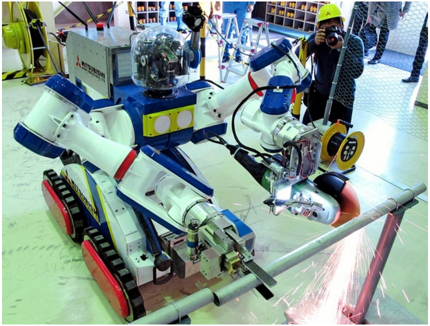
Control of a multi-robot cooperative team guided by a human operator

M. Angerer
Final Presentation Master Thesis
Betreuer: S. Musić

Lehrstuhl für Informationstechnische Regelung
Technische Universität München

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.

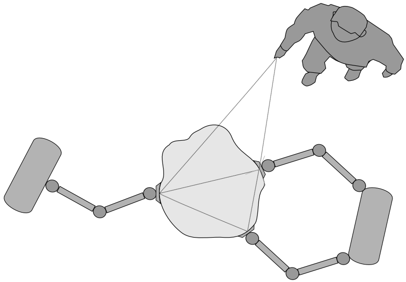
Human and robots are getting closer and intuitive user interfaces enable robot operation by untrained personnel.

We must not compromise stability and safety.

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



Goals for control design

- 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

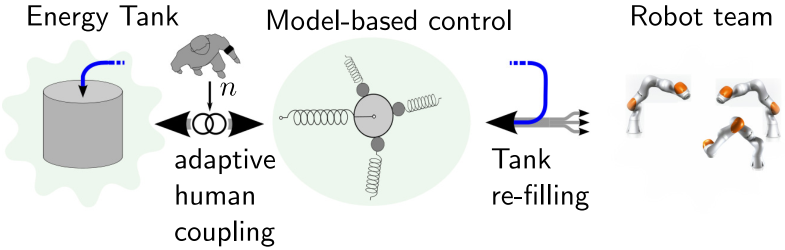
- Bilateral tele-manipulation [LS05]
- Human leader - robotic followers [SMH15,SMP14]
- Gesture-based Control [GFS+14]

Safety by energy-regulation

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

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

Overall control architecture



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

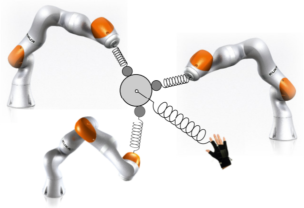
Hamiltonian $\mathcal{H}$: total energy of the system
Port: power-conjugated pair (u, y) of *flow* u and *effort* y variables

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

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

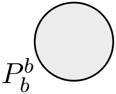
Model errors never influence passivity nor stability [Str01]

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

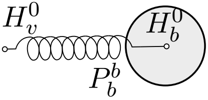
Hamiltonian $\mathcal{H} = \frac{1}{2} {P_b^b}^T M_b^{-1} P_b^b$

Example controller derivation

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

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

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



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

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

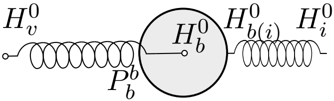
Example controller derivation

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

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

$$+ \begin{pmatrix} -H_b^v Ad_{H_0^b} & 0 \\ 0 & 0 \\ 0 & -H_{b(i)}^i Ad_{H_0^{b(i)}} \end{pmatrix} \begin{pmatrix} T_v^0 \\ T_i^0 \end{pmatrix}$$

$$\begin{pmatrix} W_v^0 \\ W_i^0 \end{pmatrix} = \begin{pmatrix} -Ad^T_{H_0^b} H_b^{vT} & 0 & 0 \\ 0 & 0 & -Ad^T_{H_0^{b(i)}} H_{b(i)}^{i\ T} \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{H}}{\partial H_b^v} \\ \frac{\partial \mathcal{H}}{\partial P_b^b} \\ \frac{\partial \mathcal{H}}{\partial H_{b(i)}^i} \end{pmatrix}$$



Hamiltonian $\mathcal{H} = \frac{1}{2} P_b^{b\,T} M_b^{-1} P_b^b + V_{\mathsf{P}}(H_b^v) + V_{\mathsf{P}}(H_{b(i)}^i)$

Modelling of rigid contact

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

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

Solved input-state-output form

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

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

Rigid connections are power-conservative.[Sch13]

Energy tanks

Virtual storage element: Energy function $\mathcal{T}(x_\mathsf{t}) = \frac{1}{2}x_\mathsf{t}^2$

$$\dot{x}_\mathsf{t} = u_\mathsf{t}$$
$$y_\mathsf{t} = \frac{\partial \mathcal{T}(x_\mathsf{t})}{\partial x_\mathsf{t}} (= x_\mathsf{t})$$

Interconnection of tank and controller by a transformer/gyrator

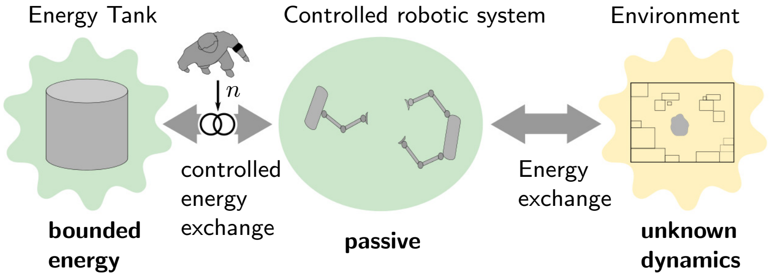
$$u = n y_\mathsf{t}$$
$$u_\mathsf{t} = -n^T y$$

The interconnection is power-continuous for any ratio n

For $n = \frac{w}{x_\mathsf{t}}$, w is the new control input

$$\dot{x} = [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x) \frac{w}{x_\mathsf{t}} y_\mathsf{t}$$
$$y = B^T(x) \frac{\partial \mathcal{H}}{\partial x}(x)$$

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. $\dot{\mathcal{T}}(x_t) + \dot{\mathcal{H}} = 0$.

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

Safety metrics and adaptive stiffness

Minimal kinetic energies that result in severe injuries [TVS14]

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

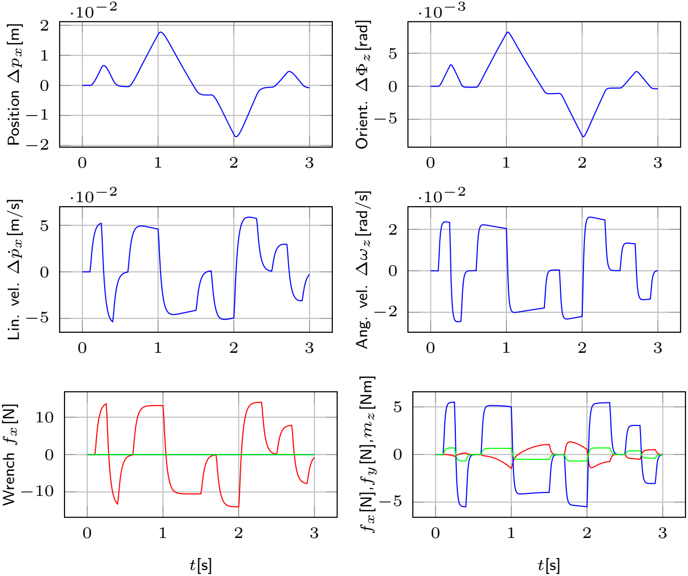
How can we change user commands to comply with these limits?

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

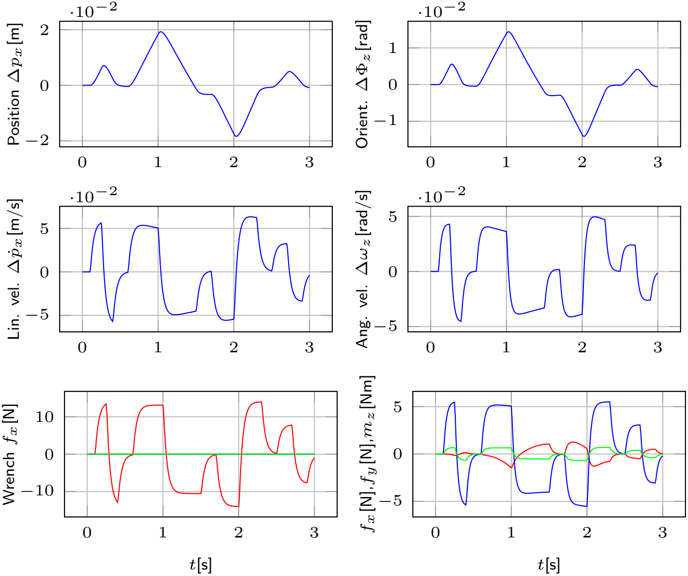
Energy-adapted human coupling: reduced stiffness κ and damping below a threshold tank level $\mathcal{T}_{\mathsf{th}}$

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

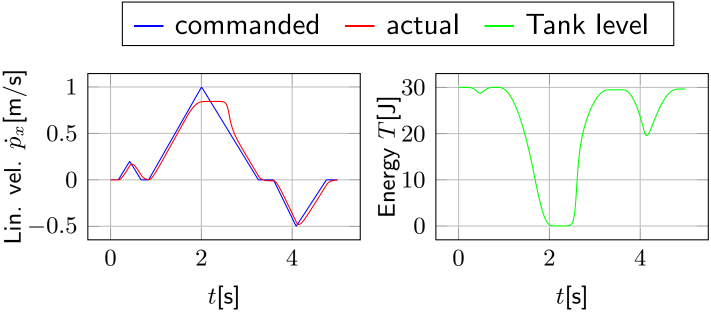
Trajectory tracking: Constrained dynamic IPC



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 save 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

References I

F. Caccavale, P. Chiacchio, A. Marino, and L. Villani.
Six-DOF Impedance Control of Dual-Arm Cooperative Manipulators.
In: *IEEE/ASME Transactions on Mechatronics* 13.5 (2008), pp. 576–586.

M. Geravand, E. Shahriari, A. De Luca, and A. Peer.
Port-based Modeling of Human-Robot Collaboration towards Safety-enhancing Energy Shaping Control.
In: *Proc. IEEE Int. Conf. on Robotics and Automation*. accepted for publication. 2016.

G. Gioioso, A. Franchi, G. Salvietti, S. Scheggi, and D. Prattichizzo.
The flying hand: A formation of UAVs for cooperative aerial tele-manipulation.
In: *Proc. IEEE Int. Conf. on Robotics and Automation*. 2014, pp. 4335–4341.

Neville Hogan. **Adaptive control of mechanical impedance by coactivation of antagonist muscles**.
In: *IEEE Transactions on Automatic Control* 29.8 (1984), pp. 681–690.

Mitsubishi Heavy Industries. **"MEISTeR" Remote Control Robot Completes Demonstration Testing At Fukushima Daiichi Nuclear Power Station**.
Press Information 1775, February 20, 2014; Online, accessed January 13, 2016. 2014.

D. Lee and M.W. Spong. **Bilateral Teleoperation of Multiple Cooperative Robots over Delayed Communication Networks: Theory**. In: *Proc. IEEE Int. Conf. Robotics and Automation*. 2005, pp. 360–365.

R. Ortega, A. J. van der Schaft, I. Mareels, and B. Maschke. **Putting energy back in control**.
In: *IEEE Control Systems Magazine* 21.2 (2001), pp. 18–33.

Arjan J. van der Schaft. **Port-Hamiltonian Differential-Algebraic Systems**.
In: *Surveys in Differential-Algebraic Equations I*. Springer, 2013, pp. 173–226.

S. Scheggi, F. Morbidi, and D. Prattichizzo.
Human-Robot Formation Control via Visual and Vibrotactile Haptic Feedback.
In: *IEEE Transactions on Haptics* 7.4 (2014), pp. 499–511.

References II

S.A. Schneider and R.H. Cannon.
Object impedance control for cooperative manipulation: theory and experimental results.
In: *IEEE Transactions on Robotics and Automation* 8.3 (1992), pp. 383–394.

D. Sieber, S. Music, and S. Hirche.
Multi-robot manipulation controlled by a human with haptic feedback.
In: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*. 2015, pp. 2440–2446.

Stefano Stramigioli.
Modeling and IPC Control of Interactive Mechanical Systems: A Coordinate-Free Approach. Vol. 266.
Lecture Notes in Control and Information Sciences. Springer, 2001.

T. S. Tadele, T. J. A. de Vries, and S. Stramigioli.
Combining energy and power based safety metrics in controller design for domestic robots.
In: *2014 IEEE International Conference on Robotics and Automation (ICRA)*. 2014, pp. 1209–1214.