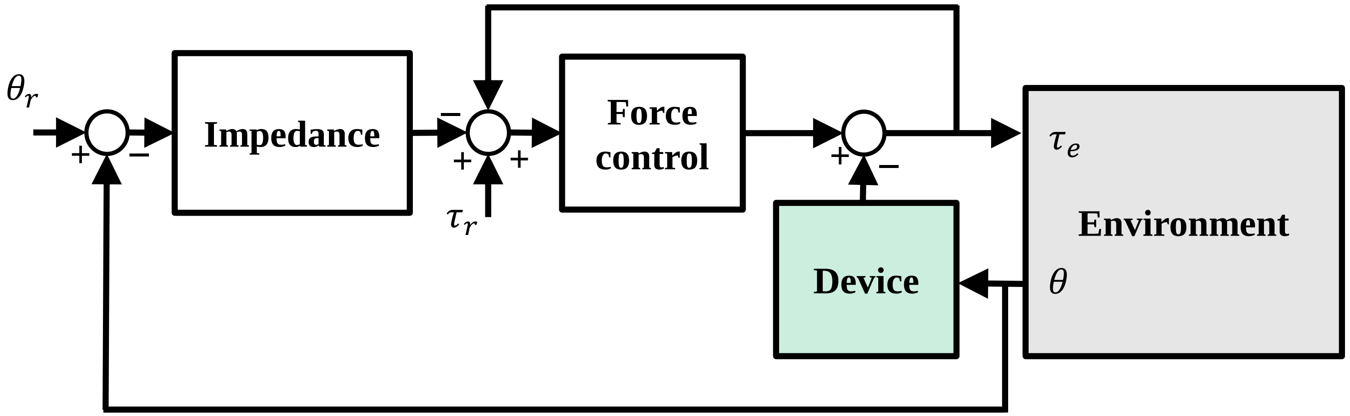
The Rehab-Exos



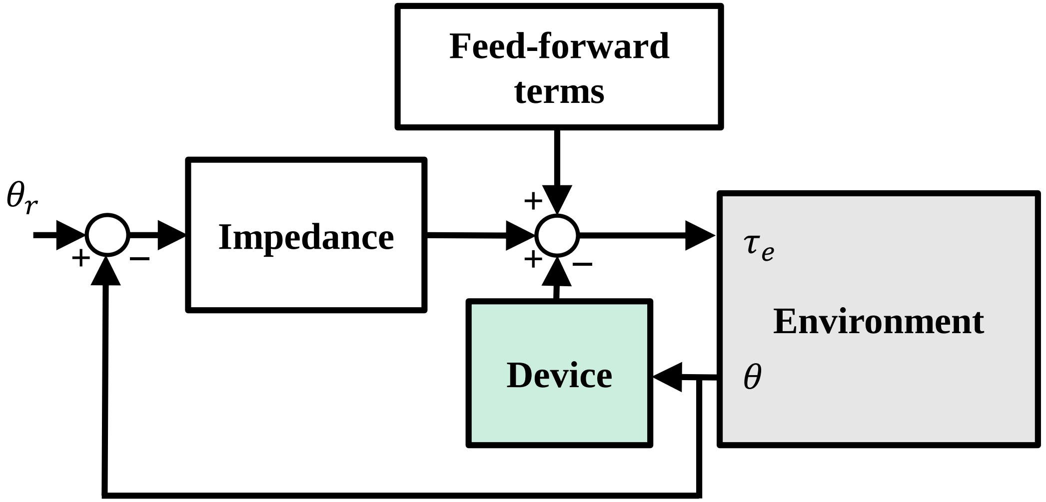
- 3 Joint Torque Sensors
- 6 axis Force/Torque Sensor at e.e.
- 150 N at the e.e. in every point of workspace

Interaction Controls

Impedance Control (Explicit)



Impedance Control (Implicit)



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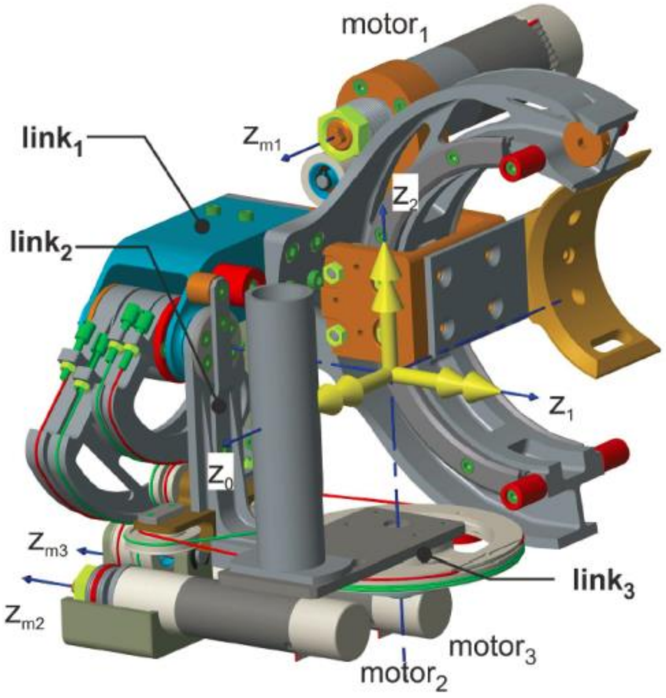
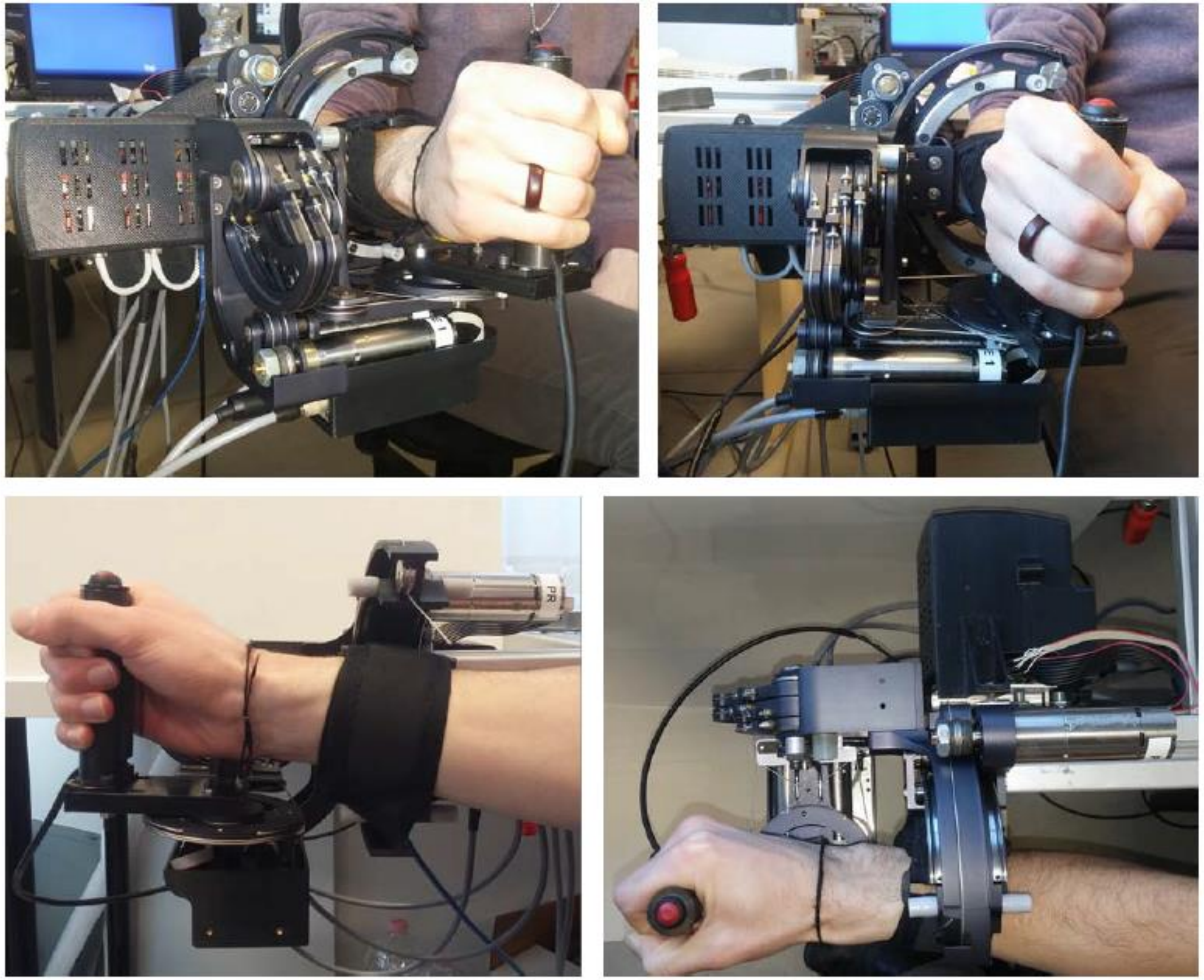
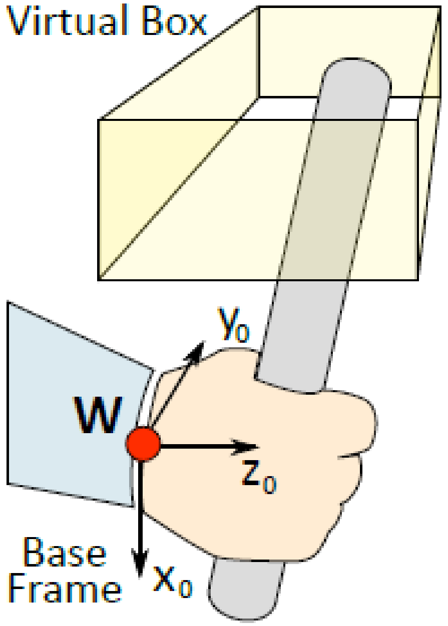
WRES: Wrist Exoskeleton

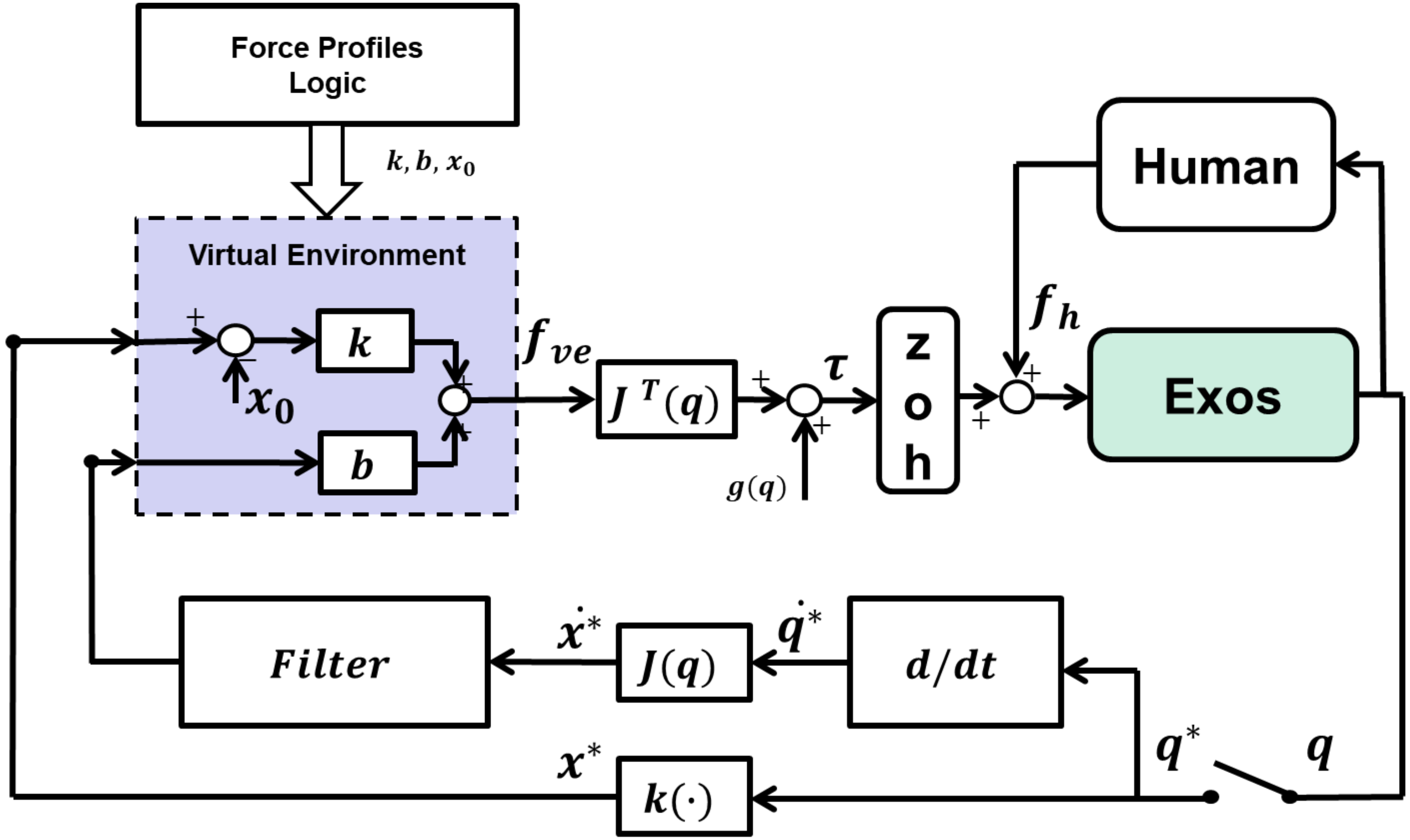


- Low weight
- Optimal mass distribution
- High torque/mass ratio



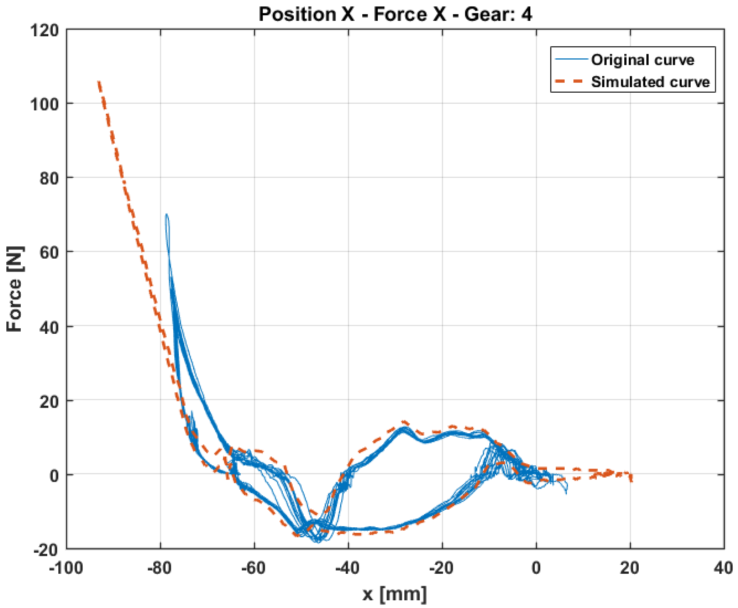
Interaction with VE

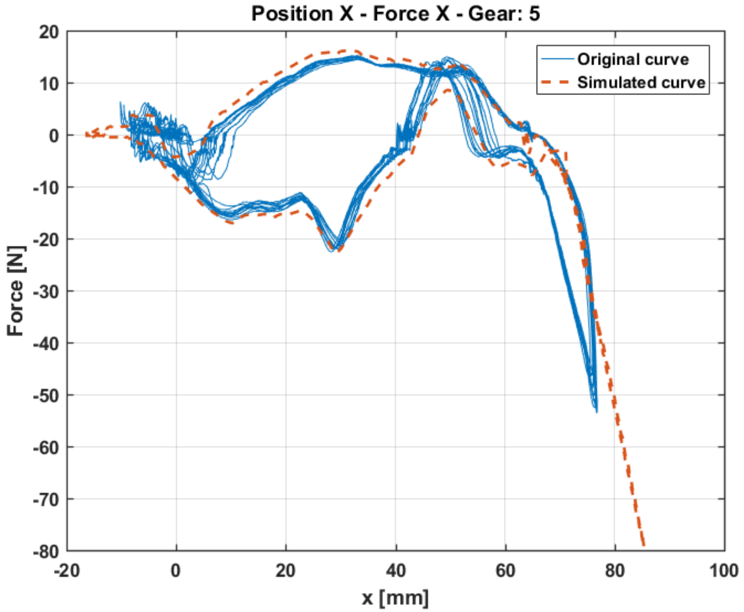




Impedance Control in Haptics

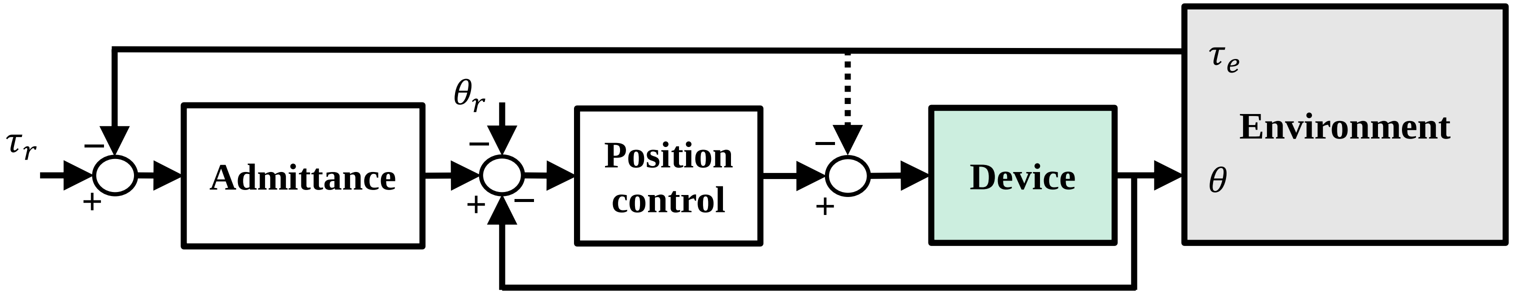
Automotive Gearshift Simulator





Interaction Controls

Admittance Control (Explicit)



Used for:

Further details later!

Passivity and Teleoperation

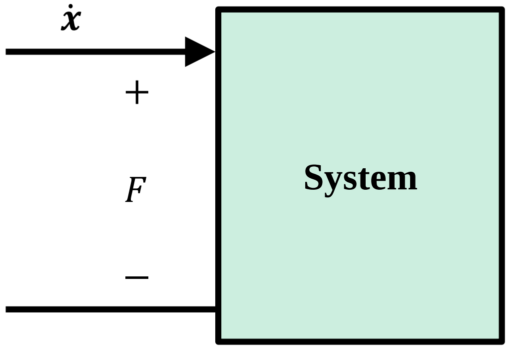
Interaction Control Limits

- It is not possible to render and infinite stiffness
- Each device is characterized by a critical stiffness

Theoretical tools

Passivity

A system is passive if it absorbs more energy than the one returned



If we define Positive the input power (P),

$$P = F * \dot{x}$$

A system is passive if:

$$P = F * \dot{x} = \frac{dE_{store}}{dt} + P_{diss}$$

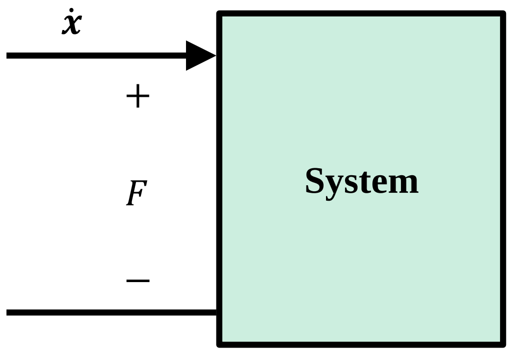
where

$E_{store} > E_{min}$,	E_{store} is a storing energy function
$P_{diss} > 0$,	P_{diss} is a dissipative power function

1. In a passive system the energy is stored or dissipated
2. The passive system cannot generate energy and can only return the stored energy
3. The energy returned by the system is limited by the stored energy

Theoretical tools

Passivity – Effect of Quantization



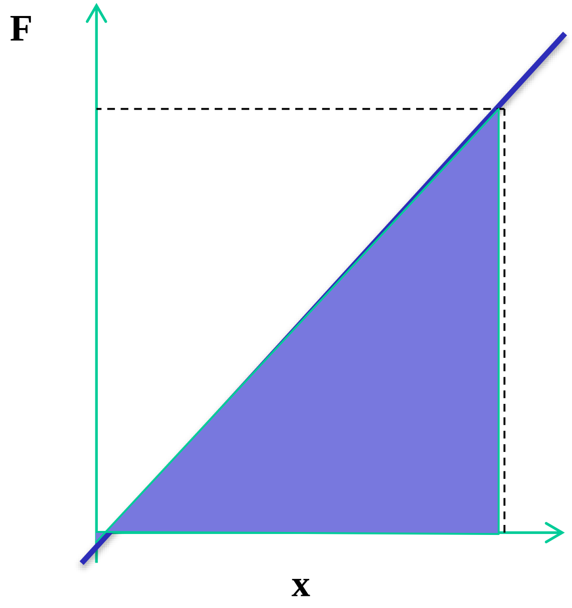
Consider the energy stored in a spring with stiffness K

$$\boldsymbol{F = K * x} \quad \text{(Hook's law)}$$

$$E = \frac{1}{2}kx^2$$

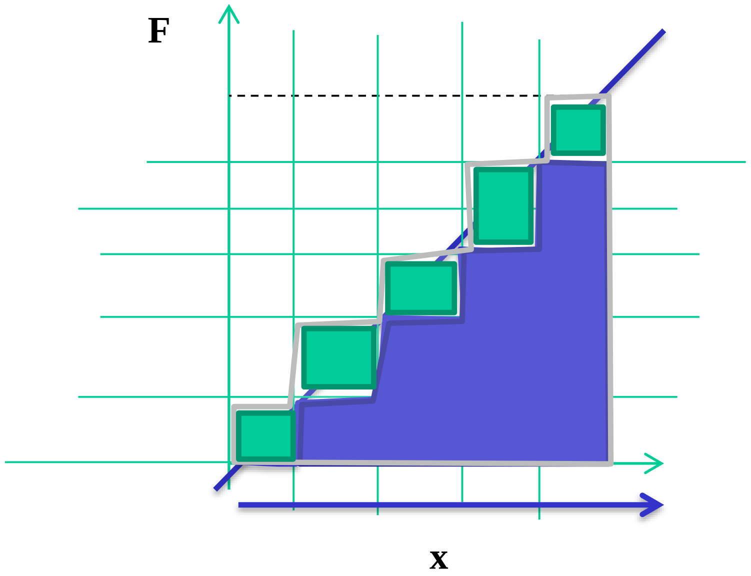
If we consider a constant velocity and a sample time of T, the system generate an amount of energy:

$$k\dot{x}^2T^2$$

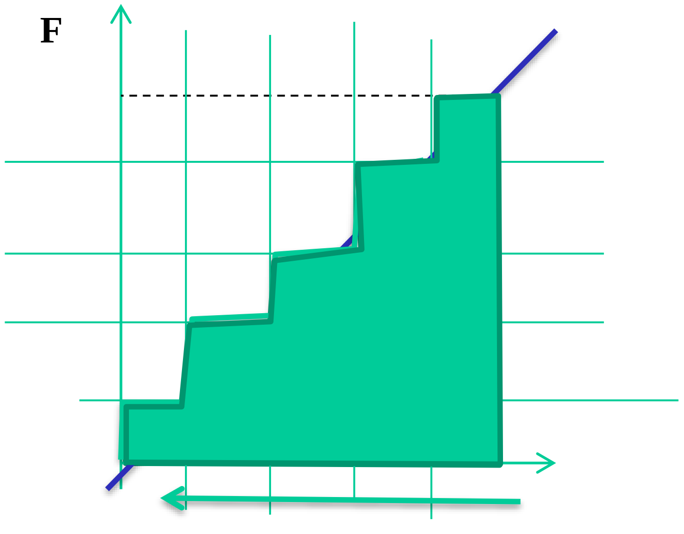


If we consider quantization

Press phase

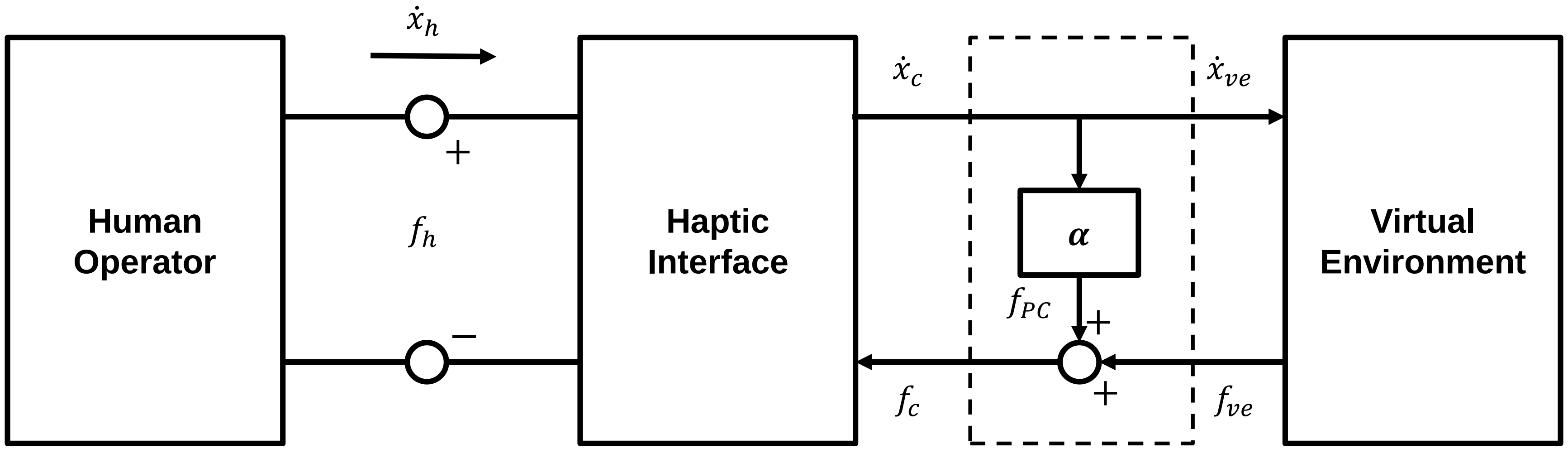


Release phase



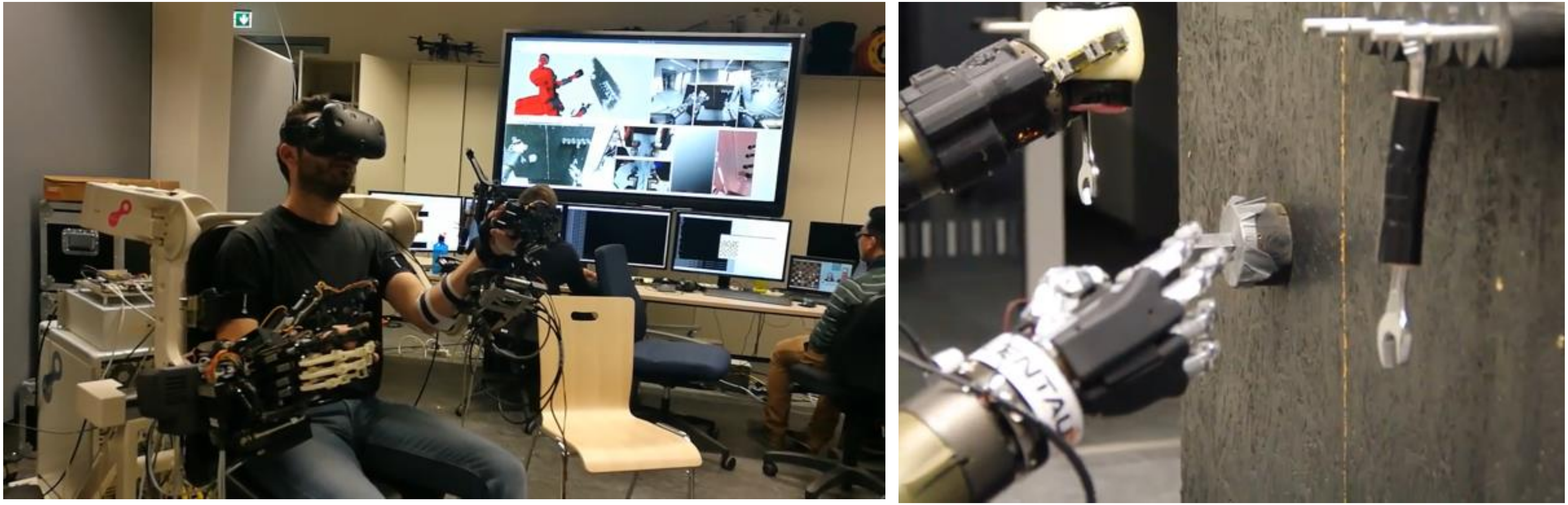
x

Time Domain Passivity Approach



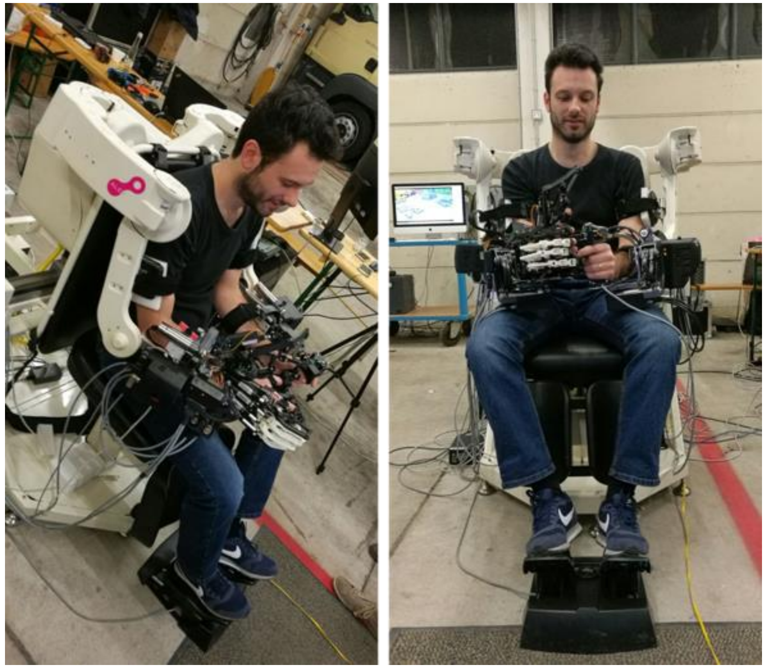
[6] B. Hannaford and J.-H. Ryu, “Time-domain passivity control of haptic interfaces”, IEEE Transactions on Robotics and Automation, 2002.

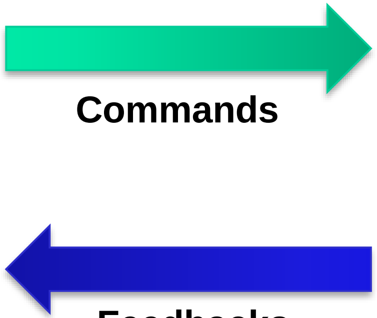
Interaction with remote env.



Interaction with remote env.

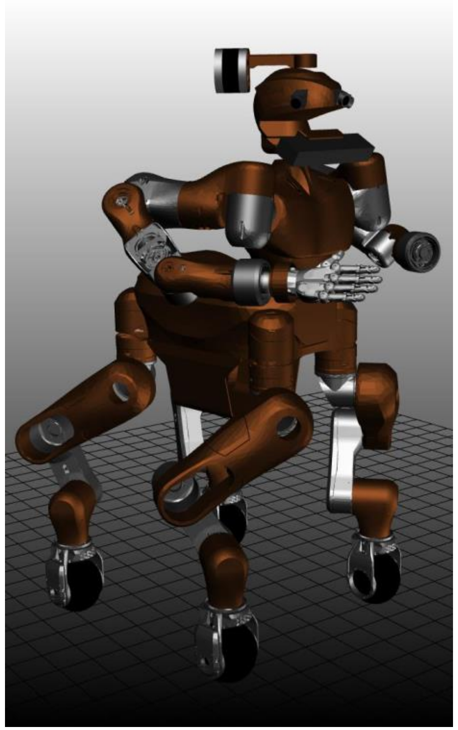
CENTAURO – Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot





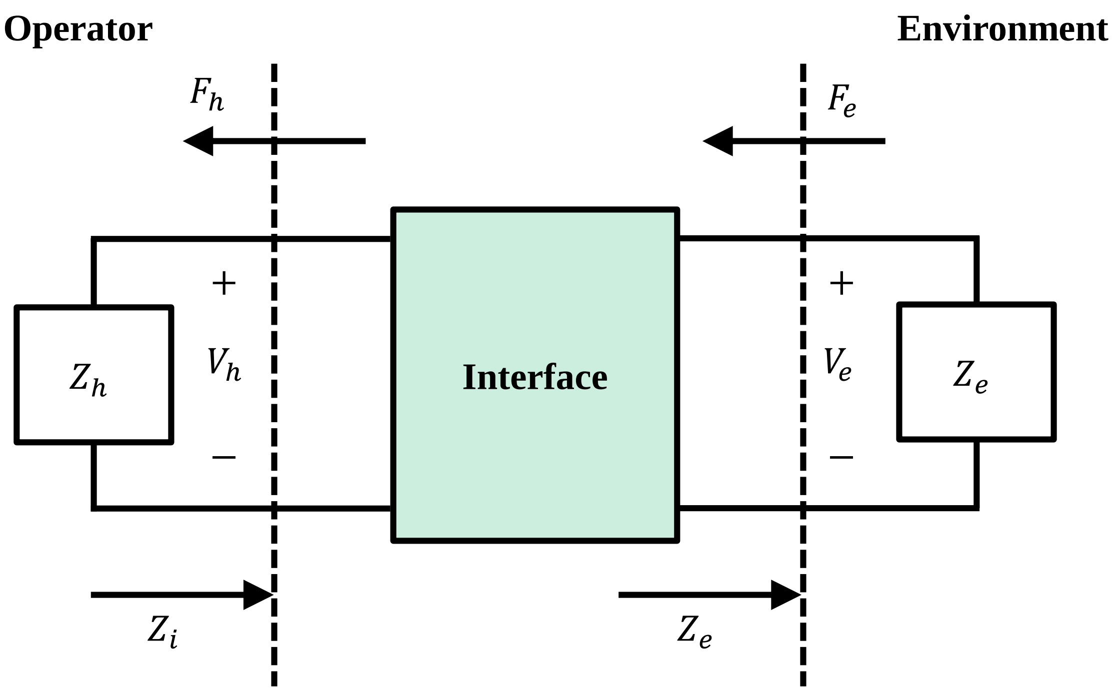
Commands

Feedbacks



Theoretical tools

Transparency



Environment force $\boldsymbol{F_e = Z_e * V_e}$

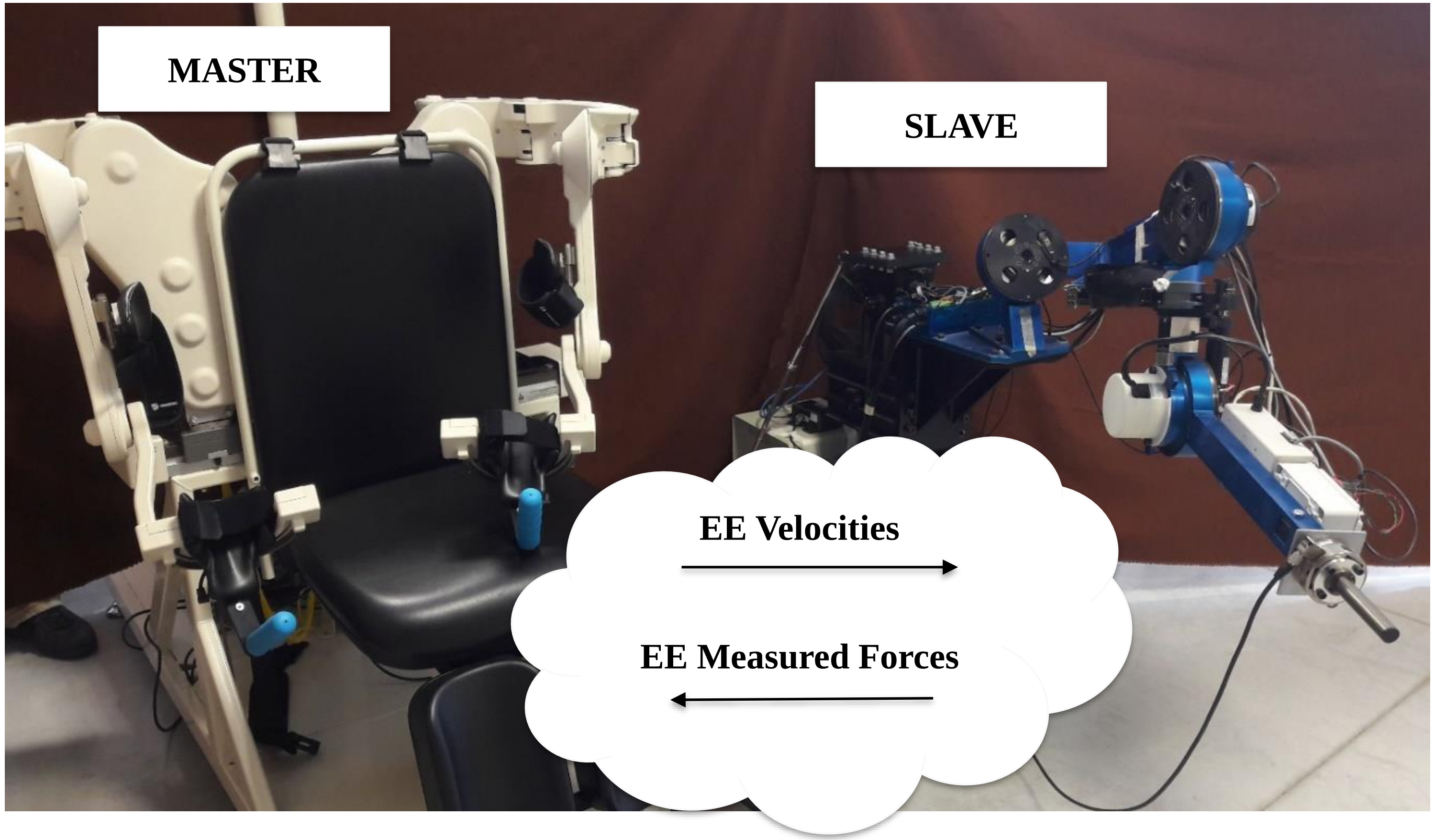
Human force $\boldsymbol{F_h = Z_i * V_h}$

The interface is transparent if [14]

$$\boxed{\boldsymbol{Z_i = Z_e}}$$

[14] D. A. Lawrence, “Stability and transparency in bilateral teleoperation”, IEEE transactions on robotics and automation, 1993

Transparency and Teleoperation



With Position - Measured Force Control Schema

Effect of delay

80ms communication delay &
NO Passivity Controller

Unstable interaction with remote environment

80ms communication delay &
Passivity Controller ON

Stable interaction with remote environment

BUT, Loss of transparency!

Soft Exosuit for Assistance

Why a soft structure?

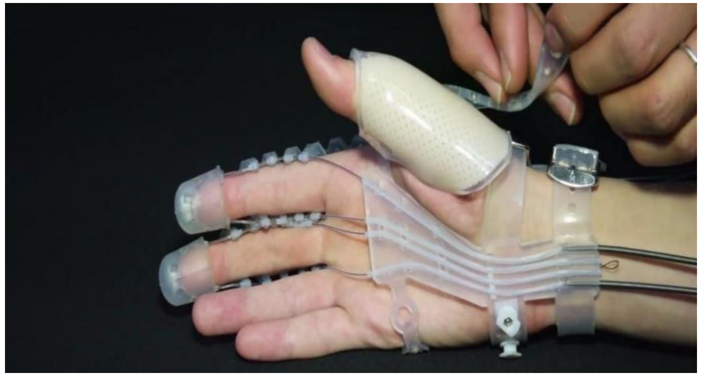
- **No rigid structures → no misalignment between the robot's and user's joints → no discomfort**

Neurological musculoskeletal disorders (WMSD)

- **On the complementary way of robotic rehabilitation based on exercising workstation, and rigid exoskeleton, the Exosuit strategy emphasize <u>portability</u> and <u>ergonomics</u> for the following applications:**
  - Stroke/SCI assistance in activities of daily living
  - Walking support/stabilization

Exosuits, Harvard

Polyglove, SNU



SuperFlex, SRI

Exosuit Effectiveness

- **Exosuits have been proven to be successful in:**
  - Reducing the metabolic cost of human walking in both stroke patients [7] and healthy subjects [8];
  - Lowering the muscular effort required for:
    - **Upper limb movements;**
    - **Sit-to-stand transitions;**
  - Aiding extension and flexion of the fingers in stroke and spinal cord injury patients [9].

[7] L. N. Awad et al., “A soft robotic exosuit improves walking in patients after stroke,” Sci. Transl. Med., 2017.

[8] B. T. Quinlivan et al., “Assistance magnitude versus metabolic cost reductions for a tethered multiarticular soft exosuit,” Sci. Robot., 2017.

[9] H. In and K.-j. Cho, “Exo-Glove : Soft wearable robot for the hand using soft tendon routing system,” IEEE Robot. Autom., 2015.

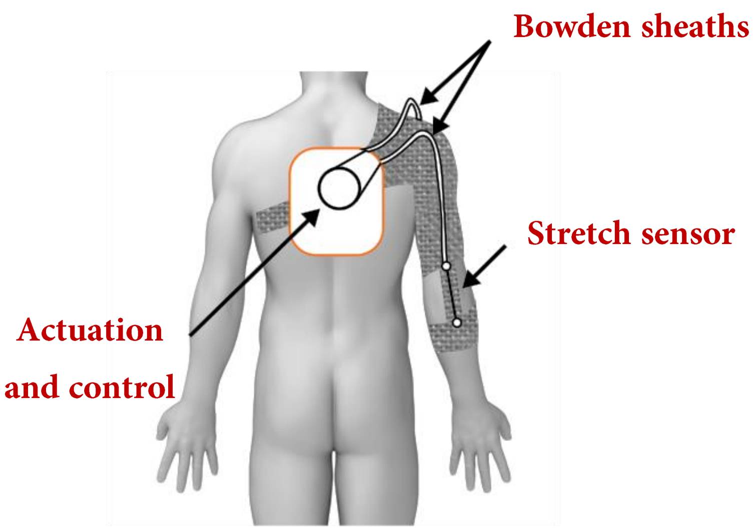
Design & Control of a Soft Elbow Exosuit

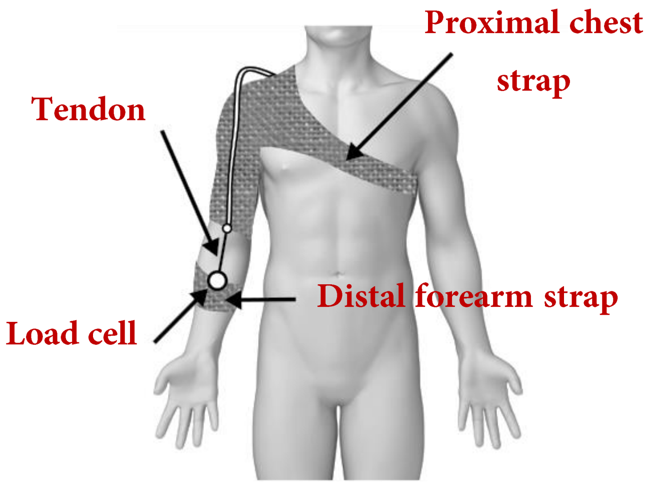
Objectives:

- **Design of a soft elbow exosuit for assistance in ADL tasks:**
  - Arm’s load relieving;
  - Muscular effort reduction in moving and sustaining external loads;
- **The assistive exosuit should not affect the human kinematics and has to be comfortable;**
- **Develop an untethered control architecture:**
  - Embeddable in a box, simple to wear;
  - Robust and safe.

Suit’s Design

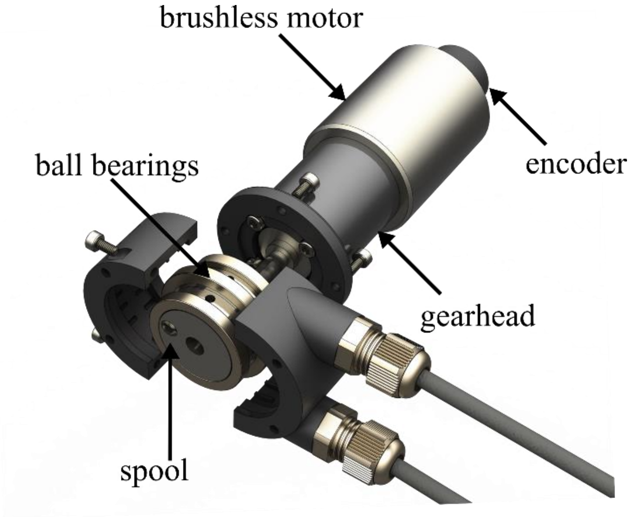
- The exosuit comprises an actuation stage, driving a pair of tendons, a wearable component made of fabric and joint sensors.
- The elbow angle is measured by a capacitive stretch sensor made of silicone. A load cell embedded in the suit reads the assistive torques.





Suit’s Design

- The actuation stage is located proximally, i.e. worn as a backpack, and transmits power to the suit via Bowden cables. It is composed by:
    - Brushless motor (70W)+ 28:1 reduction planetary gearhead;
    - Incremental encoder;
    - Spool around which two tendons (superelastic NiTi wire, Ø 0.5mm) are wrapped in opposite directions;
    - Plastic casing + 3 ball bearings keep the tendons from derailing when they’re slack.



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Control Strategy

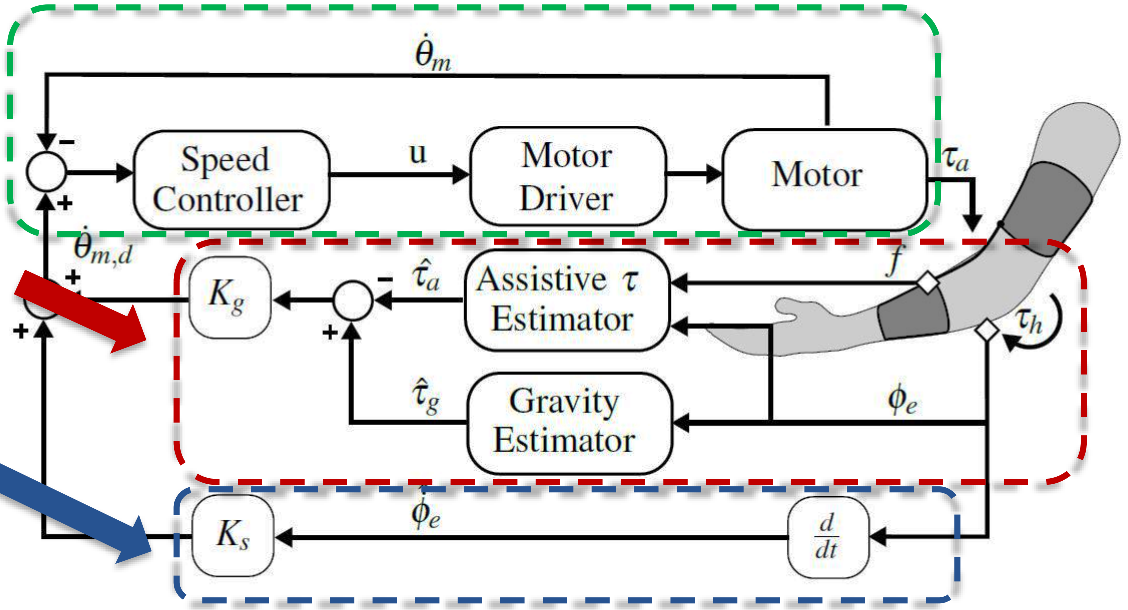
- Control strategy is to follow the user's elbow movements whilst compensating for gravity:

Speed loop

Gravity compensation

+

Motion assistance



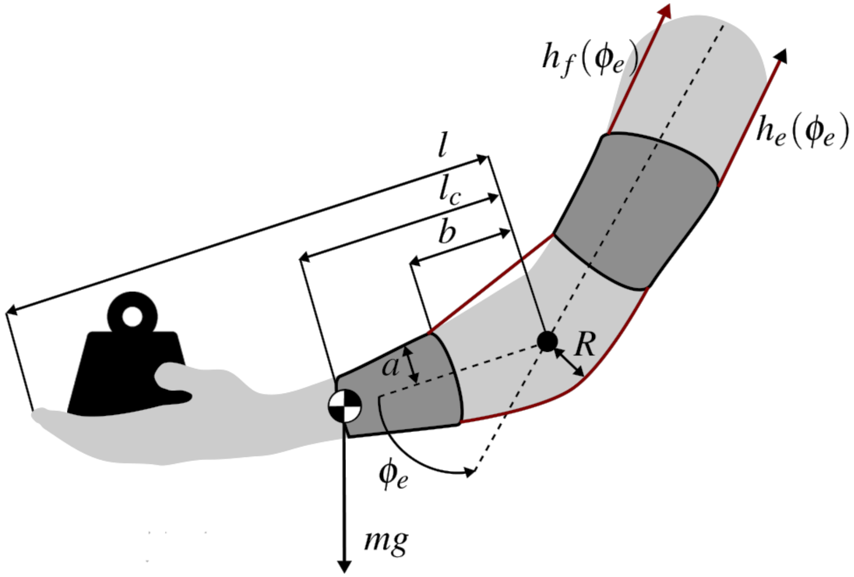
Control Stategy

Assistive Torque Estimator

$$\widehat{\tau}_a = J(\phi_e) f$$

$$J(\phi_e) = \frac{\partial h^T}{\partial \phi_e}(\phi_e)$$

$$h = \begin{bmatrix} h_f(\phi_e) & h_e(\phi_e) \end{bmatrix}^T$$



$$h_f(\phi_e) = 2\sqrt{a^2 + b^2}\cos\left(\tan^{-1}\left(\frac{a}{b}\right) + \frac{\phi_e}{2}\right) - 2b$$

$$h_e(\phi_e) = R\phi_e$$

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Control Stategy

Desired velocity computation

From arm dynamics

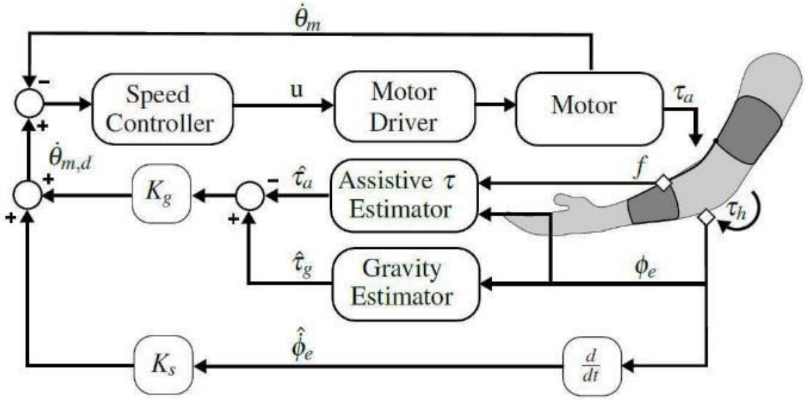
$$\tau = \tau_h + \tau_a = \frac{2}{3} m l^2 \ddot{\phi}_e + b_e \dot{\phi}_e + m g l_c \sin\phi_e$$

The human effort is

$$\tau_h = \frac{2}{3} m l^2 \ddot{\phi}_e + b_e \dot{\phi}_e + \underbrace{\boxed{m g l_c \sin\phi_e}}_{\boldsymbol{\tau_g}} - \tau_a$$

For smooth movements we can neglect the term $\frac{2}{3} m l^2 \ddot{\phi}_e$

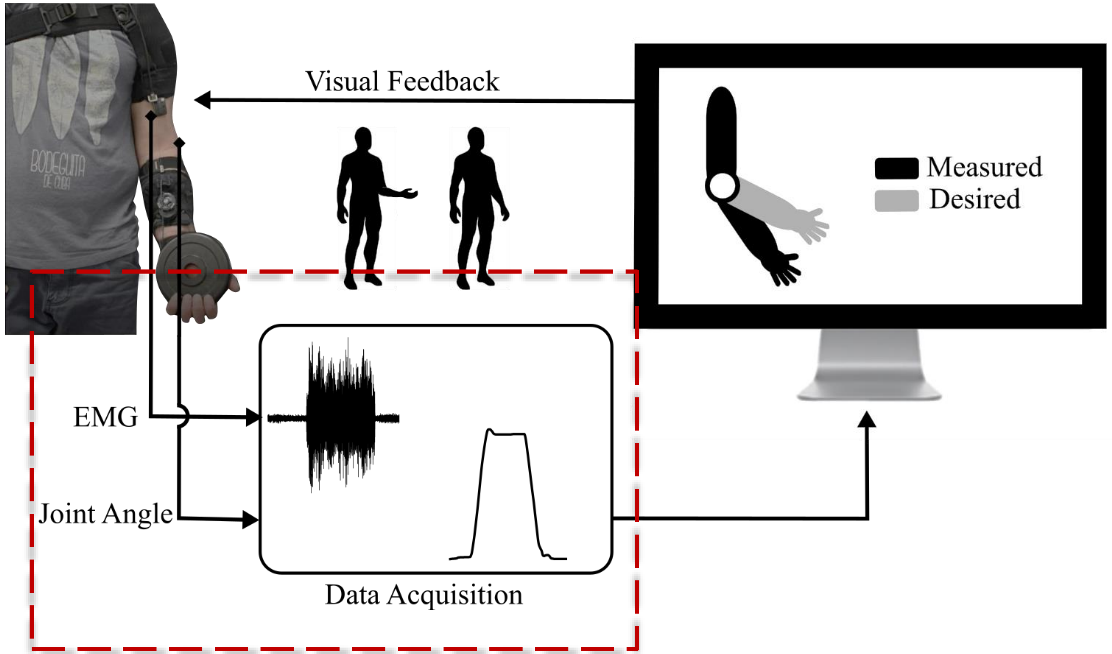
$$\dot{\theta}_{m,d} = K_g(\hat{\tau}_a - \hat{\tau}_g) + K_s \hat{\dot{\phi}}_e$$



Validation - Experiments

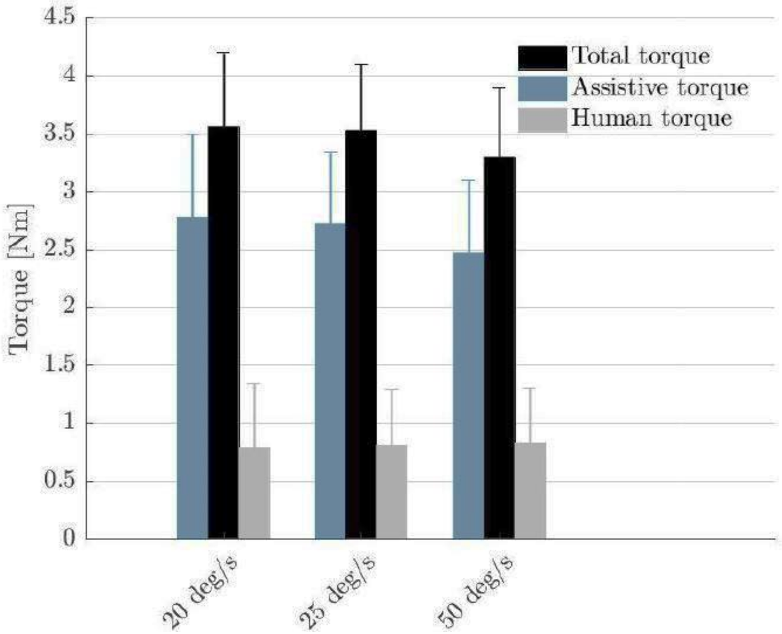
Protocol

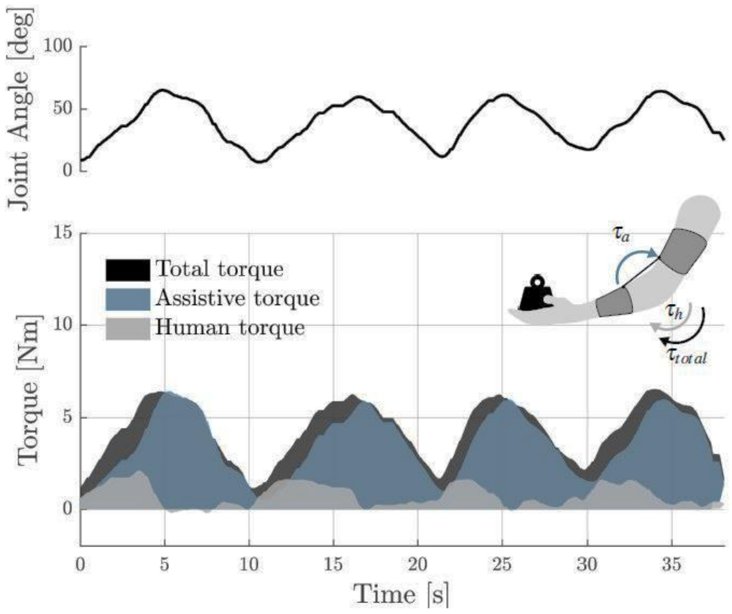
- Sinusoidal visual reference for the human;
- 3 velocities: 20%, 30% and 60% of ADL velocity;
- 1.25 Kg load;
- EMG of biceps brachii and Joint Angle acquisition.



Validation - Results

Joint Angles and Torques

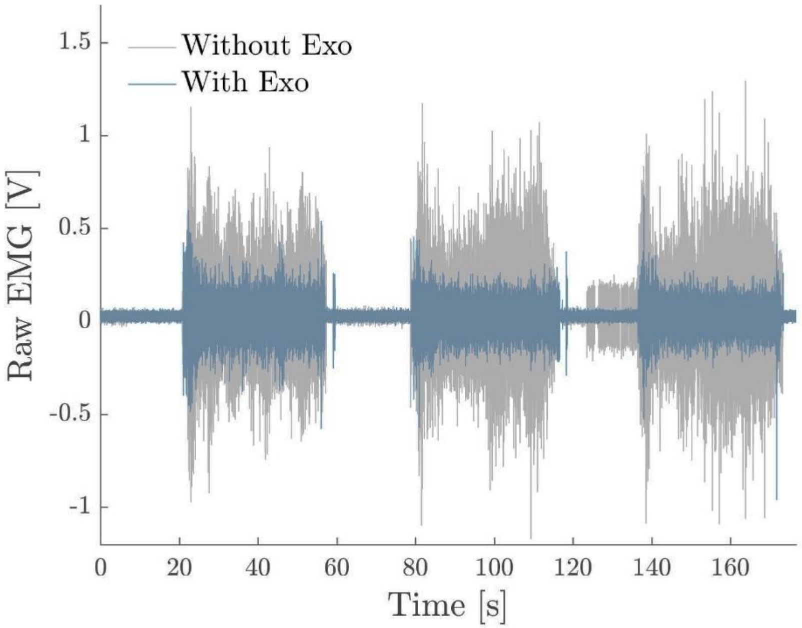


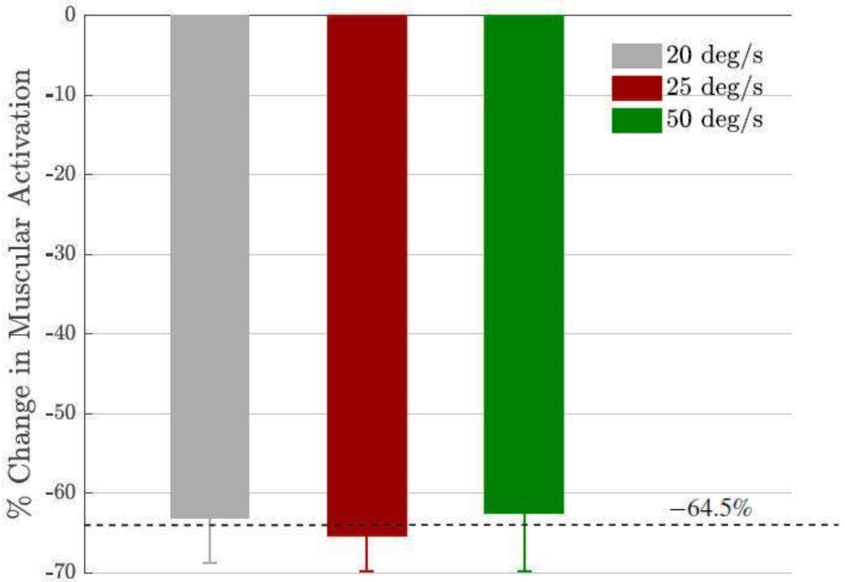


(b)

- The exosuit relieves the subject from nearly 77% of the total moment required to perform the movement.

Validation - Results





- EMG Activation decreases by 64.5% on average when the exosuit is worn.

Call for Thesis

Call for Thesis

- **Topic #1:** Development and Intelligent Control Strategies of an Assistive Soft Exosuit for the upper-body
  - Use of EMG signals for control
- **Topic #2:** Development and Control Strategies for an Assistive Soft Glove
- **Topic #3:** Development of Soft Robotic Hand

  Control Strategies for Telemanipulation and Telerehabilitation

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- **Topic #4:** Control Strategies for an Assistive Leg Exoskeleton
- **Topic #5:** Control of robots for maintenance and inspections
    - **UGV**
    - **Vision-based control**
- **Topic #6:** Development of a Driving Co-Pilot for assistance and driving style evaluation

ISTITUTO
DI TECNOLOGIE DELLA
COMUNICAZIONE,
DELL'INFORMAZIONE
E DELLA
PERCEZIONE

Scuola Superiore
Sant'Anna

Thank you for the attention!

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