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

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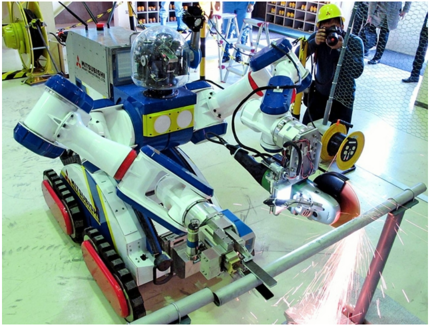
Human-robot team interaction

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.

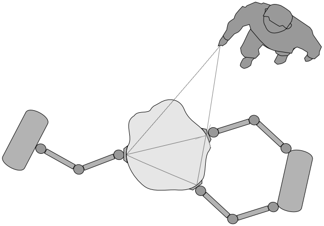
Intuitive user interfaces enable robot operation by untrained personnel.

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

- 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

- 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

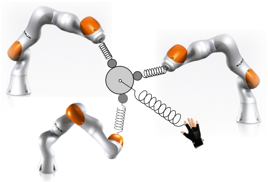
$$\dot{x} = [J(x) - R(x)] \frac{\partial \mathcal{H}}{\partial x}(x) + B(x)u$$
$$y = B^T(x) \frac{\partial \mathcal{H}}{\partial x}(x)$$

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]

Modelling leads to a **virtual structure**



	Spring	**Mass**	**Damper**
Effort variable	Wrench W	Twist T	Wrench W
Flow variable	Twist T	Wrench W	Twist T
State variable	Config. H	Momentum P	-
Energy function	$V_{\mathsf{P}}(H)$	$V_{\mathsf{K}} = \frac{1}{2}P^T M^{-1} P$	$V_{\mathsf{D}}^* = \frac{1}{2}T^T D T$

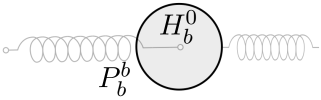
Model errors never influence passivity nor stability [Str01]

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

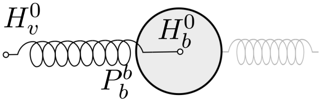
Hamiltonian $\mathcal{H} = \frac{1}{2} {P_b^b}^T M_b^{-1} P_b^b$

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

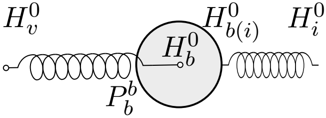
Example controller derivation (IPC)

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

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

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

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



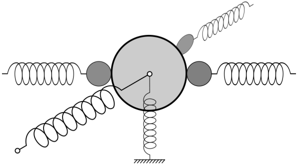
Hamiltonian $\mathcal{H} = \frac{1}{2} {P_b^b}^T M_b^{-1} P_b^b + V_\mathsf{P}(H_b^v) + V_\mathsf{P}(H_{b(i)}^i)$

Modelling of 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

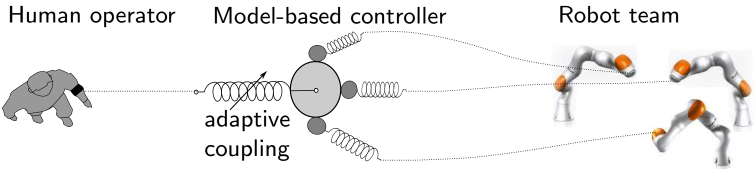
$$\dot{x} = [J - R] \frac{\partial \mathcal{H}}{\partial x} + Bu + A(A^T M^{-1} A)^{-1} A^T M^{-1} (u + C \frac{\partial \mathcal{H}}{\partial x})$$

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

Constraint matrix A, Lagrange multipliers λ

Rigid connections are power-conservative.

Adaptive coupling of the operator



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

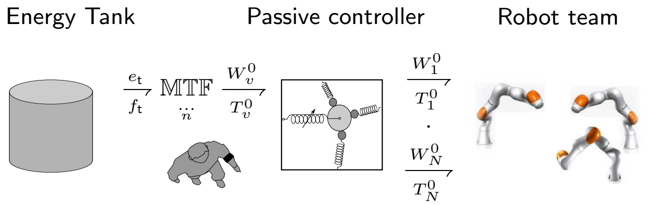
Energy-adapted human coupling: reduced stiffness κ and damping above a threshold energy level $\mathcal{H}_{\text{th}}$

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

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

Passivation of the coupling

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

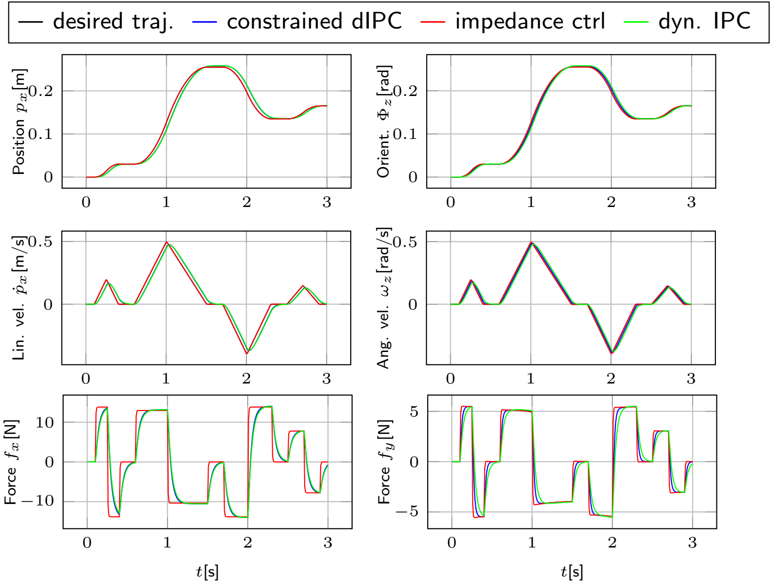


Human operator is energetically decoupled
Modulated Transformer $\mathbb{MTF}$ with ratio $\boldsymbol{n}$

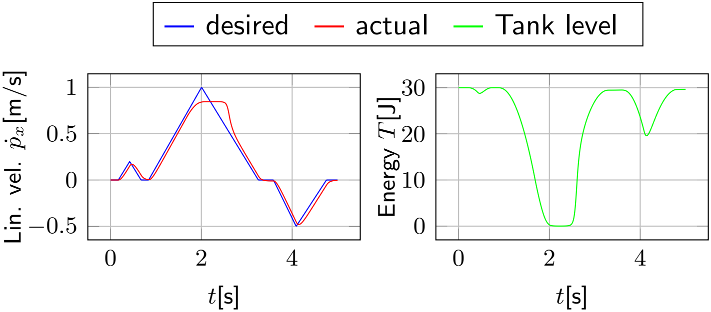
$$\begin{aligned} T_v^0 &= \boldsymbol{n} e_\mathsf{t} \\ f_\mathsf{t} &= -\boldsymbol{n}^T W_v^0 \end{aligned} \Rightarrow \text{ new input } \boldsymbol{n} = \frac{1}{e_\mathsf{t}} T_{v,h}^0$$

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

Trajectory tracking: Comparison



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

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

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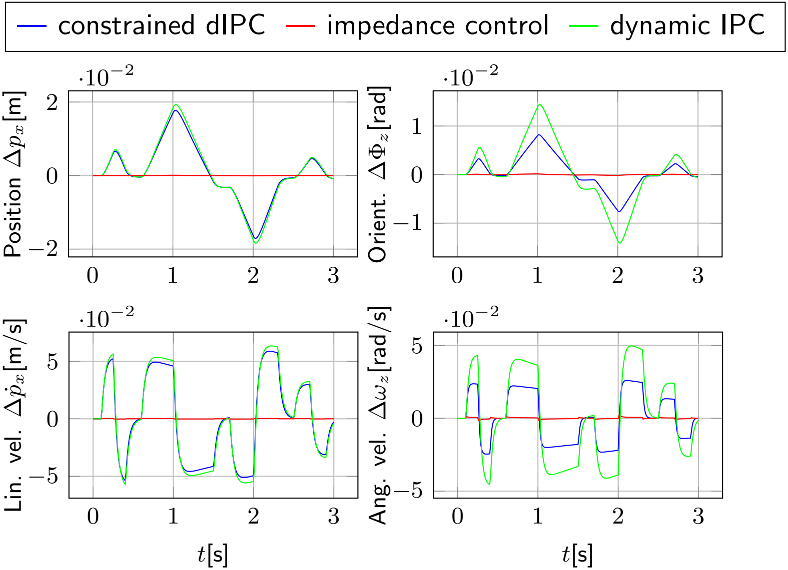
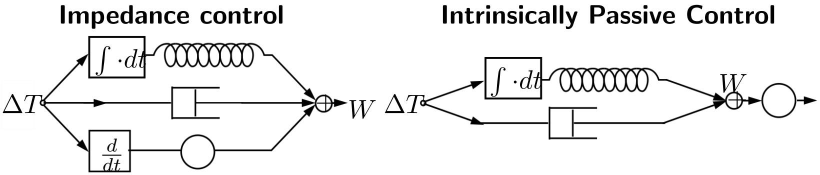
Trajectory tracking: Comparison



Trajectory tracking: Interpretation



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