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

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Why use cooperative manipulation with human guidance?

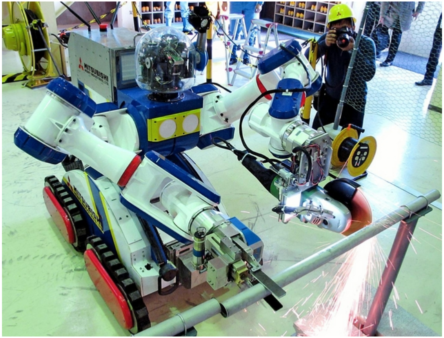


Figure : Coordinated handling of tools by a tele-operated robot [Mitsubishi Heavy Industries 2014]

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 formation constraints controlled by robots
- Assistance of the operator with suitable feedback

Related Work: Robot-team 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

- *Virtual object* concept
  - Maps object forces to manipulators
  - Stores kinetic energy
  - Changes size to adjust formation
- Controller represents energy content of the complete system
- Dampers dissipate energy: **passive system**
- Operator controls system by energy supply
- Model errors never influence passivity nor stability

System modelling

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

Port-Hamiltonian systems

- Mechanical elements
  - Spring
  - Mass
  - Damper

  } Impedance control components

- Conservative elements
  - Transformer
  - Gyrator
- Interconnection through power ports

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

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

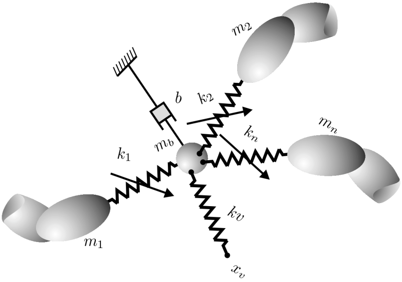


Figure : Mass-spring-damper structure of the IPC [Stramigioli 2001]

Human supervisory control

- Command value: velocity $\Leftrightarrow$ force :feedback value
- Suitable for bilateral tele-manipulation
- Energy intuition: humans can estimate possible impacts of interaction
- Spring rest-lengths: adjust to grasp/release objects

Comparison: position tracking

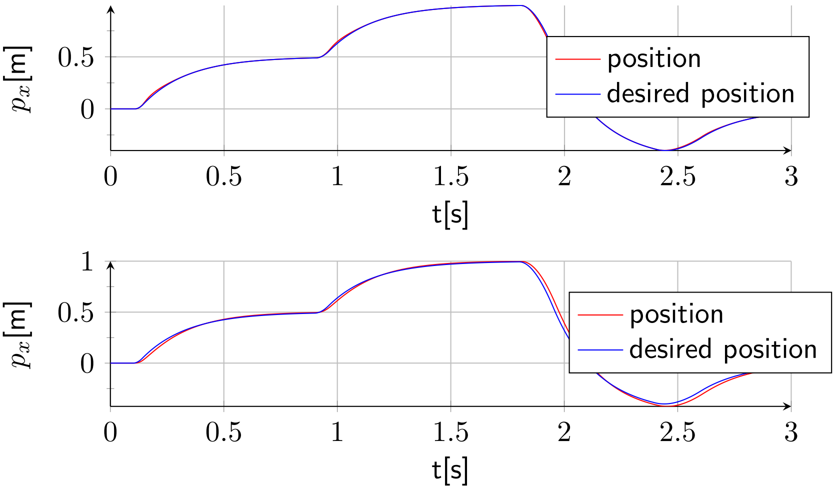
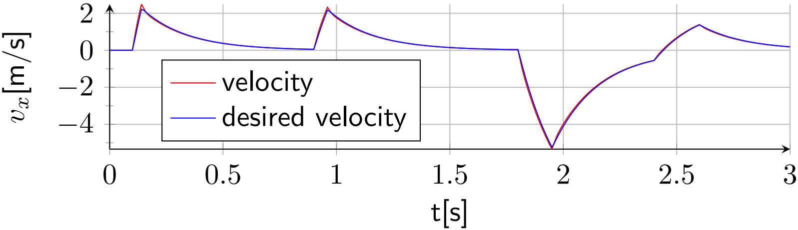


Figure : Top: Object force feed-forward; Bottom: Virtual Object

Comparison: velocity tracking



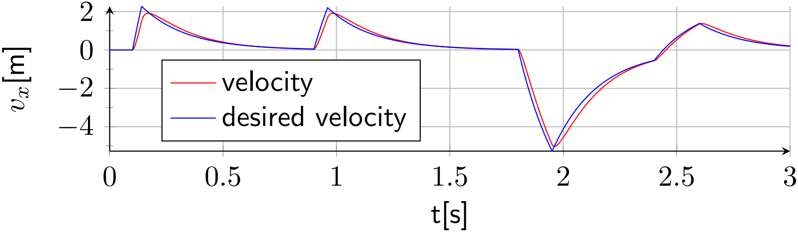


Figure : Top: External impedance based reference trajectory generation; Bottom: Virtual object

Comparison: internal forces (rotation)

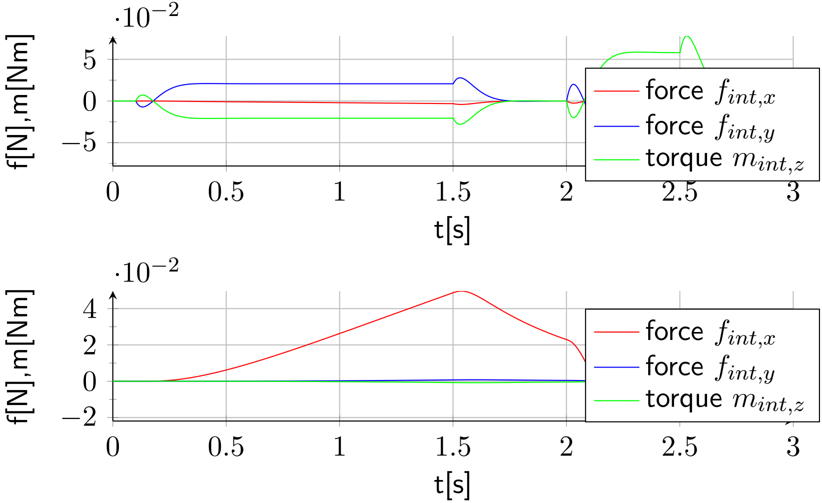


Figure : Top: Object force feed-forward; Bottom: Virtual Object

Conclusion

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