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

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Why use cooperative manipulation with human guidance?

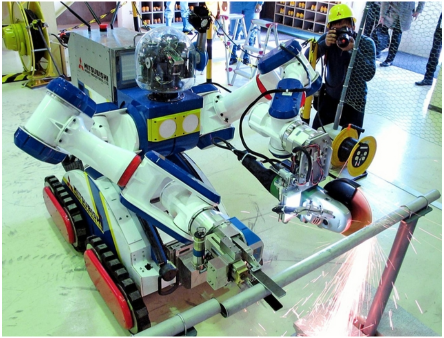

Figure : Demonstration of MHI MEISTeR at Fukushima Daiichi Nuclear Power Station[]

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 formation requirements controlled by robots
- Assistance of the operator with suitable feedback
- Preservation of stability over delayed communication (?, very vulnerable point)

Related Work: Impedance Control

- Formation control of robot team [Sieber, Music, and Hirche 2015; Wimboeck, Ott, and Hirzinger 2006]
  - object not part of control loop
- Intrinsically Passive Control [Stramigioli 2001; Wimboeck, Ott, and Hirzinger 2008]
  - virtual object simulation
- Internal impedance control + object dynamics' feed-forward [De Pascali et al. 2015]
  - object tracking required
- Internal and external impedance control [Caccvale and Villani 2001; Caccavale et al. 2008]
  - Force/Torque sensors at the manipulators required

Related Work: Human in the loop

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

Energy consistent modelling and control

- controlled robots are passive
- operator and environment can supply energy
- effort-flow pair: force and velocity

$\Rightarrow$ enhanced human perception through control of a meaningful quantity and appropriate feedback

$\Rightarrow$ stability over a wide class of environments

If a controlled robot is not passive there is always a passive environment that destabilizes the interconnected system [Stramigioli 2015]

Interconnection of energy-discrete elements

- interconnection through power ports

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

- mechanical elements
  - spring
  - mass
  - damper
- conservative elements
  - transformer
  - gyrator
- Example: variable rest-length spring

$$\dot{H}_i^j = \left(\begin{pmatrix} 1 & Ad_{H_b^j} \end{pmatrix} \begin{pmatrix} T_b^j \\ T_i^b \end{pmatrix} \right) H_i^j \tag{1}$$

$$\begin{pmatrix} W_b^{j,j} \\ W_i^{b,b} \end{pmatrix} = \left(\begin{pmatrix} 1 \\ Ad_{H_b^j}^T \end{pmatrix} \frac{\partial V_{i,j}}{\partial H_i^j} \right) (H_i^j)^T \tag{2}$$

Structure of the IPC

- Spring-mass-damper system
- Simulated virtual object
- Manipulators modelled by inertias
- Potential (inertia) and kinetic (springs) energy
- Energy dissipation in damper: passivity

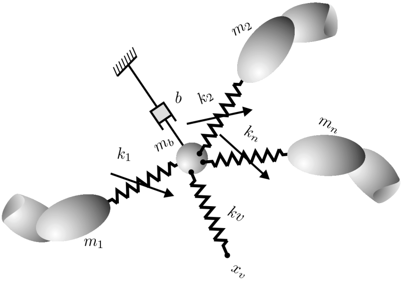

Figure : Mass-spring-damper structure of the IPC [Stramigioli 2001]

Grasping an object

- Variable rest-length springs
- Rest-length: virtual object size
- Distinct power port

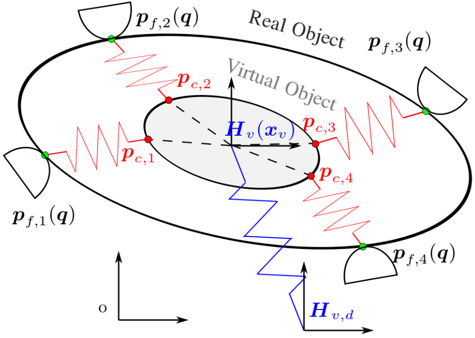

Figure : Virtual and real object [Wimboeck, Ott, and Hirzinger 2008]

Grasping force optimization for friction contacts

- required contact normal force is dependent on tangential forces
- high tangential forces arise during acceleration
- other requirements: safety margin, maximum grasping force ⇒ cost function
- linear matrix inequality (LMI) problem

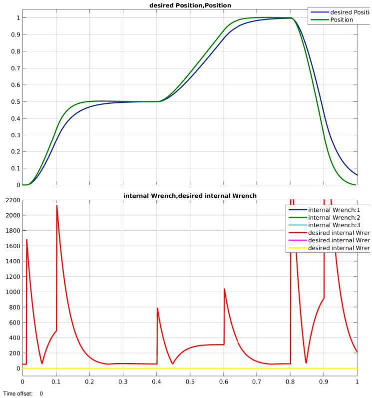

Figure : Position, Internal wrench

Comparison of Grasp Controllers 1

Impedance-based reference trajectory generation [Caccvale and Villani 2001]

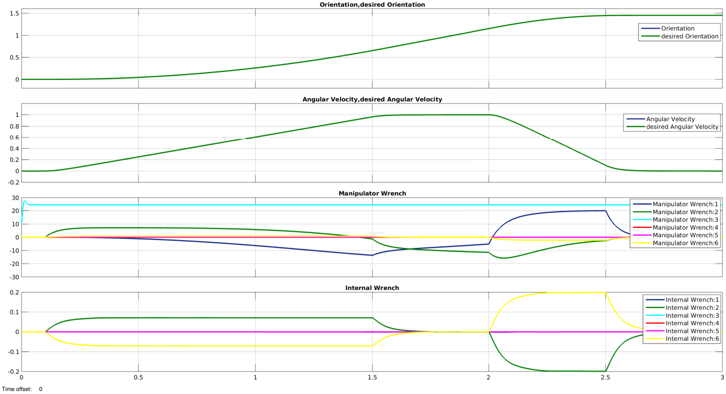

Figure : Position, Velocity, Manipulator wrench, Internal wrench

Comparison of Grasp Controllers 2

Internal impedance control with object force-feedforward [De Pascali et al. 2015]

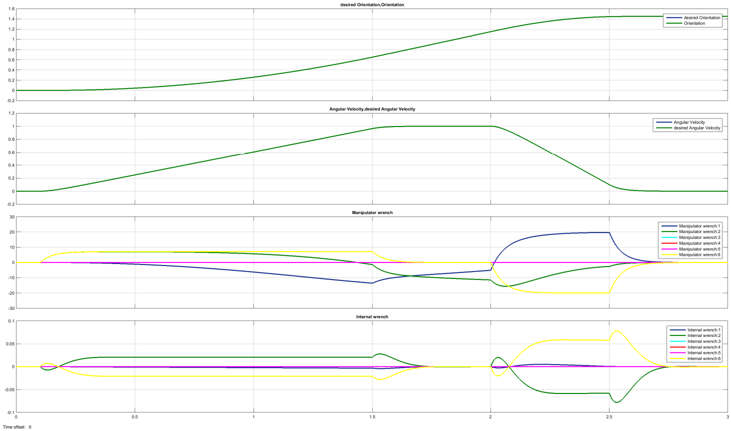

Figure : Position, Velocity, Manipulator wrench, Internal wrench

Conclusion

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