

# Control of a multi-robot cooperative team guided by a human operator

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Final Presentation Master Thesis

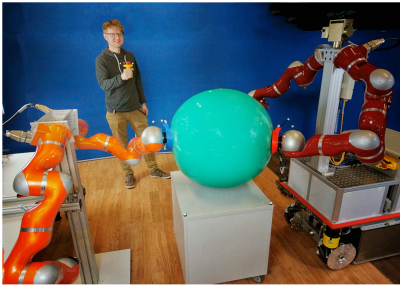
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# Shared control with a human in the loop

Human reasoning combines with the enhanced flexibility of multiple robots

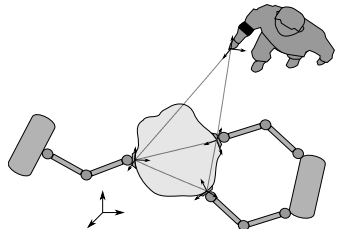


Non-restrictive input interfaces allow for almost arbitrary trajectories

*How can we ensure stability and safety with a human in the loop?*

# Problem setting

- A set of robots manipulating a common object
- A human guiding the formation by hand motion



## Goals for control design

- Automatic preservation of formation
- Stability with arbitrary trajectories
- Safe behaviour with humans on-site

# Related Work

## Robot-team control

- (Inverse) grasp-matrix approaches [SC92,CCMV08]
- Virtual structures [Str01,SMH15]

## Human in the loop

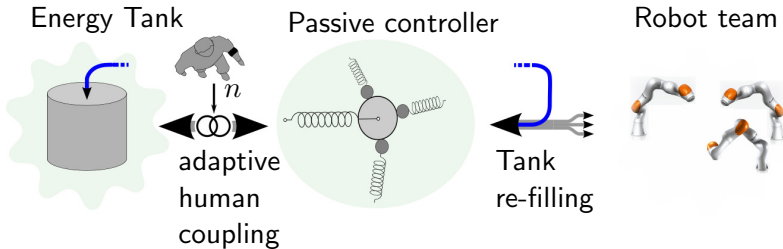
- Bilateral tele-manipulation [LS05]
- Human leader - robotic followers [SMH15,SMP14]
- Gesture-based Control [GFS+14]

## Safety by energy-regulation

- Adaptive impedance control of a single manipulator [TVS14]
- Energy observer in physical human-robot interaction [GSLP16]

- Stability with non-restrictive input interfaces is unexplored
- Passivity is commonly used to cope with unmodelled dynamics
- Energy-based safety metrics apply for impact limitation

# Overview



- Source for the passive robot-team controller: Energy Tank
- Human user controls the power flow
- Energy supplied to the robots is re-fed into the tank

Energy-consistent description in the *port-Hamiltonian* framework

# port-Hamiltonian systems

Visualize power flow, allow for model-based control design,  
facilitate stability proofs

**Hamiltonian**  $\mathcal{H}$ : total energy of the system

**Port**: power-conjugated pair  $(u, y)$  of *flow*  $u$  and *effort*  $y$  variables

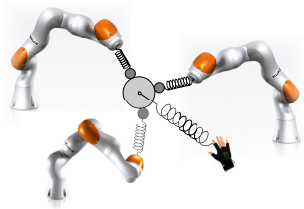
$$\begin{aligned}\dot{x} &= [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x)u \\ y &= B^T(x) \frac{\partial \mathcal{H}}{\partial x}(x)\end{aligned}$$

input-state-output form with *structure*-  $J(x)$ , *dissipation*-  $R(x)$   
and *mapping* matrix  $B(x)$

**Energy balance:**  $\frac{d}{dt} \mathcal{H} = y^T u - \frac{\partial^T \mathcal{H}}{\partial x} R(x) \frac{\partial \mathcal{H}}{\partial x}$  ( $\rightarrow$  passive)

# Model-based control design

*Plants and controllers are energy-transforming devices, which we interconnect to achieve the desired behaviour.* [OSMM01]



## Virtual structure

- Geometric composition of springs, masses and dampers
- Establishing a formation of robots
- Virtually coupling the human
- Energetic model of the real system
- Connection by physical rules (actio = reactio)

## Stability

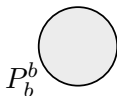
Model errors never influence passivity nor stability [Str01]

# Example controller derivation

Starting from the virtual object...

$$\dot{P}_b^b = C_b \frac{\partial \mathcal{H}}{\partial P_b^b} + I_6 W_b^b$$

$$T_b^{b,0} = I_6 \frac{\partial \mathcal{H}}{\partial P_b^b}$$



Momentum  $P_b^b$  (state), wrench  $W_b^b$  (flow), twist  $T_b^{b,0}$  (effort), centripetal and Coriolis terms  $C_b$

**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b$

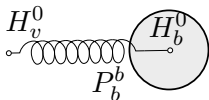


## Example controller derivation

... adding a coupling spring to the user...

$$\begin{pmatrix} \dot{H}_b^v \\ \dot{P}_b^b \end{pmatrix} = \begin{pmatrix} 0 & H_b^v \\ -H_b^{vT} & C_b \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{H}}{\partial H_b^v} \\ \frac{\partial \mathcal{H}}{\partial P_b^b} \end{pmatrix} + \begin{pmatrix} -H_b^v \text{Ad}_{H_0^b} & 0 \\ 0 & I_6 \end{pmatrix} \begin{pmatrix} T_v^0 \\ W_b^b \end{pmatrix}$$

$$\begin{pmatrix} W_v^0 \\ T_b^{b,0} \end{pmatrix} = \begin{pmatrix} -\text{Ad}_{H_0^b}^T H_b^{vT} & 0 \\ 0 & I_6 \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{H}}{\partial H_b^v} \\ \frac{\partial \mathcal{H}}{\partial P_b^b} \end{pmatrix}$$



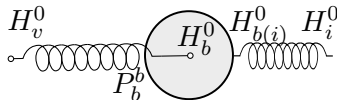
relative configuration  $H_b^v$  (state), desired twist  $T_v^0$  (flow), wrench  $W_v^0$  (effort), adjoint mapping  $\text{Ad}_{H_0^b}$

**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b + V_P(H_b^v)$

## Example controller derivation

... and another spring to the  $i$ -th manipulator.

$$\begin{pmatrix} \dot{H}_b^v \\ \dot{P}_b^b \\ \dot{H}_{b(i)}^i \end{pmatrix} = \begin{pmatrix} 0 & H_b^v & 0 \\ -H_b^{vT} & C_b & -Ad_{H_b^{b(i)}}^T H_{b(i)}^i{}^T \\ 0 & H_{b(i)}^i Ad_{H_b^{b(i)}} & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{H}}{\partial H_b^v} \\ \frac{\partial \mathcal{H}}{\partial P_b^b} \\ \frac{\partial \mathcal{H}}{\partial H_{b(i)}^i} \end{pmatrix} \\ + \begin{pmatrix} -H_b^v Ad_{H_0^b} & 0 \\ 0 & 0 \\ 0 & -H_{b(i)}^i Ad_{H_0^{b(i)}} \end{pmatrix} \begin{pmatrix} T_v^0 \\ T_i^0 \end{pmatrix} \\ \begin{pmatrix} W_v^0 \\ W_i^0 \end{pmatrix} = \begin{pmatrix} -Ad_{H_0^b}^T H_b^{vT} & 0 & 0 \\ 0 & 0 & -Ad_{H_0^{b(i)}}^T H_{b(i)}^i{}^T \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{H}}{\partial H_b^v} \\ \frac{\partial \mathcal{H}}{\partial P_b^b} \\ \frac{\partial \mathcal{H}}{\partial H_{b(i)}^i} \end{pmatrix}$$



**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b + V_P(H_b^v) + V_P(H_{b(i)}^i)$

# Modelling of rigid contact

In cooperative manipulation it is common to assume a rigid connection of manipulators and object.

**Kinematic constraints**  $0 = A^T(x) \frac{\partial \mathcal{H}}{\partial x} \rightarrow \text{DAEs}$

## Solved input-state-output form

$$\begin{aligned}\dot{x} &= [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x)u \\ &\quad + A(A^T M^{-1} A)^{-1} A^T M^{-1} (u + C \frac{\partial \mathcal{H}}{\partial x}) \\ y &= B^T(x) \frac{\partial \mathcal{H}}{\partial x}(x)\end{aligned}$$

Constraint matrix  $A$ , inertia matrix  $M$ , centripetal force matrix  $C$

Rigid connections are power-conservative.[Sch13]

# Energy tanks

**Virtual storage element:** Energy function  $\mathcal{T}(x_t) = \frac{1}{2}x_t^2$

$$x_t = u_t$$

$$y_t = \frac{\partial \mathcal{T}(x_t)}{\partial x_t} (= x_t)$$

Interconnection of tank and controller by a transformer/gyrator

$$u = ny_t$$

$$u_t = -n^T y$$

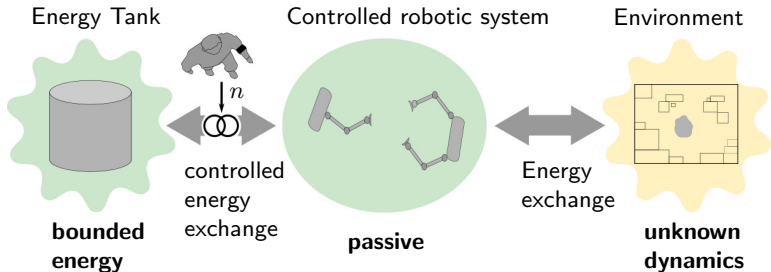
The interconnection is power-continuous for any ratio  $n$

For  $n = \frac{w}{x_t}$ ,  $w$  is the new control input

$$\dot{x} = [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x) \frac{w}{x_t} y_t$$

$$y = B^T(x) \frac{\partial \mathcal{H}}{\partial x}(x)$$

# Re-filling and energy balance



*Lossy robots and unknown energy exchange with the environment*  
 Controller dissipation and power supplied to the robots is re-fed into the tank, i.e.  $\dot{\mathcal{T}}(x_t) + \dot{\mathcal{H}} = 0$ .

$$\underbrace{\dot{\mathcal{T}}(x_t) + \frac{\partial^T \mathcal{H}}{\partial x} R(x) \frac{\partial \mathcal{H}}{\partial x} + \sum_{i=1}^n W_i^{0T} T_i^0}_{\text{compensation}} = -\dot{\mathcal{H}} + \sum_{i=1}^n W_i^{0T} T_i^0$$

# Safety metrics and adaptive stiffness

Minimal kinetic energies that result in severe injuries TVS14

$$V_{K,\min} = \begin{cases} 517 \text{ J} & \text{adult cranium bone failure} \\ 127 \text{ J} & \text{infant cranium bone failure} \\ 30 \text{ J} & \text{neck fracture} \end{cases}$$

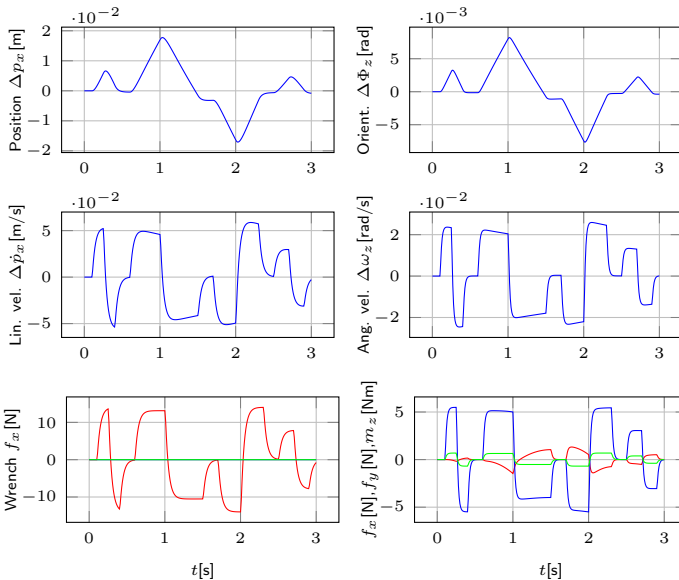
*How can we change user commands to comply with these limits?*

Human hand is stiff when moving slow, compliant when fast [Hog84]

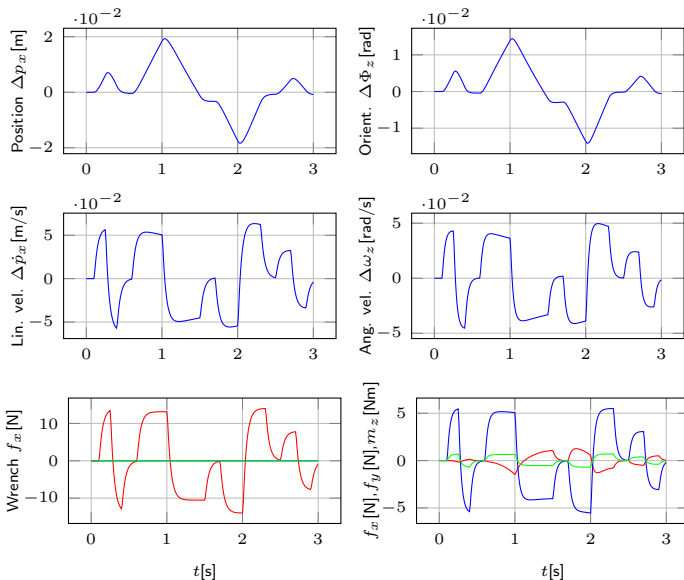
**Energy-adapted human coupling:** reduced stiffness  $\kappa$  and damping below a threshold tank level  $\mathcal{T}_{\text{th}}$

$$\kappa = \begin{cases} k_{vb} & \text{if } \mathcal{T}(x_t) \geq \mathcal{T}_{\text{th}} \\ k_{vb} \frac{\mathcal{T}(x_t)}{\mathcal{T}_{\text{th}}} & \text{if } \mathcal{T}(x_t) < \mathcal{T}_{\text{th}} \end{cases}$$

# Trajectory tracking: Constrained dynamic IPC

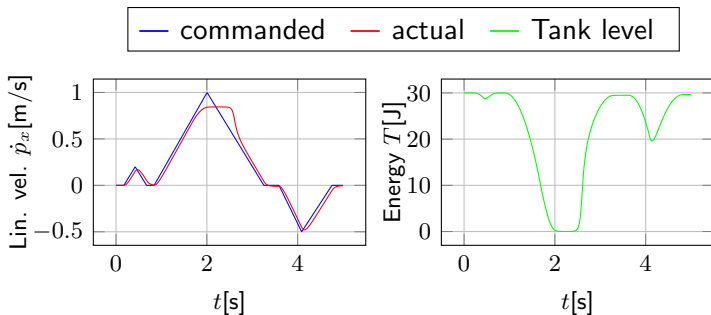


# Trajectory tracking: Classic (enhanced) IPC





# Energy-bounded trajectory tracking



- Controller is an energetic model of the real system
- Velocity and possible forces are limited by the energy budget
- Robots return to the desired position as fast as possible
-

# Conclusion & future work

- Energy-consistent modelling and control of a cooperative set-up
- Intrinsically passive controller with energy-adapted coupling of the user
- Energy budget at the user's disposal to operate the system
- System behaves safe and stable with arbitrary user commands

## Future work

- Experimental implementation
- Evaluation of safety metrics for violent pressure
- Generalization for a wider class of teleoperated systems

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