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

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Why use cooperative manipulation with human guidance?

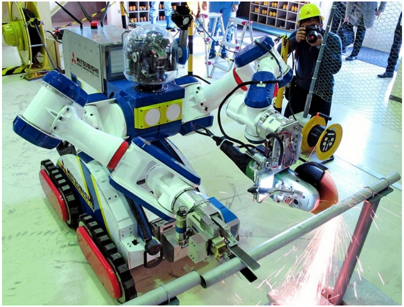


Figure: Coordinated handling of tools by a tele-operated robot [MHI 2014]

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 Formulation

- Precise and stable control during free-motion/contact transition
- Enhance versatility by performing friction grasps
- (Intuitive) high-level human supervisory control
- Local control of formation, independent of the operator
- Assistance of the operator with suitable feedback

Goal

Enable a human to **intuitively** control a robot team executing **versatile** tasks

Related Work: Robot-team control

- Virtual object based impedance control [Schneider and Cannon 1992]
- Internal and external impedance control [Caccvale and Villani 2001; Caccavale et al. 2008]
  - Force/Torque sensors at the manipulators required
- Intrinsically Passive Control [Stramigioli 2001; Wimboeck, Ott, and Hirzinger 2008]
  - no object tracking, virtual object simulation
- Internal impedance control + object dynamics' feed-forward [Erhart and Hirche 2015]
- Formation control of a robot team [Sieber, Music, and Hirche 2015; Wimboeck, Ott, and Hirzinger 2006]
  - no object dynamics considered

Related Work: Human in the loop

- Bilateral tele-manipulation [Lee and Spong 2005]
  - Single master coupled to human, constrained system as slave
  - Local control of interaction dynamics
  - Force feedback
- Formation-based control [Sieber, Music, and Hirche 2015; Scheggi, Morbidi, and Prattichizzo 2014]
  - Single leader, multiple followers
  - Robots preserve formation autonomously
  - Tactile feedback
- Gesture-based Control [Gioioso et al. 2014]
  - Free-hand motion controls constrained system
  - Visual feedback

System modelling

How can we consistently model different forms of energy stored in a system?

Port-Hamiltonian systems

- Mechanical elements (spring, mass, damper)

$$\begin{pmatrix} \dot{x}_B \\ \dot{x}_S \end{pmatrix} = \begin{pmatrix} J_B & -Ad^T_{H_b^0}\phi_b^T \\ \phi_b Ad_{H_b^0} & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial V}{\partial x_B} \\ \frac{\partial V}{\partial x_S} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ \phi_v & \phi_i & \phi_{rl} \end{pmatrix} \begin{pmatrix} T_v^0 \\ T_i^0 \\ T_{rl}^b \end{pmatrix}$$

$$\begin{pmatrix} W_v^0 \\ W_i^0 \\ W_{rl}^b \end{pmatrix} = \begin{pmatrix} 0 & \phi_v^T \\ 0 & \phi_i^T \\ 0 & \phi_{rl}^T \end{pmatrix} \begin{pmatrix} \frac{\partial V}{\partial x_B} \\ \frac{\partial V}{\partial x_S} \end{pmatrix}$$

- Conservative elements (transformer, gyrator)
- Interconnection through power ports

$$\mathcal{P} = \mathcal{V} \times \mathcal{V}^*$$

Energy consistent modelling and control

- *Virtual object* concept
  - Maps object forces to manipulators
  - Stores kinetic energy
  - Changes size to adjust formation
- Model represents energy content of the complete system
- Dampers dissipate energy: **passive system**
- Operator controls system by energy supply

Stability

Model errors never influence passivity nor stability [Stramigioli 2001]

Intrinsically Passive Control

- Geometric interconnection of springs, masses and dampers
- Internal and external *impedance* relations
- No manipulator inertia re-shaping
- Energy supplied by operator/environment
- Grasping with variable rest-length springs

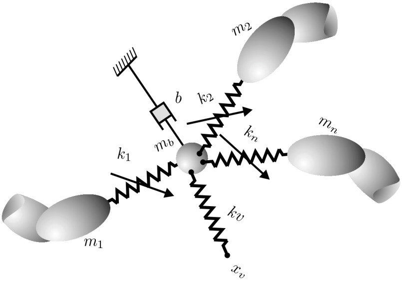


Figure: Mass-spring-damper structure of the IPC [Stramigioli 2001]

Human in the loop

- Virtual object position is connected with a spring to the desired position
- Delays and time-discrete reference changes possibly violate passivity
- Passive Set Position Modulation [**Lee˙10**]
- Suitable for bilateral tele-manipulation
- Spring rest-lengths: adjust to grasp/release objects

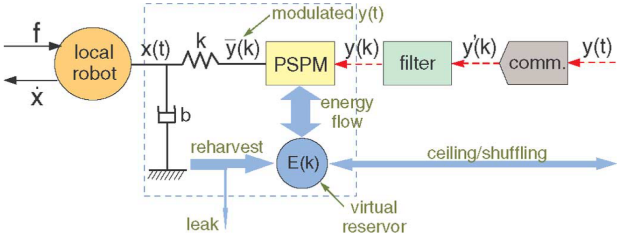


Figure: Overview over the PSPM[**Lee˙10**]

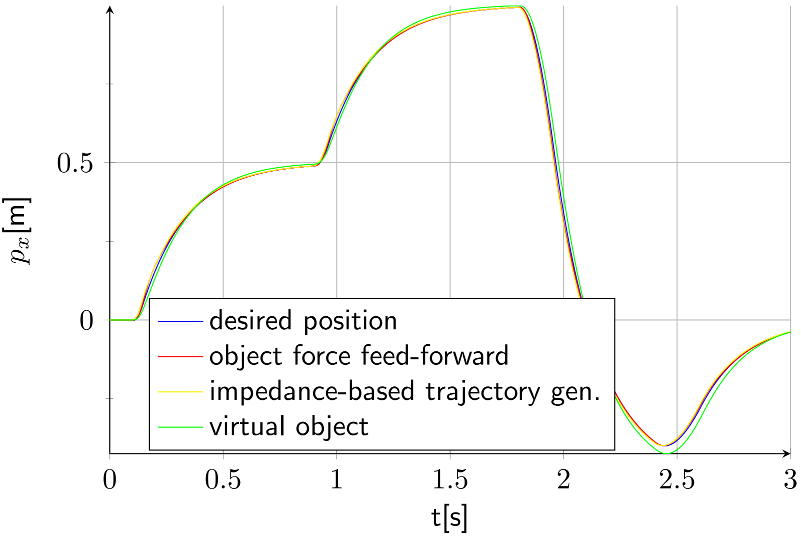
Friction grasps: Internal force control

Friction constraint of a *soft finger*

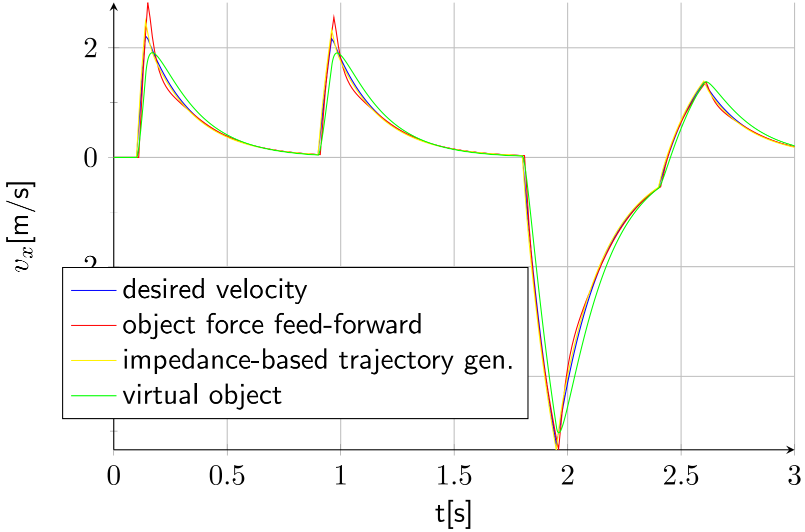
$$f_N \geq \frac{1}{\mu_f}|f_T| + \frac{1}{\mu_m}|m_N|$$

- Autonomous control of grasping forces subject to dynamic manipulation requirements
- Energy taken from virtual object spring
- Operator sets constant grasping forces

Comparison: position tracking



Comparison: velocity tracking



Comparison: internal forces (rotation)

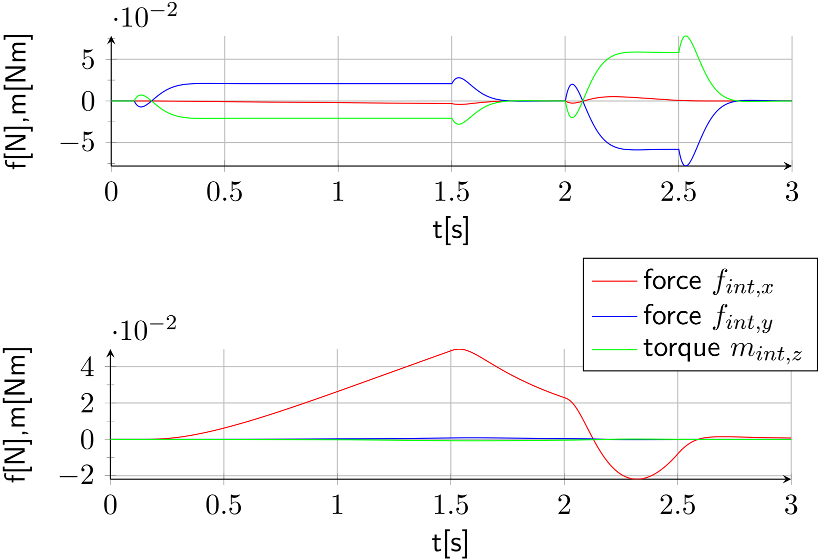


Figure: Top: Object force feed-forward; Bottom: Virtual Object

Overview & open issues

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Open issues

- Experimental evaluation
- Evaluation of different human-in-the-loop set-ups
- Suitable control design

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