# Control Challenges in Physical Human-Robot Interaction

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# Anthropomorphic collaborative robots


ABB R&D (http://abb.com)

- collaborative manufacturing, logistics, handling, service
- care and assistance for elderly and disabled

# Wearable robots

HAL (Cyberdyne Inc.) certified for rehabilitation

Supernumerary Robotic Limbs (d'Arbeloff Lab/MIT)

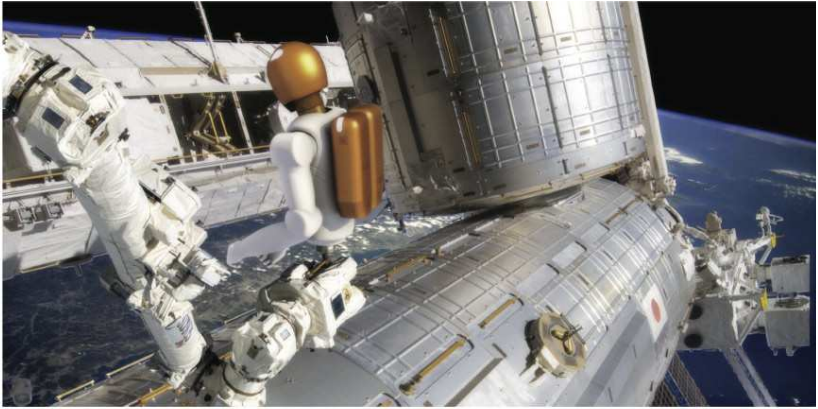
- physical rehabilitation, training and skill transfer
- force amplification, manipulation and mobility aid

# (Teleoperated) robots in medical applications

da Vinci Surgical System (http://intuitivesurgical.com)

- minimal invasive surgery, remote medical examination

# Teleoperated robots in space



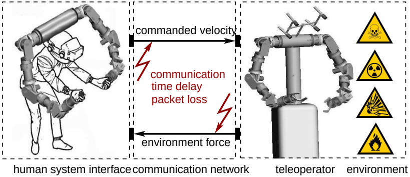
http://robonaut.jsc.nasa.gov

- diagnosis, maintenance, assembly in inaccessible places
- teleoperation in nano/macro environments

# pHRI - physical coupling of human & machine

⇒ continuous control challenges w.r.t. stability and performance

## Telerobotics




- master-slave

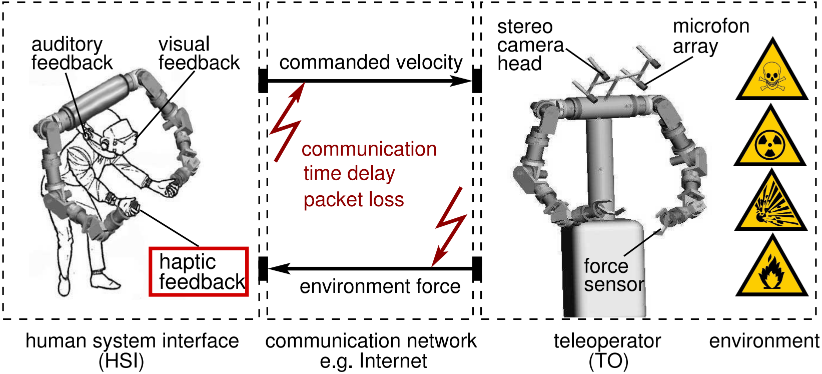
## Cooperative pHRI

- collaborative partners

**Talk today**

1. telerobotics (teleoperation, telemanipulation)
2. cooperative physical human-robot interaction (pHRI)

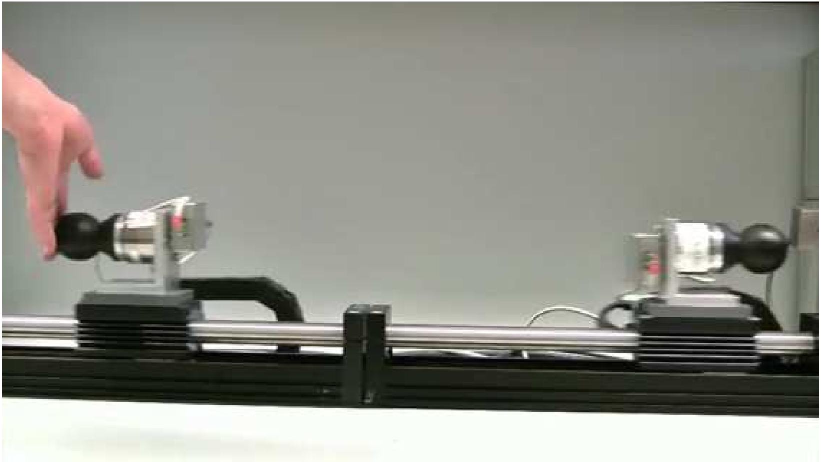
# Telerobotics control challenges




**Goal "transparency" - feel like directly interacting, but**

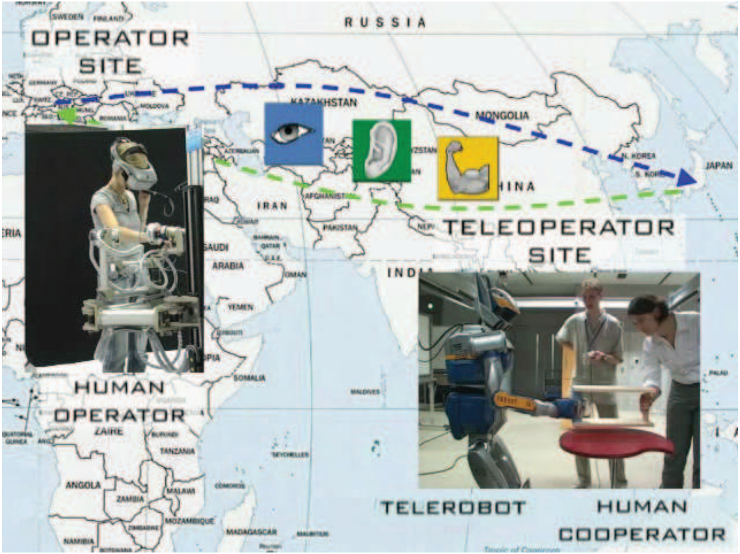
- destabilizing communication effects
- human (and environment) model largely unknown

# Destabilizing effect of time delay



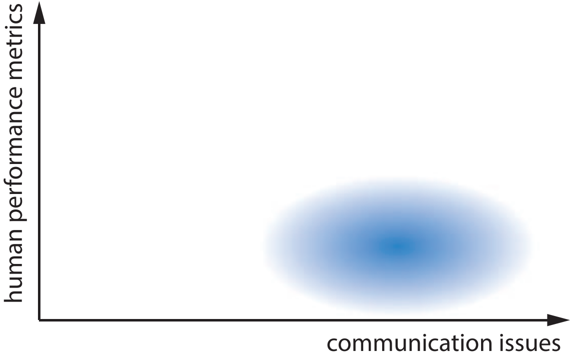
[Hirche et al. "Bilateral Control Architectures for Telerobotics," STAR series, Springer 2007]

# Intercontinental telerobotic experiment




[Peer et al. "Intercontinental multimodal Tele-Cooperation using a Humanoid Robot," IROS 2008]

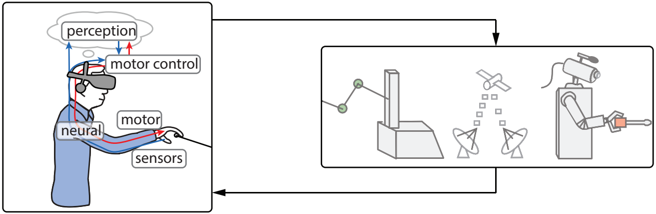
# Overview telerobotics




**First part in telerobotics: communication issues**

- constant time delay
- varying delay, packet loss, event-triggered communication

# Stability with human in the closed loop




**Problem:** human motor control difficult to model/identify

[Tsuji et al. 1995, Rahma/Ikeura/Mizutani 1999, Buerger/Hogan 2006]

**The good news - passivity works**

- **trained human behaves passive** [Hogan 1989]
- typically encountered environments are also passive

# Stabilization with time delay

- **passivity-based control**
  - scattering/wave variable [Anderson/Spong 1989, Niemeyer/Slotine 1991]
  - port-Hamiltonians [Stramigioli et al. 2002]
  - Llewelyn [Hashtrudi-Zaad/Salcudean 1999]
  - time-domain [Ryu/Kim/Hannaford 2004]
  - PD-type/Lyapunov-Krasowskii [Lee/Spong 2006]
- input-to-state stability [Polushin/Marquez 2003]
- robust control [Leung/Francis/Apkarian 1995]
- model-mediated control [Mitra/Niemeyer 2008]
- adaptive and switching [Zhu/Salcudean 1999]
- predictive methods [Munir/Book 2001]

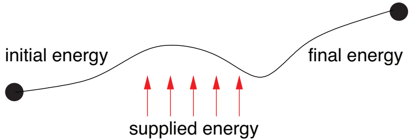
**General question: model-based or "model-free"?**

- depends on assumptions on human/environment
- trade-off transparency vs. robust stability certificates

# Passive systems

Consider $\Sigma$ : $\begin{aligned} \dot{x} &= f(x,u) \\ y &= h(x) \end{aligned}$

with $x \in \mathbb{R}^n$, $u, y \in \mathbb{R}^p$
$f(0,0) = 0,\ h(0) = 0$




**$\Sigma$ is passive if ...**

... $\exists$ positive definite (storage) function $V(x) : R^n \to R$ s.t.

$$V(x(t)) - V(x(0)) \leq \int_0^t u^T y \, d\tau.$$

**Ingredients for passivity-based control:**

- appropriately controlled robot manipulators passive
- feedback interconnection of passive systems is passive
- passivity $\Rightarrow$ stability

$\Rightarrow$ **tele-robotic system without time delay is stable**

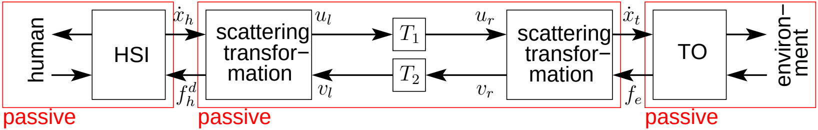
# Stabilization using scattering transformation

**Stability for arbitrary large constant time delay with**
**[Anderson/Spong 1989,Niemeyer/Slotine 1991]**

(i) velocity-force-architecture

(ii) scattering transformation with wave impedance $b > 0$

$$u = (2b)^{-\frac{1}{2}}(f + b\dot{x}); \quad v = (2b)^{-\frac{1}{2}}(f - b\dot{x}),$$




- applicable also in networked control systems
- **very robust but quite conservative**

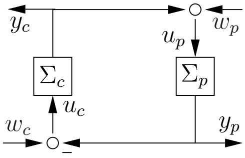
[Matiakis et al. "Control of Networked Systems Using the Scattering Transformation," IEEE Trans Control Systems Techn. 2009]

# Exploit excess passivity for less conservatism

- controlled manipulator and human are $(QSR)$-*dissipative*

$$V(x(t)) - V(x(0)) \leq \int_0^t u^T Q u + 2u^T S y + y^T R y \, d\tau$$

- passivity and finite gain $\mathcal{L}_2$-stability are special cases

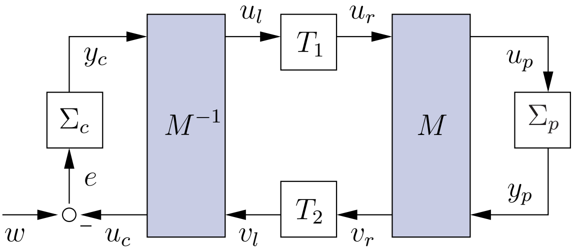



**Theorem: feedback interconnection $\mathcal{L}_2$-stable if** [Willems 1972]

$$\begin{bmatrix} Q_p & S_p \\ S_p^T & R_p \end{bmatrix} + \begin{bmatrix} R_c & -S_c \\ -S_c^T & Q_c \end{bmatrix} = P_p + P_c \prec 0.$$

# Idea of generalized scattering transformation

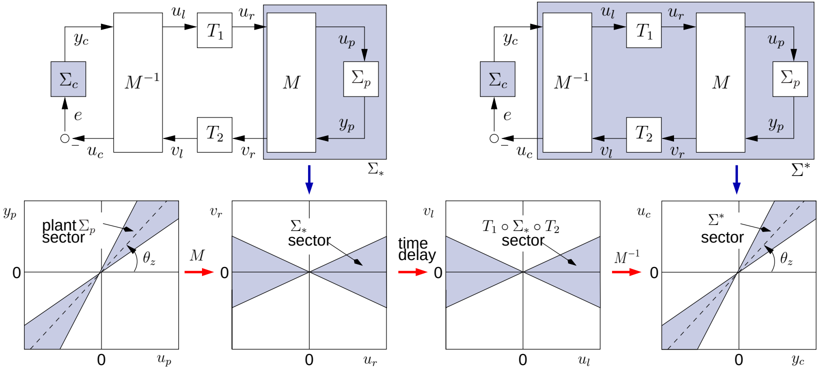
- assume that $\Sigma_p$, $\Sigma_c$ are $(QSR)$-dissipative with $P_p + P_c \prec 0$
  $\Rightarrow \mathcal{L}_2$-stability without time delay
- generalized scattering transf. $M$ (standard is special case)




[Hirche et al. "A Distributed Controller Approach for Delay-Independent Stability of NCS," automatica 2009]

# Idea of generalized scattering transformation

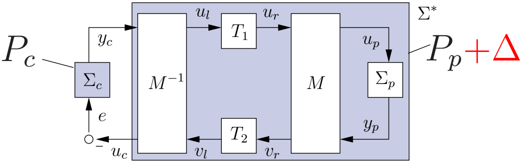
- rotation of generalized input-output cones
- exploits finite-gain-property of constant delay




[Hirche et al. "A Distributed Controller Approach for Delay-Independent Stability of NCS," automatica 2009]

# Generalized scattering transformation

Assume $\Sigma_p$, $\Sigma_c$ are $(Q,S,R)$-dissipative and $\begin{bmatrix} u_r \\ v_r \end{bmatrix} = M \begin{bmatrix} u_p \\ v_p \end{bmatrix}$



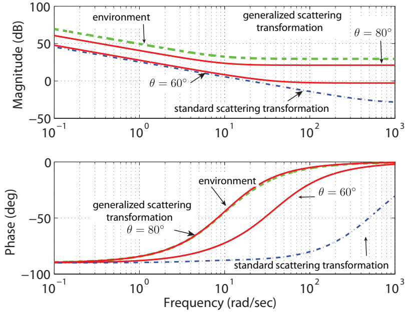

**Theorem: delay-independent $\mathcal{L}_2$-stability**

If there exists a $\Delta = \Delta^T \succeq 0$ s.t. $P_c + P_p + \Delta \prec 0$.
Choose $M$ s.t. $\Delta + P_p = M^T \Lambda M$ for some diagonal $\Lambda$

- $M \in R^{n \times n}$ exists if $\Sigma_p$ is scalar feedback-stabilizable
- if $M$ chosen s.t. $\Delta = 0 \Rightarrow$ nominal stability reserve

[Hirche et al. "A Distributed Controller Approach for Delay-Independent Stability of NCS," automatica 2009]

# Comparison with standard scattering




Spring-damper environment:

- $Z_e(s) = \frac{300}{s} + 30$
- $(Q, S, R) = (-30, 0, \frac{1}{2})$
- stable if $\theta \in [45°, 89°]$,
- $T_1 + T_2 = 100$ms

## Significantly improved transparency

| $k_e$ | $k_h$ standard scattering | $k_h$ generalized scattering |
|---|---|---|
| 300 N/m | 36 N/m | 166 N/m |

$\Rightarrow$ validated in experiments

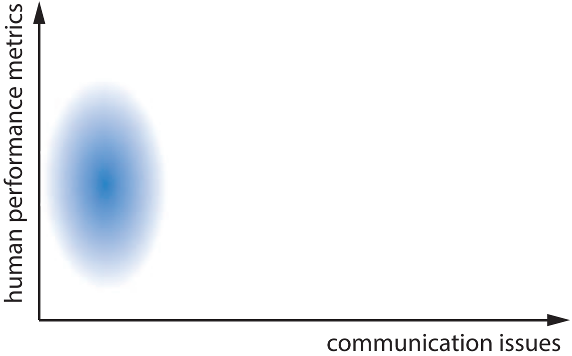
[Hirche et al. "Human-oriented Control for Haptic Teleoperation," Proceedings of the IEEE 2012]

# It really works - in real world applications!

- passivity/dissipativity-based approaches well-suited to cope with human/environment uncertainty
- delay-independent stability and improved transparency by generalized scattering transformation (excess passivity!)
- extensions for time-varying delay, packet loss and event-triggered control available (not in this talk)
- generalizes to other networked control problems
- challenges for wireless: high variability decreases performance

**How does it feel? $\Rightarrow$ Transparency!**

# Overview telerobotics



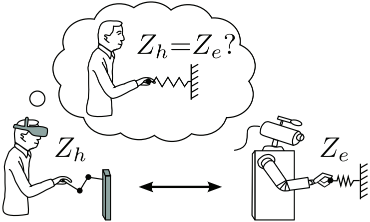

**Second part on telerobotics: human performance metrics**

- perceptual design and analysis with constant delay
- effects of event-triggered control, jitter, packet loss

# How good feels good enough?

- transparency: displayed $Z_h$ = environment $Z_e$ [Lawrence1993]
- not achievable with uncertainties, time delay & packet loss

**Idea: consider perceptual limits in analysis & control design**




**Perceived transparency**

if $Z_h \in (Z_e - \Delta, Z_e + \Delta)$, with $\Delta$ determined by perceptual limit

[Hirche et al. "Human-oriented Control for Haptic Teleoperation," Proceedings of the IEEE 2012]

# Psychophysics in a nutshell

Human cannot perceive arbitrarily small stimulus differences.

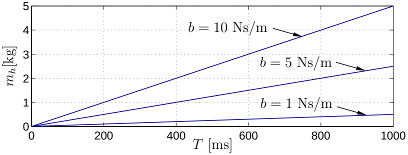
**Weber's law** [Weber 1851]

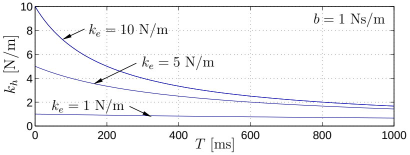
$$\frac{\Delta I}{I} = \text{constant} = \text{JND}$$

where $I$ stimulus intensity, $\Delta I$ just noticeable absolute difference

- determined in psychophysical experiments
- examples from haptics:
  - JND stiffness $= (23 \pm 3)\%$ [Jones/Hunter 1990]
  - JND viscosity $= (34 \pm 5)\%$ [Jones/Hunter 1993]
  - JND motion $= (8 \pm 4)\%$ [Jones/Hunter 1992]

# Transparency with constant time delay




**Summary results: for $T \uparrow$**

- displayed inertia $\uparrow$
- displayed stiffness $\downarrow$
- maximum displayable stiffness $\downarrow$
- displayed stiffness difference $\downarrow$

**Perception models for transparency analysis**

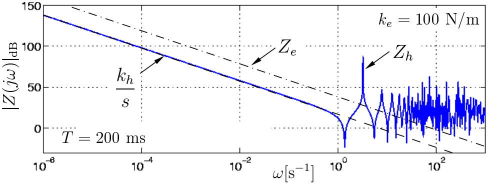
Example: delay does not affect stiffness perception if $T < \frac{\text{JND}}{1-\text{JND}} \frac{2b}{k_e}$

[Hirche et al. "Human-oriented Control for Haptic Teleoperation," Proceedings of the IEEE 2012]

# Perception-oriented control design

Example "stiff wall" (spring characteristics):

- $Z_e = k_e/s$, $k_e > 0$
- $Z_h \approx k_h/s$ mit
  $1/k_h = 1/k_e + T/2b$




**Transparency:** $k_h = k_e$

$b \to \infty \Rightarrow$ not realizable

**Perceived transparency:** $k_h \in k_e(1 - \mathbf{JND}, 1 + \mathbf{JND})$

$$b > \frac{1 - \mathsf{JND}}{\mathsf{JND}} \frac{Tk_e}{2} \Rightarrow$$ perceptual lower bound validated in user studies

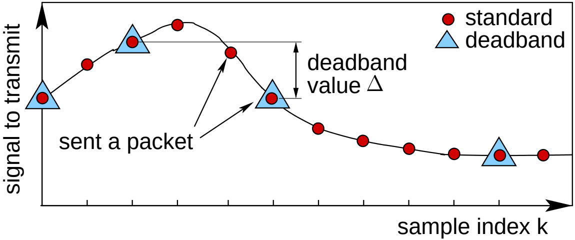
[Hirche et al. "Human-oriented Control for Haptic Teleoperation," Proceedings of the IEEE 2012]

# Transparency with communication constraints

- at least 1000Hz haptic loop sampling rate ⇒ high packet rate

**Idea: transmit when necessary ⇒ event-triggered control**

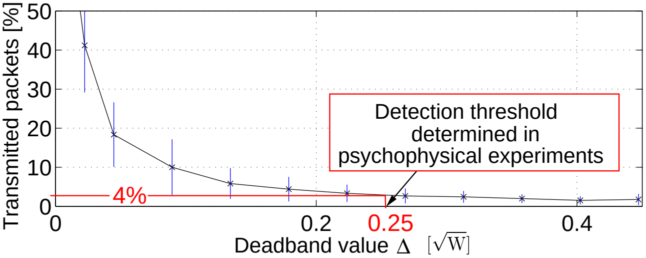
- goal: min communication s.t. distortion not perceivable
- stability guaranteed by $\mathcal{L}_2$-gain constrained estimation




[Steinbach et al. "Haptic Communications," Proceedings of the IEEE 2012]
[Hirche et al., "Network traffic reduction in haptic telepresence systems by deadband control," IFAC Worldcongress 2005]
[Molin et al. "On the Optimality of Certainty Equivalence for Event-triggered Control Systems," IEEETrans Automatic Control 2013]

# Transparent reduction of network traffic

- threshold policy on scattering variables
- detection threshold value by psychophysical experiments




**Result** [Steinbach/Hirche 2005-2012]

Traffic reduction by 96% without perceivable transparency loss

[Hirche et al. "Transparent Data Reduction in Networked Telepresence and Teleaction Systems - Part I/II," PRESENCE 2007]

# Advantages by including human models

- human performance metric from human perception model
- based on human perception limits we can
  - quantify how much delay (packet loss, jitter) acceptable
  - do a sophisticated control design for human performance
  - significantly reduce network traffic
- open problem: dynamic and multi-modal sensorimotor models

**Systematic human-oriented control design is a key challenge!**

# Control challenges in telerobotics

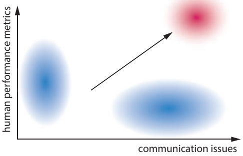
## What we have

- many results for stabilizing control over communications
- only few results available for performance-oriented control

**Telerobotics = human-in-the-loop networked system**

**Progress towards performance-oriented control by**

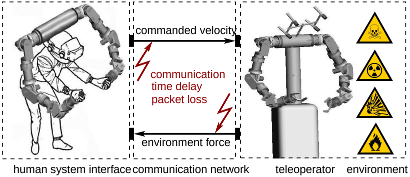
- control ⇔ communication:
  joint design of control/protocol
- control ⇔ psychophysics:
  human-model-based control design
- trends: wearable haptics, team control



# pHRI - physical coupling of human & machine

⇒ continuous control challenges w.r.t. stability and performance

## Telerobotics




- master-slave

## Cooperative pHRI

- collaborative partners

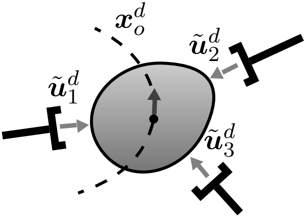
**Talk today**

1. telerobotics (teleoperation, telemanipulation)
2. **cooperative physical human-robot interaction (pHRI)**

# The robot as collaborative partner

# Cooperative object manipulation

- prototypical control challenge in physical interaction
- special case: direct coupling between human and robot




## Cooperative control objective

Track desired object trajectory $\boldsymbol{x}_o^d(t)$ while applying $\tilde{\boldsymbol{u}}_i^d(t)$

$$\lim_{t\to\infty} \boldsymbol{x}_o(t) \to \boldsymbol{x}_o^d(t) \quad \text{and} \quad \lim_{t\to\infty} \tilde{\boldsymbol{u}}_i(t) \to \tilde{\boldsymbol{u}}_i^d(t)$$

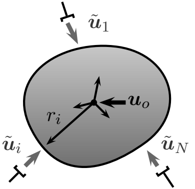
# Modeling physical interaction

Consider $N$ agents applying forces $\tilde{\boldsymbol{u}}_1$, ..., $\tilde{\boldsymbol{u}}_N$ on rigid object

$$\boldsymbol{M}_o \ddot{\boldsymbol{x}}_o + \boldsymbol{C}_o(\dot{\boldsymbol{x}}_o) = \boldsymbol{u}_o = J\tilde{\boldsymbol{u}}$$

where $J$ describes kinematic constraint and defines resulting force

$$\boldsymbol{u}_o = \underbrace{\begin{bmatrix} I & 0 & \cdots & I & 0 \\ r_1 \times & I & \cdots & r_N \times & I \end{bmatrix}}_{J} \cdot \underbrace{\begin{pmatrix} \tilde{\boldsymbol{u}}_1 \\ \vdots \\ \tilde{\boldsymbol{u}}_N \end{pmatrix}}_{\tilde{\boldsymbol{u}}}$$




**General assumption:**

- input redundancy $\dim(\tilde{\boldsymbol{u}}) > \dim(\boldsymbol{u}_o)$

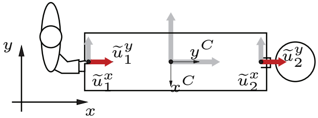
[Erhart et al. "An impedance-based control architecture for multi-robot cooperative dual-arm mobile manipulation," IROS 2013]

# Input allocation & effort sharing

- input redundancy facilitates different effort sharing policies
- allocation by choice of generalized inverse $\tilde{\boldsymbol{u}} = J^{+}\boldsymbol{u}_o^d$

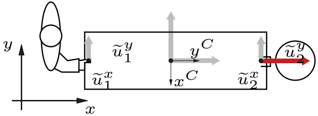
**Balanced-effort policy**

minimize total effort: $\min_{J^+} \|\tilde{\boldsymbol{u}}\|$



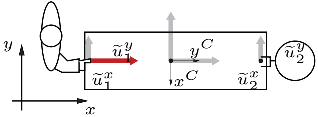

**Maximum-robot-effort policy**

minimize human effort: $\min_{J^+} \|\tilde{\boldsymbol{u}}_1\|$




**Minimum-robot-effort policy**

minimize robot effort: $\min_{J^+} \|\tilde{\boldsymbol{u}}_2\|$

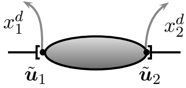



[Mörtl et al. "The Role of Roles: Physical Cooperation between Humans and Robots," Int. J. Robotics Research 2012]

# Internal forces & disagreement

- internal forces $\tilde{\boldsymbol{u}}_{int} = \{\tilde{\boldsymbol{u}} | J\tilde{\boldsymbol{u}} = 0\}$ induce no object motion


- internal forces arise from different desired trajectories and other model/control mismatches between agents




$\Rightarrow$ internal forces may indicate disagreement of agents

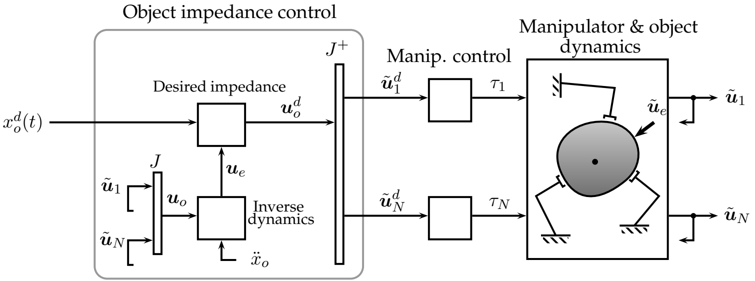
**The nullspace of $J$ is a haptic negotiation channel ...**

... used for communicating disagreement and motion intentions

# If there are robots only ...

**Control objective:** track $x_o^d$ while exhibiting desired impedance

$$M_o^d\,(\ddot{\boldsymbol{x}}_o - \ddot{\boldsymbol{x}}_o^d) + D_o^d\,(\dot{\boldsymbol{x}}_o - \dot{\boldsymbol{x}}_o^d) + K_o^d\,(\boldsymbol{x}_o - \boldsymbol{x}_o^d) = \boldsymbol{u}_e$$




**Hierarchical approach to multi-robot control**

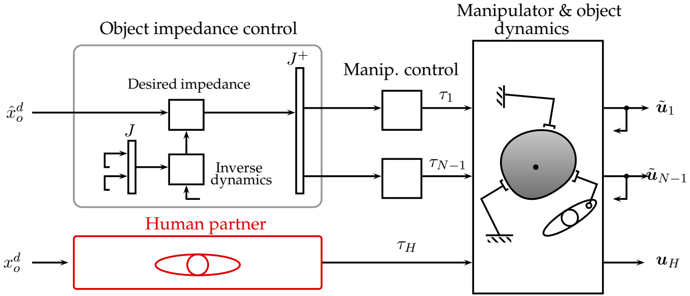
Tracking and kinematic constraint satisfaction achieved by hierarchical coordination scheme ⇒ no disagreement

# Experiment cooperative mobile manipulation


- challenge from uncertain $J$, adaptive control achieves tracking
- stability via Lyapunov and passivity arguments

[Erhart et al. "Adaptive Force/Velocity Control for Cooperative Manipulation under Uncertain Kinematic Parameters," IROS 2013]
[Sieber et al. "Iterative optimal feedback control with relaxed rigidity constraints for multi-robot cooperative manipulation," CDC 201

# If there is a human ...




**multi-robot: globally known**

- reference $\hat{x}_o^d$
- desired impedance
- input allocation $J^+$

$\Leftrightarrow$

**pHRI: uncertain/different**

- human reference $x_o^d \neq \hat{x}_o^d$
- human desired impedance
- human contribution

# Cooperative manipulation by robots & humans

= control with redundant inputs

**multi-robot**

- control goals and dynamics assumed globally known
- classical modeling, analysis and control design applicable

**pHRI**

- uncertainty about human control goals and controls
- open question: which modeling and analysis tools?
- divergence likely, negotiation required

**Control design is key challenge!**

# Control design for haptic assistance

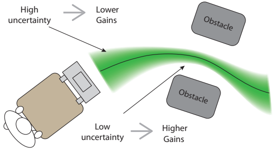
Object impedance control $\Rightarrow$ adapt $J^+$, $\hat{x}_o^d$, and/or impedance?

**Goal: robot pro-actively supports human-intended motion**

**P1: How to choose $J^+$ to reduce human effort while complying with uncertain human motion intention?**

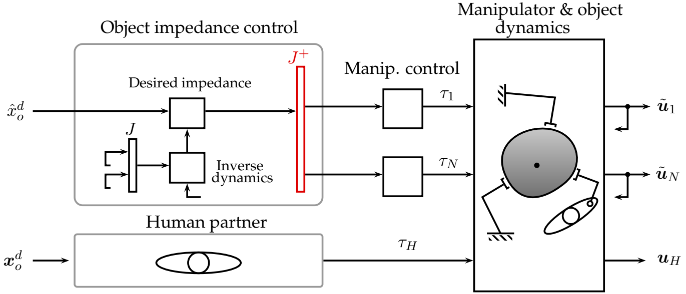
**P2**: How to infer/adapt trajectory based on human feedback?

**P3**: How to tune impedance control to human uncertainty?



# Input allocation in haptic assistance

- assume $\hat{\boldsymbol{x}}_o^d$ given and desired impedance fixed
- divergence of human and robot trajectory reflected in $\widetilde{\boldsymbol{u}}_{\text{int}}$




**Idea: human feedback-based dynamic input allocation**

Adapt level of assistance via $J^+$ to observed disagreement $\widetilde{\boldsymbol{u}}_{\text{int}}$

[Mörtl et al. "The Role of Roles: Physical Cooperation between Humans and Robots," Int. J. Robotics Research 2012]

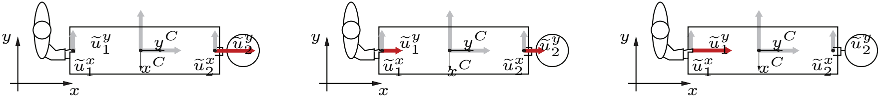
# Disagreement-based dynamic role allocation

Adapt assistance between max & min robots effort via $J^+$:

**WPRA** smooth change $J^+(\widetilde{\boldsymbol{u}}_{\text{int}})$: robot effort $\downarrow$ with $\|\widetilde{\boldsymbol{u}}_{\text{int}}\| \uparrow$

**DPRA** switching robot role $J^+(\widetilde{\boldsymbol{u}}_{\text{int}})$ (discretized WPRA)

**CRA** constant balanced policy $J^+$ (no feedback/baseline)



**For all 3 strategies:**

If the human is minimally cooperative, then the system converges to the desired configuration.

[Mörtl et al. "The Role of Roles: Physical Cooperation between Humans and Robots," Int. J. Robotics Research 2012]

# Large-scale user study for role allocation

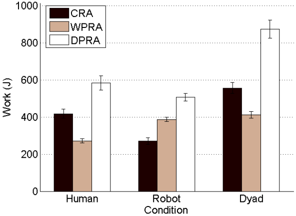

[Mörtl et al. "The Role of Roles: Physical Cooperation between Humans and Robots," Int. J. Robotics Research 2012]

# Dynamic role allocation successful

**Result from experiments**

- human feedback ⇒ haptic negotiation channel important
- adaptation scheme affects joint performance and acceptance

- human effort and completion time lowest for WPRA ⇒ most efficient
- BUT: user acceptance highest for constant role (CRA)




**Interesting: effort minimization not primary for acceptance**

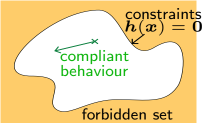
- contradicts optimization-based human motor control theories
- robot behavior predictability seems to be important

[Mörtl et al. "The Role of Roles: Physical Cooperation between Humans and Robots," Int. J. Robotics Research 2012]

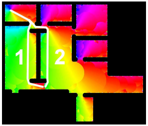
# Other challenges and results - not in this talk

**Risk-sensitive impedance control**
explicit consideration of human prediction uncertainty for improved assistive behavior

**Invariance control for safety in pHRI**
keep states within constraints while achieving desired interaction behavior




**Planning in pHRI**
feedback-planning and LQ-primitive sequencing for real-time reaction to disturbances




[Medina et al. "Disagreement-Aware Physical Assistance Through Risk-Sensitive Optimal Feedback Control," IROS 2012]
[Kimmel et al. "6D Workspace Constraints for pHRI using Invariance Control with Chattering Reduction," IROS 2012]
[Lawitzky et al. "Trajectory Generation under the Least Action Principle for Physical Human-Robot Cooperation," ICRA 2013]

# Control challenges in cooperative pHRI

**What we have**

- some results for multi-robot cooperative manipulation
- very few results for control design in cooperative pHRI

**cooperative pHRI =**
**cooperation of agents with uncertain control goals/models**

**Emerging field ⇒ many open research questions**

- modeling and identification of human behavior
- systematic control design with guarantees
- system identification, statistical learning, stochastic control, inverse optimization, approximate dynamic programming, games, ...
- control ⇔ machine learning: control based on learned models
- control ⇔ psychology: human behavior models for control

# Conclusions

**pHRI is an emerging area with important applications**

e.g. manufacturing, assistive for elderly, rehabilitation, ...

- physical cooperation/performance of human & robot together
- **systematic control design is largely open problem**

**Control research beyond the traditional boundaries is fun too ...**

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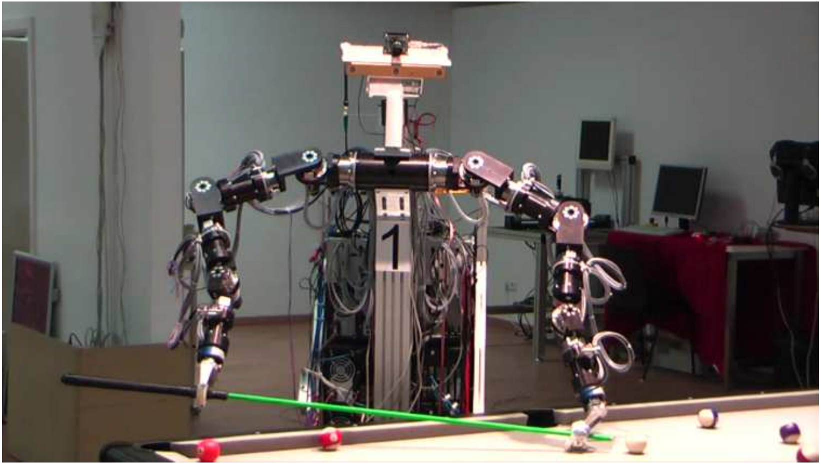
# … having fun.




[Nierhoff et al. “Playing Pool with a Dual-Armed Robot,” ICRA 2011]
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