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

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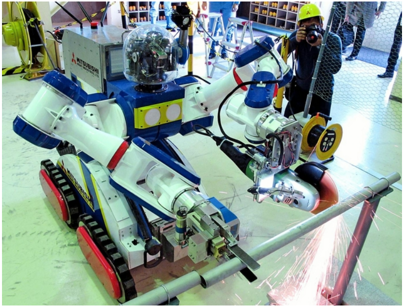
Why use human guided cooperative manipulation?



Human reasoning

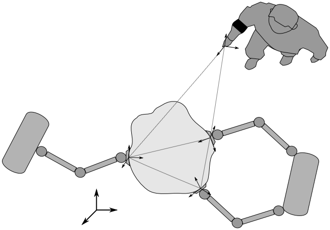
- Foresight and adaptiveness to incidents
- Superior planning capabilities

Enhanced flexibility of multiple robots

- Transportation of large/heavy objects
- Assembly of multiple parts
- Coordinated use of tools

Problem setting

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



Goal

- Consistent modelling of constrained systems
- Model-based control with human-in-the-loop

Related Work

Robot-team control

- Virtual object based impedance control [SC92]
- Internal and external impedance control [CV01,CCMV08]
- Intrinsically Passive Control [Str01,WOH08]
- Object dynamics' feed-forward [EH15]
- Formation control of a robot team [SMH15,WOH06]

Human in the loop

- Formation-based control [SMH15,SMP14]
- Bilateral tele-manipulation [LS05]
- Gesture-based Control [GFS+14]

- port-Hamiltonian systems allow for energy consistent modelling of complex physical systems
- *IPC* concept based on a physical model
- Closed loop stability for bounded energy supply

port-Hamiltonian systems

Idea

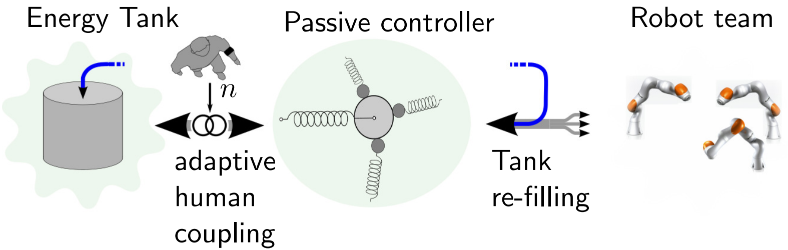
Network representation of interconnected non-linear physical systems

Hamiltonian H: total energy of the system
Port: a pair (f, e) of *flow* f and *effort* e variables

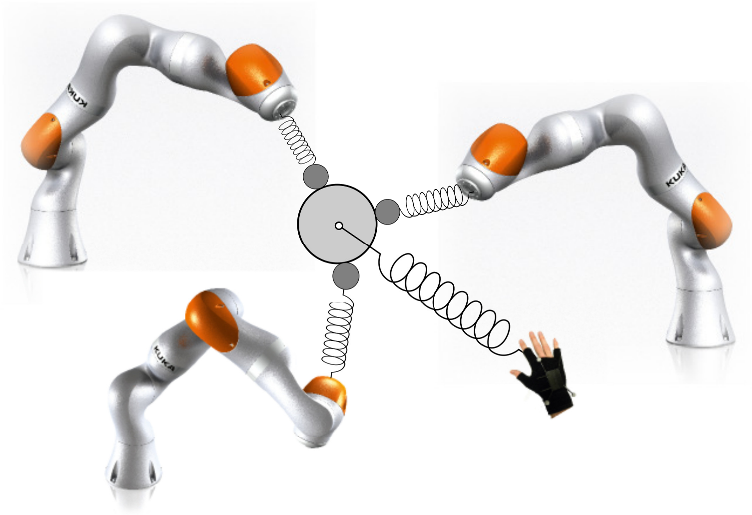
$$\dot{x} = J(x)\frac{\partial H}{\partial x}(x) + g(x)f$$
$$e = g^T(x)\frac{\partial H}{\partial x}(x)$$

state-space representation with *structure matrix* $J(x)$,
input matrix $g(x)$
Energy balance: power exchanged through a port $\frac{d}{dt}H = e^T f$

Overview


Energy Tank
Passive controller
Robot team
n
adaptive
human
coupling
Tank
re-filling

Virtual structure

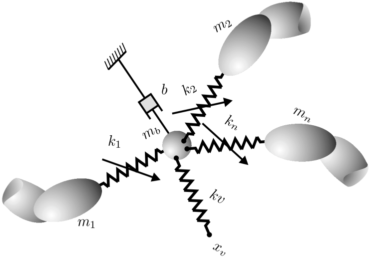


System model

$$\begin{pmatrix} \dot{x}_M \\ \dot{x}_S \end{pmatrix} = \begin{pmatrix} J_M & -(\phi_M)^T \\ \phi_M & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_M} \\ \frac{\partial H}{\partial x_S} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ \phi_h & \phi_{rl} & \phi_m \end{pmatrix} \begin{pmatrix} T_h \\ T_{rl} \\ T \end{pmatrix}$$

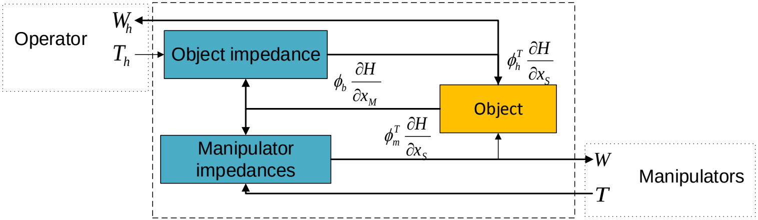
$$\begin{pmatrix} W_h \\ W_{rl} \\ W \end{pmatrix} = \begin{pmatrix} 0 & \phi_h^T \\ 0 & \phi_{rl}^T \\ 0 & \phi_m^T \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_M} \\ \frac{\partial H}{\partial x_S} \end{pmatrix}$$

- x_M: inertia state vector
- x_S: spring state vector
- T_h: desired object twist
- T_{rl}: desired rest-length twist
- T: manipulator twist
- W_h, W_{rl}, W: wrenches



Intrinsically Passive Control

Control based on the model of an impedance controlled cooperative manipulation set-up

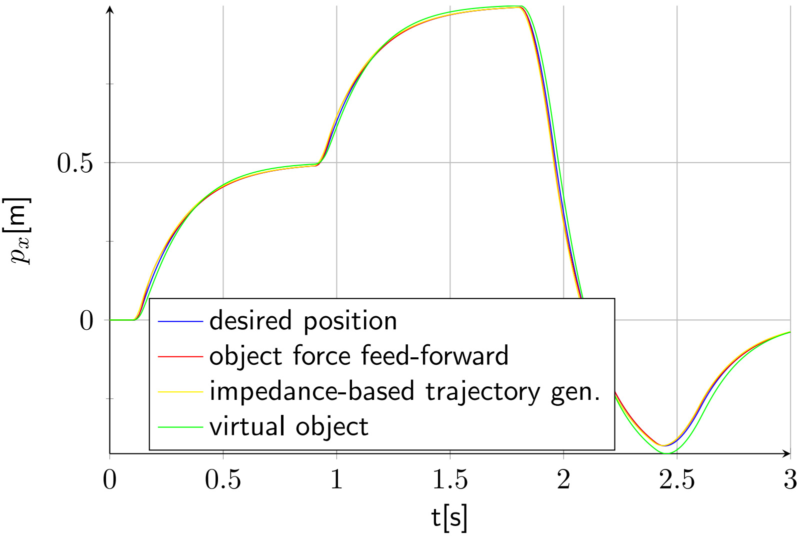


- Internal and external *impedance* relations
- Energy supplied by operator/environment

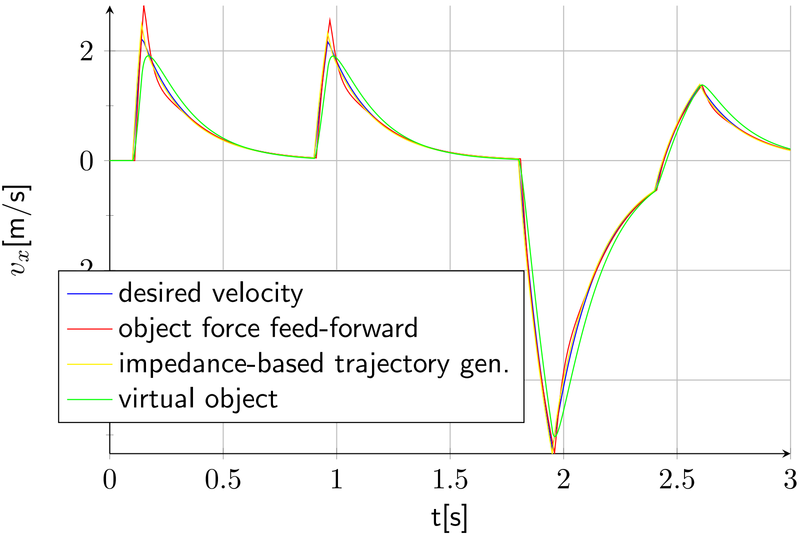
Stability

Model errors never influence passivity nor stability [Str01]

Comparison: position tracking

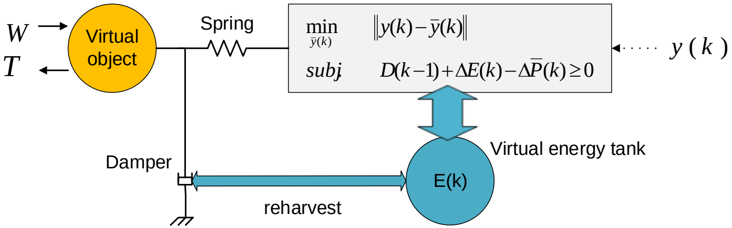


Comparison: velocity tracking



Human in the loop

- Desired object position is connected with a spring to the human
- Time-discrete reference changes possibly violate passivity
- Spring energy leap $\Delta\bar{P}(k) = H_S(t_k) - H_S(t_k^-)$
- Pre-filled energy tank to allow for initial twist



Overview & open issues

- port-Hamiltonian model of a cooperative manipulation set-up
- Appropriate dynamic performance of the model-based controller

Open issues

- Formulation of the HIL in the Hamiltonian framework
- Passive, stable closed loop behaviour
- Experimental evaluation

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