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

M. Angerer
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Betreuer: S. Musić

Lehrstuhl für Informationstechnische Regelung
Technische Universität München

Why use cooperative manipulation with human guidance?

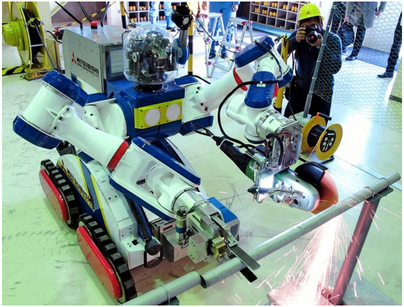


Figure : Coordinated handling of tools by a tele-operated robot [MHI 2014]

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

port-Hamiltonian system modelling

Network representation of non-linear physical systems

- Mechanical energy storing elements (spring, mass)
- Dissipation element (Damper)
- Conservative elements (transformer, gyrator)
- Interconnection: power port $\mathcal{P} = \mathcal{V} \times \mathcal{V}^*$
  $\mathcal{V}$: space of efforts; $\mathcal{V}*$: (dual) space of flows

Example: Inertia

$$\dot{P}^b = C_b \frac{\partial H(P^b)}{\partial P^b} + W^b$$

$$T_b^{b,0} = \frac{\partial H(P^b)}{\partial P^b}$$

$H = \frac{1}{2}(P^b)^T M_b^{-1} P^b$: Hamiltonian energy function;
P^b: momentum (state); $T_b^{b,0}$: twist (effort); W^b: wrench (flow)

Intrinsically Passive Control

Virtual system model as a controller for the real system

- Geometric interconnection of springs, masses and dampers
- Internal and external *impedance* relations
- No manipulator inertia re-shaping + dampers: **passivity**
- Energy supplied by operator/environment
- Formation changes through variable virtual object shape

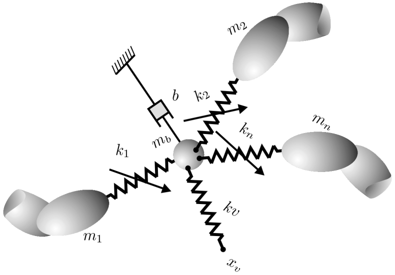


Figure : Mass-spring-damper structure of the IPC [Stramigioli 2001]

Stability

Model errors never influence passivity nor stability [Stramigioli 2001]

Controller Model

$$\begin{pmatrix} \dot{x}_M \\ \dot{x}_S \end{pmatrix} = \begin{pmatrix} J_M & -(\phi_M)^T \\ \phi_M & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_M} \\ \frac{\partial H}{\partial x_S} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \phi_h & \phi_{rl} \end{pmatrix} \begin{pmatrix} T_h \\ T_{rl} \end{pmatrix}$$

$$\begin{pmatrix} W_h \\ W_{rl} \end{pmatrix} = \begin{pmatrix} 0 & (\phi_h)^T & 0 \\ 0 & (\phi_{rl})^T & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_M} \\ \frac{\partial H}{\partial x_S} \end{pmatrix}$$

- x_M, x_S: state vectors of the inertias and springs
- $H = H_V + H_S + H_M$: sum of energies
- $J_V, \phi_V, \phi_M, J_M, \phi_h, \phi_{rl}$: geometric description matrices
- T_h, T_{rl}: desired object and rest-length twists
- W_h, W_{rl}: corresponding wrenches

Reference inputs: T_h, T_{rl}
Control output: end-effector wrenches $W_E = (\phi_E)^T \frac{\partial H}{\partial x_S}$

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 and Huang 2010]
- Suitable for bilateral tele-manipulation
- Spring rest-lengths: adjust to grasp/release objects

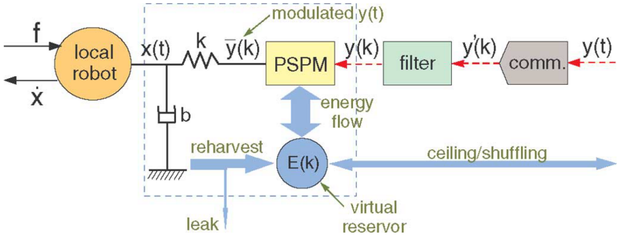


Figure : Overview over the PSPM[Lee and Huang 2010]

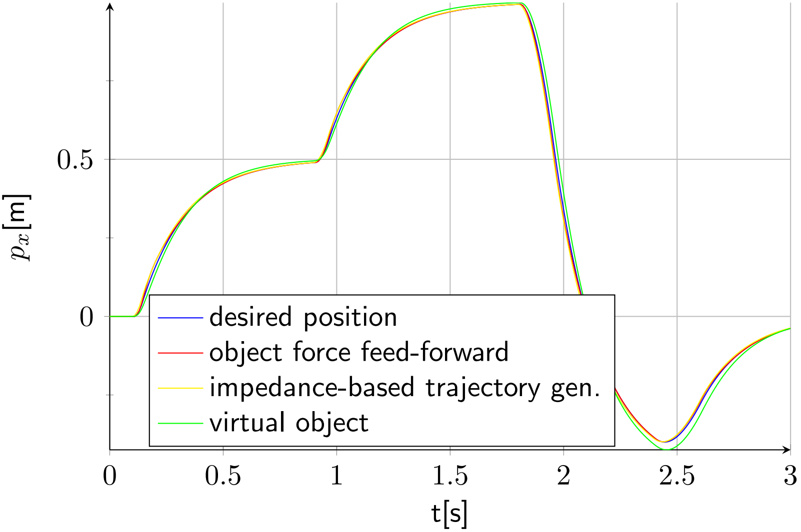
Friction grasps: Internal force control

Friction constraint of a *soft finger*

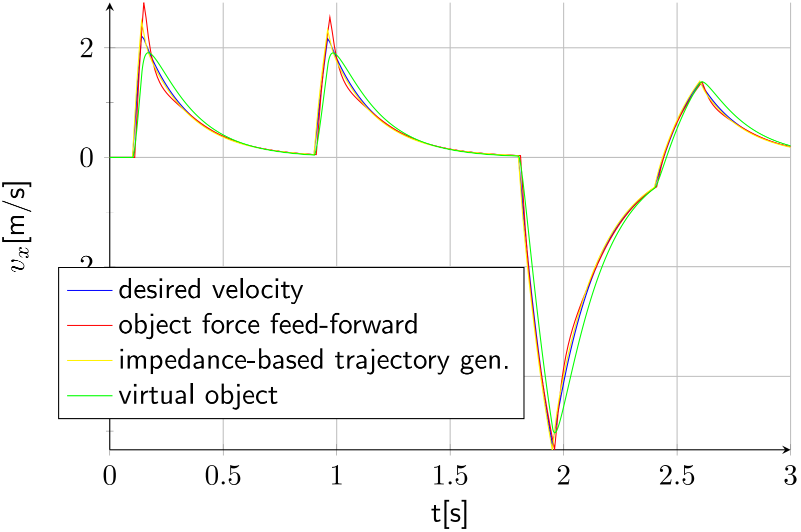
$$f_N \geq \frac{1}{\mu_f}|f_T| + \frac{1}{\mu_m}|m_N|$$

- 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)

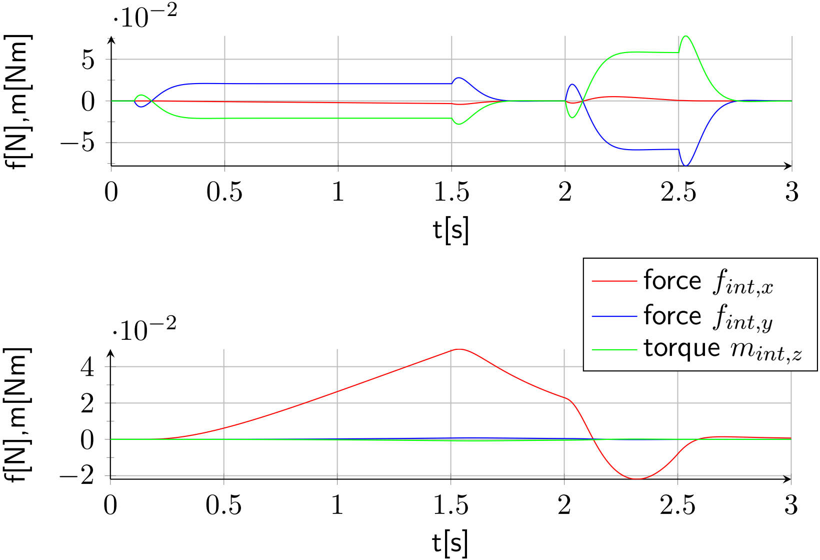


Figure : Top: Object force feed-forward; Bottom: Virtual Object

Overview & open issues

- Passive control architecture $\Rightarrow$ stability with passive humans and environments
- Flexibility through changeable formation
- Automatic and passive friction grasp stabilization

Open issues

- Formulation of the PSPM in the Hamiltonian framework
- Energy conservative design of the grasp force assignment
- Experimental evaluation
- Evaluation of different human-in-the-loop set-ups

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