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

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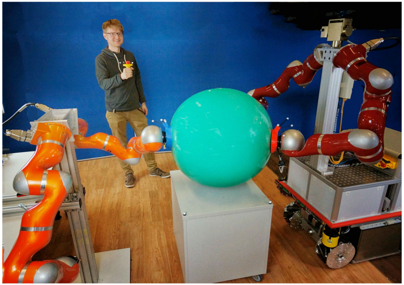
Shared control with a human in the loop

Human reasoning combines with the enhanced flexibility of multiple robots

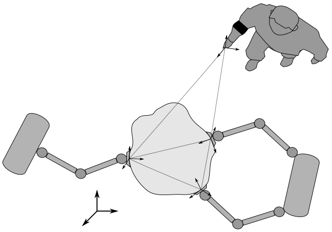


Non-restrictive input interfaces allow for almost arbitrary trajectories

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

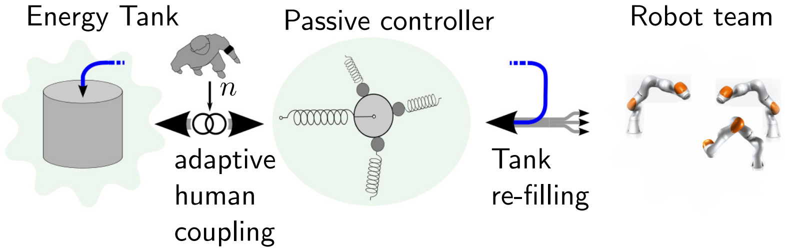
- Bilateral tele-manipulation [LS05]
- Human leader - robotic followers [SMH15,SMP14]
- Gesture-based Control [GFS+14]

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

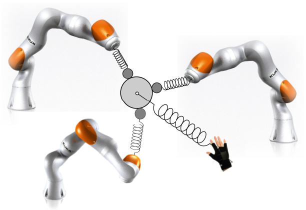
Hamiltonian $\mathcal{H}$: total energy of the system
Port: power-conjugated pair (u, y) of *flow* u and *effort* y variables

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

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

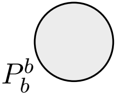
Model errors never influence passivity nor stability [Str01]

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

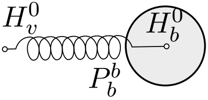
Hamiltonian $\mathcal{H} = \frac{1}{2} {P_b^b}^T M_b^{-1} P_b^b$

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

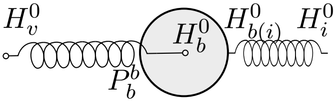
Example controller derivation

... 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 $\mathcal{T}(x_{\mathsf{t}}) = \frac{1}{2}x_{\mathsf{t}}^2$

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

Interconnection of tank and controller by a transformer/gyrator

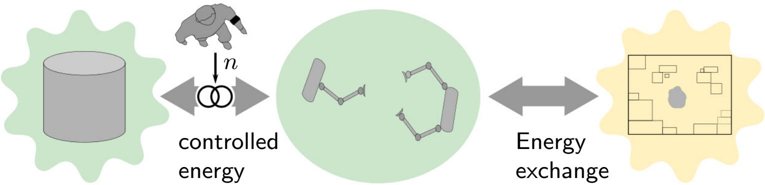
$$
\begin{aligned}
u &= n y_{\mathsf{t}} \\
u_{\mathsf{t}} &= -n^T y
\end{aligned}
$$

The interconnection is power-continuous for any ratio n

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

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

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. $\dot{\mathcal{T}}(x_{\mathrm{t}}) + \dot{\mathcal{H}} = 0$.

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

Safety metrics and adaptive stiffness

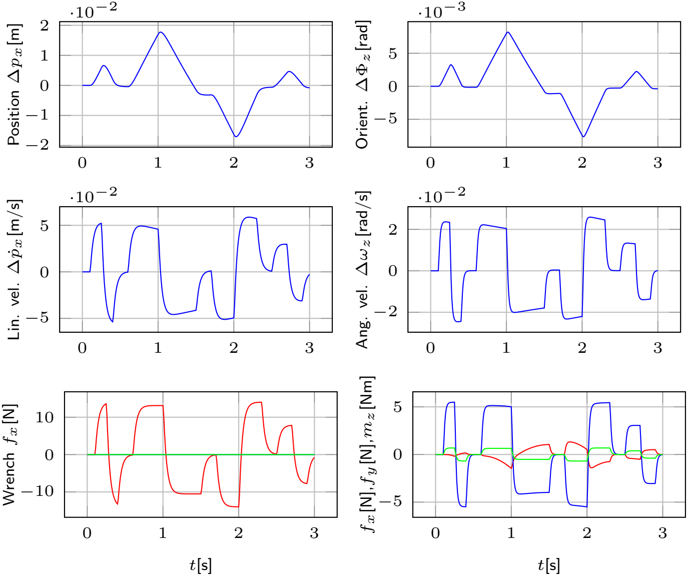
Minimal kinetic energies that result in severe injuries TVS14

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

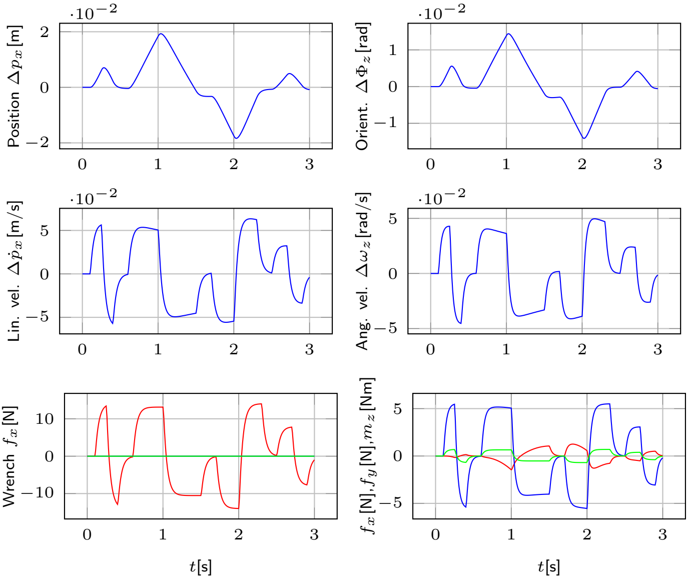
How can we change user commands to comply with these limits?
Human hand is stiff when moving slow, compliant when fast [Hog84]
Energy-adapted human coupling: reduced stiffness κ and damping below a threshold tank level $\mathcal{T}_{\mathsf{th}}$

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

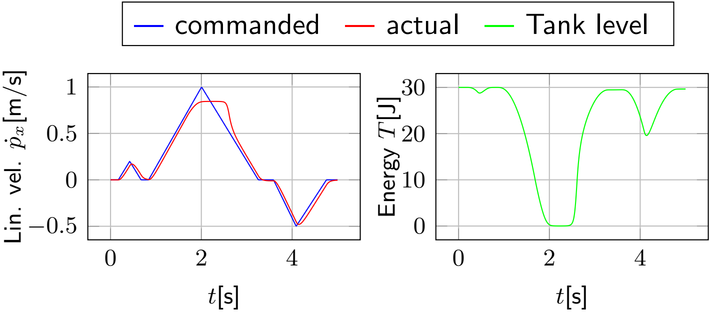
Trajectory tracking: Constrained dynamic IPC



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

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