

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

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Final Presentation Master Thesis

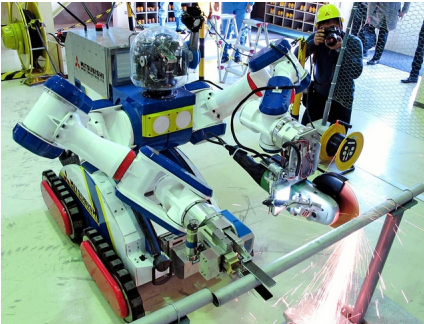
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# Human-robot team interaction

Humans come with superior foresight and robustness to incidents. Cooperative robot teams allow for a variety of complex tasks.



Coordinated use of tools: Pipe cutting [MHI14]

Unstructured environments demand the human's direct involvement in the control loop.

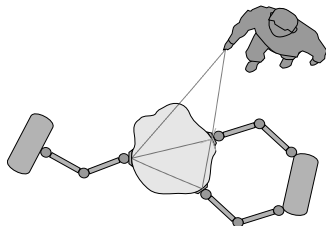
Intuitive user interfaces enable robot operation by untrained personnel.

Is the human a fail-safe mechanism?

# Problem setting

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

- Multiple robots need to be controlled simultaneously
- The formation constraints have to be satisfied
- The input method is non-reactive - any trajectory is possible



## Goal

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- Object-centred user interface
- Autonomous preservation of formation
- Stability and safety with arbitrary commands

# Related Work

## Low-level coordination

- (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]

## Conclusion

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- 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

# 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 dual pair  $(u, y)$  of *flow*  $u$  and *effort*  $y$

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

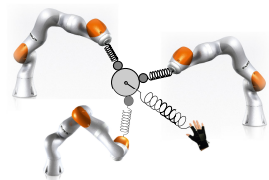
input-state-output form with *structure*-  $J(x)$ , *dissipation*-  $R(x)$  and *mapping* matrix  $B(x)$

**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]

Modelling leads to a **virtual structure**



	<b>Spring</b>	<b>Mass</b>	<b>Damper</b>
<b>Effort variable</b>	Wrench $W$	Twist $T$	Wrench $W$
<b>Flow variable</b>	Twist $T$	Wrench $W$	Twist $T$
<b>State variable</b>	Config. $H$	Momentum $P$	-
<b>Energy function</b>	$V_P(H)$	$V_K = \frac{1}{2} P^T M^{-1} P$	$V_D^* = \frac{1}{2} T^T D T$

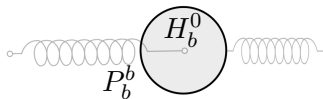
Model errors never influence passivity nor stability [Str01]

# Example controller derivation (IPC)

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), centrifugal and Coriolis terms  $C_b$

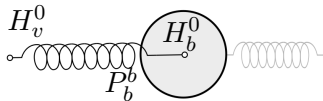
**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b$

## Example controller derivation (IPC)

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

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

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



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

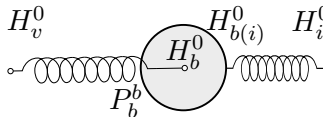
**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b + V_P(H_b^v)$



# Example controller derivation (IPC)

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

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

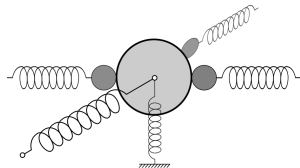


**Hamiltonian**  $\mathcal{H} = \frac{1}{2} P_b^{bT} M_b^{-1} P_b^b + V_P(H_b^v) + V_P(H_{b(i)}^i)$

# Modelling of constrained contact

Manipulator inertias, connected rigidly to the object, impose **kinematic constraints**.

$$\dot{x} = [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x)u + A(x)\lambda$$
$$0 = A^T(x) \frac{\partial \mathcal{H}}{\partial x} \rightarrow \text{DAE form}$$

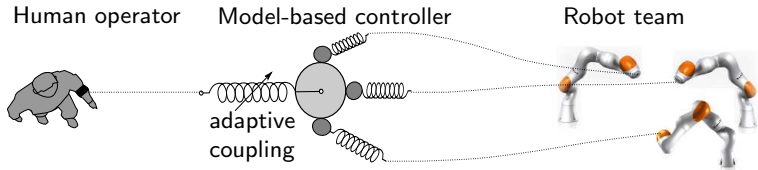


## Solved input-state-output form

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

Constraint matrix  $A$ , Lagrange multipliers  $\lambda$   
**Rigid connections are power-conservative.**

# Adaptive coupling of the operator



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

**Energy-adapted human coupling:** reduced stiffness  $\kappa$  and damping above a threshold energy level  $\mathcal{H}_{th}$

$$\kappa = \begin{cases} k_{vb} & \text{if } \mathcal{H}(x) < \mathcal{H}_{th} \\ k_{vb} \frac{\mathcal{H}_{max} - \mathcal{H}(x)}{\mathcal{H}_{max} - \mathcal{H}_{th}} & \text{if } \mathcal{H}(x) \geq \mathcal{H}_{th} \end{cases}$$

At a maximum energy level  $\mathcal{H}_{max}$  the operator is decoupled

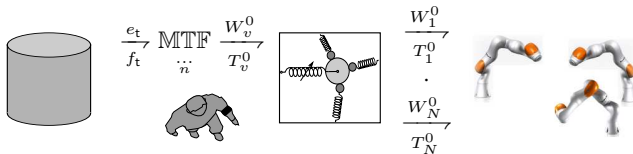
# Passivation of the coupling

Varying the stiffness  $\kappa$  changes the energy  $V_P$  of the spring  
Buffered with an **Energy Tank** by the power port  $(\dot{\kappa}, \frac{\partial V_P}{\partial \kappa})$

Energy Tank

Passive controller

Robot team



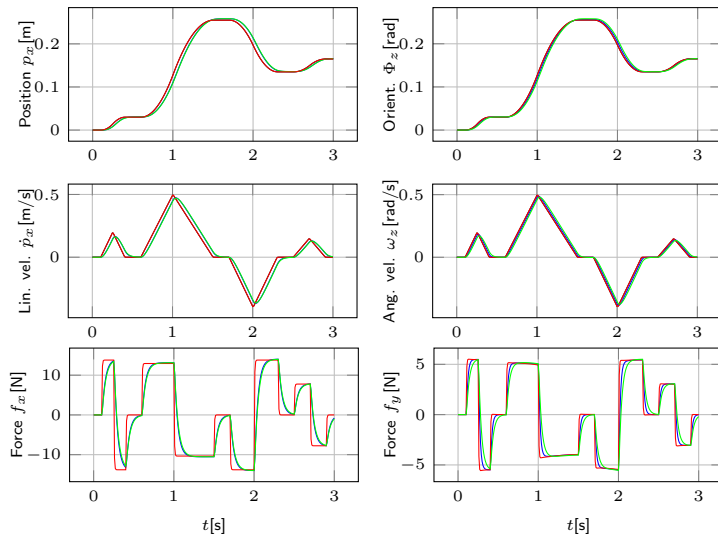
Human operator is energetically decoupled  
Modulated Transformer MTF with ratio  $n$

$$\begin{aligned} T_v^0 &= n e_t \\ f_t &= -n^T W_v^0 \end{aligned} \Rightarrow \text{new input } n = \frac{1}{e_t} T_{v,h}^0$$

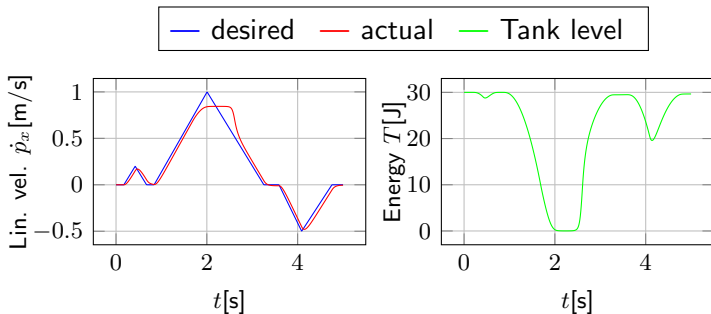
Tank effort  $e_t$  and flow  $f_t$ , human trajectory input  $T_{v,h}^0$

# Trajectory tracking: Comparison

— desired traj. — constrained dIPC — impedance ctrl — dyn. IPC



# Energy-bounded trajectory tracking



- Controller is an energetic model of the real system
- Velocity and possible forces are limited by the energy budget
- No permanent deviations in position tracking
- Maximum energy defined by safety metrics: Safe human-robot co-working

# 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 save and stable with arbitrary user commands

## Future work

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- Experimental implementation
- Evaluation of safety metrics for violent pressure
- Leader-follower guidance in direct human-robot team interaction

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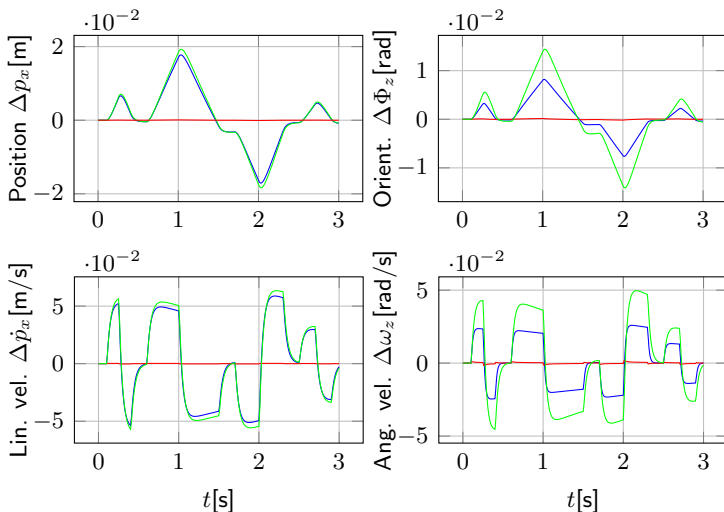


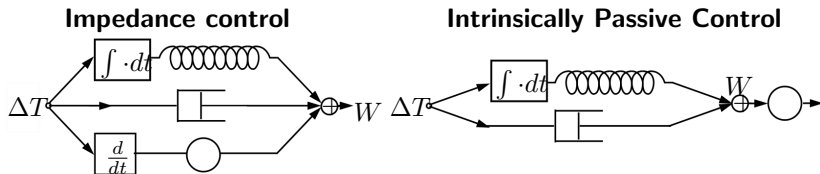
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— constrained dIPC — impedance control — dynamic IPC





Different role of inertias in the controllers: force gradients cause performance gap

