Robot Control

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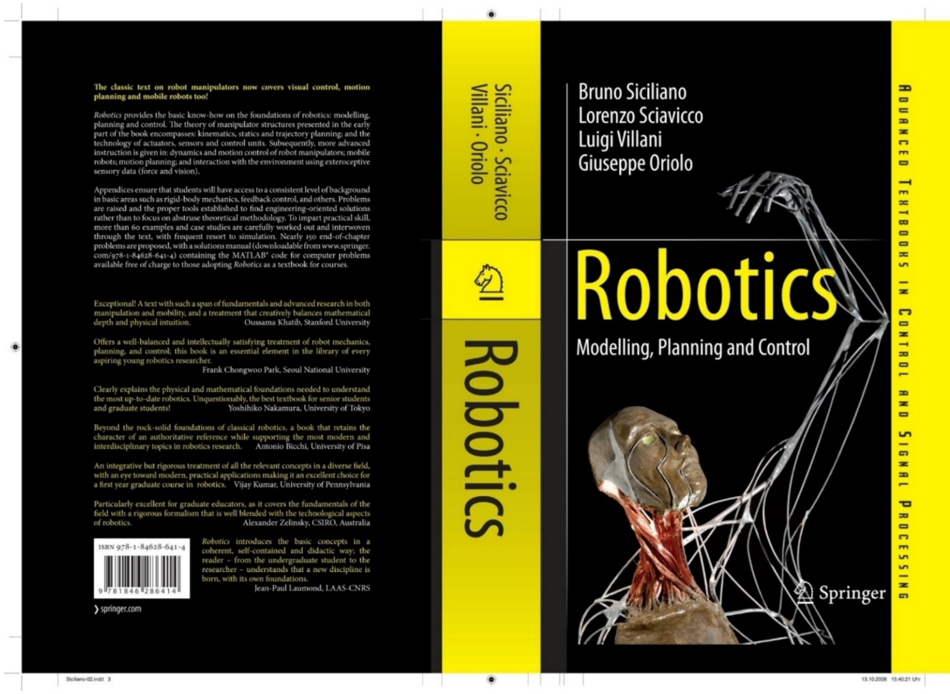
Outline

- Motion control
- Indirect force control
- Direct force control
- Interaction control using vision and force
- Experiments

The Textbook

B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo, *Robotics: Modelling, Planning and Control*, Springer, London, 2009, DOI 10.1007/978-1-4471-0449-0

- Chapter 8 — Motion Control
- Chapter 9 — Force Control
- Chapter 10 — Visual Control



MOOC Robotics Foundations – Robot Control

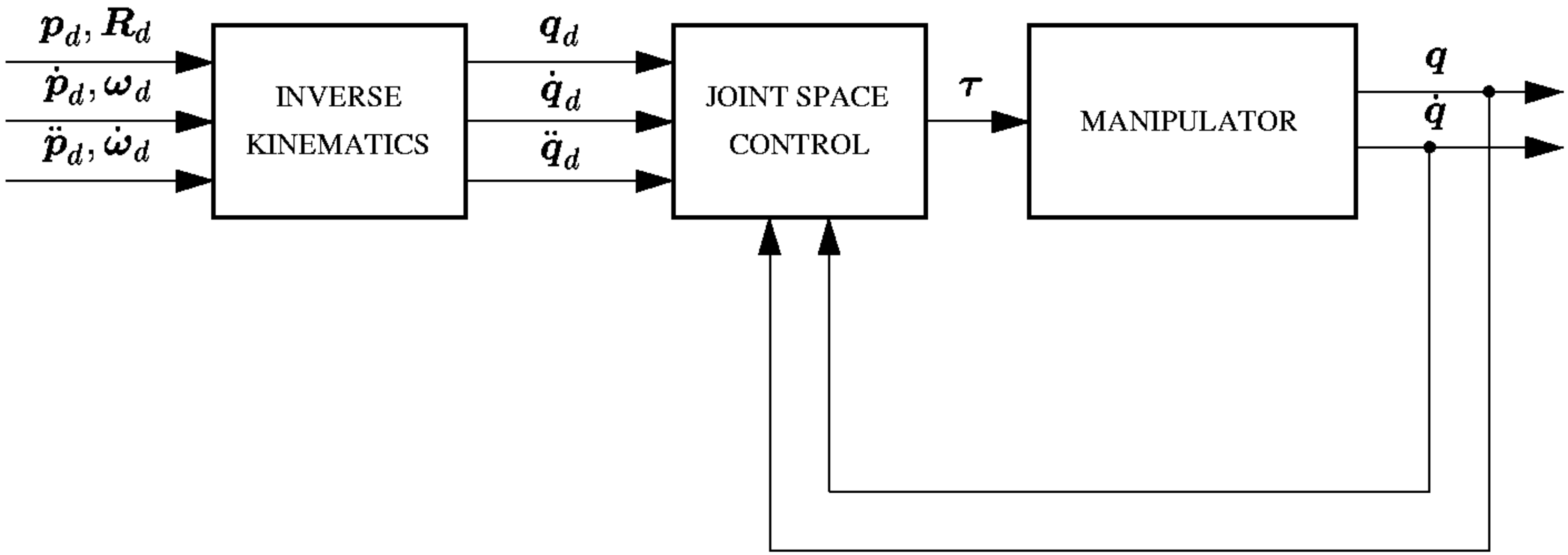
Coming up soon … https://youtu.be/JwfRk-U3aPw

The Handbook

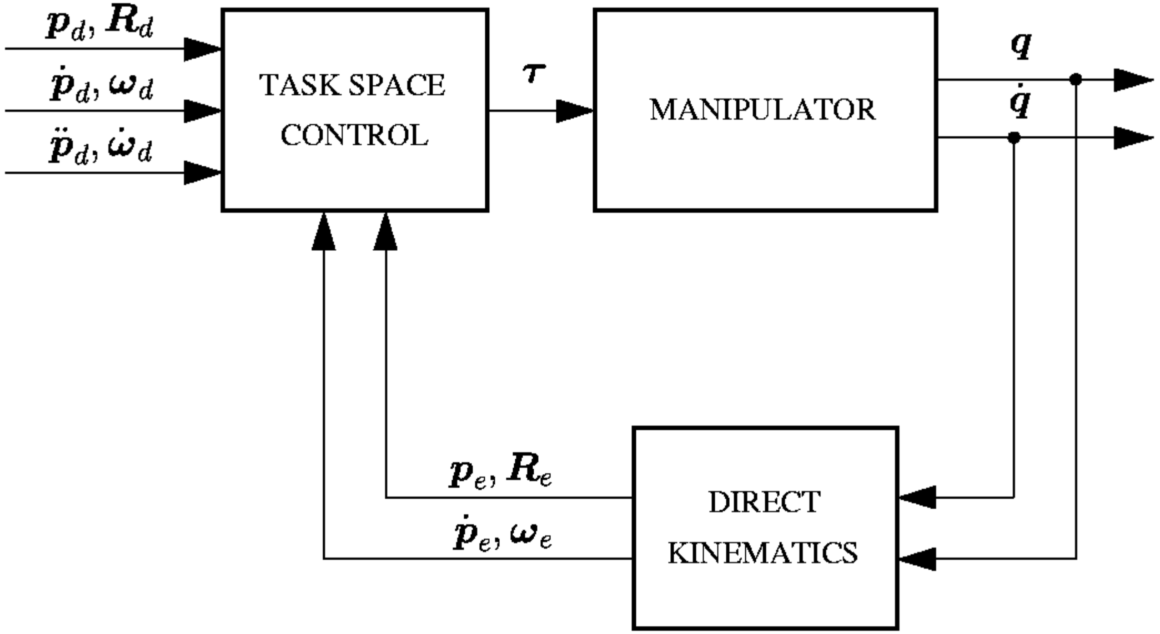
B. Siciliano, O. Khatib, *Springer Handbook of Robotics 2nd Edition*, Springer, Heidelberg, 2016, DOI 10.1007/978-3-319-32552-1

- Chapter 8 — Motion Control
- Chapter 9 — Force Control
- Chapter 34 — Visual Servoing

- Joint space control
  - Task references transformed into joint references
  - Redundancy resolution at kinematic level



- Task space control
  - Control directly in task (operational) space
  - Redundancy resolution at dynamic level



- Tracking control
  - Dynamic model-based compensation
  - Euler angles
  - Angle/axis
  - Quaternion
  - Computational issues
  - Redundancy resolution
- Regulation
  - Static model-based compensation
  - Orientation errors

Dynamic Model-Based Compensation

- Inverse dynamics

$$\boldsymbol{\tau} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\alpha} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$$

$$\dot{\boldsymbol{v}}_e = \boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$$

$$\boldsymbol{\alpha} = \boldsymbol{J}^{-1}(\boldsymbol{q})\left(\begin{bmatrix}\boldsymbol{a}_p \\ \boldsymbol{a}_o\end{bmatrix} - \dot{\boldsymbol{J}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\right)$$

  - Position control $\Delta\boldsymbol{p}_{de} = \boldsymbol{p}_d - \boldsymbol{p}_e$

$$\boldsymbol{a}_p = \ddot{\boldsymbol{p}}_d + \boldsymbol{K}_{Dp}\Delta\dot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Pp}\Delta\boldsymbol{p}_{de} \Longrightarrow \Delta\ddot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Dp}\Delta\dot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Pp}\Delta\boldsymbol{p}_{de} = \boldsymbol{0}$$

  - Orientation control

$\boldsymbol{a}_o$ ⇒ Euler angles / Angle/axis / Quaternion

- Orientation error: $\Delta\boldsymbol{\varphi}_{de} = \boldsymbol{\varphi}_d - \boldsymbol{\varphi}_e$
  - Resolved angular acceleration

$$\boldsymbol{a}_o = \boldsymbol{T}(\boldsymbol{\varphi}_e)(\ddot{\boldsymbol{\varphi}}_d + \boldsymbol{K}_{Do}\Delta\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{de}) + \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_e, \dot{\boldsymbol{\varphi}}_e)\dot{\boldsymbol{\varphi}}_e$$

representation singularities (!)

$$\boldsymbol{\omega}_e = \boldsymbol{T}(\boldsymbol{\varphi}_e)\dot{\boldsymbol{\varphi}}_e$$

$$\dot{\boldsymbol{\omega}}_e = \boldsymbol{T}(\boldsymbol{\varphi}_e)\ddot{\boldsymbol{\varphi}}_e + \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_e, \dot{\boldsymbol{\varphi}}_e)\dot{\boldsymbol{\varphi}}_e$$

  - Error dynamics

$$\Delta\ddot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Do}\Delta\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{de} = \boldsymbol{0}$$

$$\dot{\boldsymbol{\varphi}}_d = \boldsymbol{T}^{-1}(\boldsymbol{\varphi}_d)\boldsymbol{\omega}_d$$

$$\ddot{\boldsymbol{\varphi}}_d = \boldsymbol{T}^{-1}(\boldsymbol{\varphi}_d)\left(\dot{\boldsymbol{\omega}}_d - \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_d, \dot{\boldsymbol{\varphi}}_d)\dot{\boldsymbol{\varphi}}_d\right)$$

Alternative Euler Angles

- Orientation error: ${}^{e}\boldsymbol{R}_d = \boldsymbol{R}_e^{\mathrm{T}}\boldsymbol{R}_d \Longrightarrow \boldsymbol{\varphi}_{de}$
  - Resolved angular acceleration

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_d + \boldsymbol{T}_e(\boldsymbol{\varphi}_{de})(\boldsymbol{K}_{Do}\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\boldsymbol{\varphi}_{de}) - \dot{\boldsymbol{T}}_e(\boldsymbol{\varphi}_{de}, \dot{\boldsymbol{\varphi}}_{de})\dot{\boldsymbol{\varphi}}_{de}$$

$$\dot{\boldsymbol{\omega}}_e = \dot{\boldsymbol{\omega}}_d - \boldsymbol{T}_e(\boldsymbol{\varphi}_{de})\ddot{\boldsymbol{\varphi}}_{de} - \dot{\boldsymbol{T}}_e(\boldsymbol{\varphi}_{de}, \dot{\boldsymbol{\varphi}}_{de})\dot{\boldsymbol{\varphi}}_{de}$$

$$\boldsymbol{T}_e(\boldsymbol{\varphi}_{de}) = \boldsymbol{R}_e\boldsymbol{T}(\boldsymbol{\varphi}_{de})$$

choose $\boldsymbol{\varphi}_{de}$ so that $\boldsymbol{T}(\mathbf{0})$ is nonsingular (!)

  - Error dynamics

$$\ddot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Do}\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\boldsymbol{\varphi}_{de} = \mathbf{0}$$

- Orientation error: ${}^{e}\boldsymbol{R}_{d} = \boldsymbol{R}_{e}^{\mathrm{T}}\boldsymbol{R}_{d} \Longrightarrow {}^{e}\boldsymbol{o}_{de} = f(\vartheta_{de})\,{}^{e}\boldsymbol{r}_{de}$

Representation	$f(\vartheta)$
Classical angle/axis	$\sin(\vartheta)$
Quaternion	$\sin(\vartheta/2)$
Rodrigues parameters	$\tan(\vartheta/2)$
Simple rotation	ϑ

angle axis

- Angle/axis error: ${}^{e}\boldsymbol{o}'_{de} = \sin(\vartheta_{de})\,{}^{e}\boldsymbol{r}_{de}$
  - Resolved angular acceleration

$$\boldsymbol{a}_o = \boldsymbol{L}^{-1}\left(\boldsymbol{L}^{\mathrm{T}}\dot{\boldsymbol{\omega}}_d + \dot{\boldsymbol{L}}^{\mathrm{T}}\boldsymbol{\omega}_d - \dot{\boldsymbol{L}}\boldsymbol{\omega}_e + \boldsymbol{K}_{Do}\dot{\boldsymbol{o}}'_{de} + \boldsymbol{K}_{Po}\boldsymbol{o}'_{de}\right)$$

$$\boldsymbol{o}'_{de} = \boldsymbol{R}_e\,{}^{e}\boldsymbol{o}'_{de} \quad = \frac{1}{2}\left(\boldsymbol{S}(\boldsymbol{n}_e)\boldsymbol{n}_d + \boldsymbol{S}(\boldsymbol{s}_e)\boldsymbol{s}_d + \boldsymbol{S}(\boldsymbol{a}_e)\boldsymbol{a}_d\right)$$

$$\boldsymbol{L} = -\frac{1}{2}\left(\boldsymbol{S}(\boldsymbol{n}_d)\boldsymbol{S}(\boldsymbol{n}_e) + \boldsymbol{S}(\boldsymbol{s}_d)\boldsymbol{S}(\boldsymbol{s}_e) + \boldsymbol{S}(\boldsymbol{a}_d)\boldsymbol{S}(\boldsymbol{a}_e)\right)$$

$$\boldsymbol{n}_e^{\mathrm{T}}\boldsymbol{n}_d > 0,\ \boldsymbol{s}_e^{\mathrm{T}}\boldsymbol{s}_d > 0,\ \boldsymbol{a}_e^{\mathrm{T}}\boldsymbol{a}_d > 0$$

  - Error dynamics

$$\ddot{\boldsymbol{o}}'_{de} + \boldsymbol{K}_{Do}\dot{\boldsymbol{o}}'_{de} + \boldsymbol{K}_{Po}\boldsymbol{o}'_{de} = \boldsymbol{0}$$

- Simpler choice: $\boldsymbol{R}_e \simeq \boldsymbol{R}_d \implies \boldsymbol{L} \simeq \boldsymbol{I}$

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_d + \boldsymbol{K}_{Do}\Delta\boldsymbol{\omega}_{de} + \boldsymbol{K}_{Po}\boldsymbol{o}'_{de}$$

- Error dynamics

$$\Delta\dot{\boldsymbol{\omega}}_{de} + \boldsymbol{K}_{Do}\Delta\boldsymbol{\omega}_{de} + \boldsymbol{K}_{Po}\boldsymbol{o}'_{de} = \boldsymbol{0}$$

  - Stability via Lyapunov argument $\mathcal{Q} = \{\eta, \boldsymbol{\epsilon}\}$

$${}^e\boldsymbol{o}'_{de} = 2\eta_{de}\,{}^e\boldsymbol{\epsilon}_{de} \qquad \boldsymbol{K}_{Po} = k_{Po}\boldsymbol{I} \quad \boldsymbol{K}_{Do} = k_{Do}\boldsymbol{I}$$

$$\mathcal{V} = 2k_{Po}\,{}^e\boldsymbol{\epsilon}_{de}^{\mathrm{T}}\,{}^e\boldsymbol{\epsilon}_{de} + \frac{1}{2}\Delta\boldsymbol{\omega}_{de}^{\mathrm{T}}\Delta\boldsymbol{\omega}_{de}$$

- Orientation error: $\boldsymbol{o}''_{de} = \sin\frac{\vartheta_{de}}{2}\,{}^{e}\boldsymbol{r}_{de} = {}^{e}\boldsymbol{\epsilon}_{de}$

- Resolved angular acceleration

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_d + \boldsymbol{K}_{Do}\Delta\boldsymbol{\omega}_{de} + \boldsymbol{K}_{Po}\boldsymbol{R}_e\,{}^{e}\boldsymbol{\epsilon}_{de}$$

- Error dynamics

$$\Delta\dot{\boldsymbol{\omega}}_{de} + \boldsymbol{K}_{Do}\Delta\boldsymbol{\omega}_{de} + \boldsymbol{K}_{Po}\boldsymbol{R}_e\,{}^{e}\boldsymbol{\epsilon}_{de} = \boldsymbol{0}$$

  - Stability via Lyapunov argument

$$\mathcal{V} = k_{Po}\left((\eta_{de}-1)^2 + {}^{e}\boldsymbol{\epsilon}_{de}^{\mathrm{T}}\,{}^{e}\boldsymbol{\epsilon}_{de}\right) + \frac{1}{2}\Delta\boldsymbol{\omega}_{de}^{\mathrm{T}}\Delta\boldsymbol{\omega}_{de}$$

Computational Issues

- Number of floating-point operations and function calls

	Resolved acceleration		*Trajectory generation*	
Orientation error	*Flops*	*Funcs*	*Flops*	*Funcs*
Classical Euler angles	68	8	52	8
Alternative Euler angles	136	8	0	0
Angle/axis	55	0	0	0
Quaternion	60	1	21	1

Computational Issues

- Comparison

	Resolved acceleration		*Trajectory generation*	
Orientation error	*Flops*	*Funcs*	*Flops*	*Funcs*
Classical Euler angles	68	8	52	8
Alternative Euler angles	136	8	0	0
Angle/axis	55	0	0	0
Quaternion	60	1	21	1

- Null-space motion

$$\boldsymbol{\tau} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\alpha} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$$

$$\boldsymbol{\alpha} = \boldsymbol{J}^{\dagger}(\boldsymbol{q})\left(\boldsymbol{a} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}}\right) + \boldsymbol{\alpha}_n$$

$$\boldsymbol{J}^{\dagger} = \boldsymbol{B}^{-1}\boldsymbol{J}^{\mathrm{T}}\left(\boldsymbol{J}\boldsymbol{B}^{-1}\boldsymbol{J}^{\mathrm{T}}\right)^{-1}$$

dynamically consistent pseudo-inverse

$$\boldsymbol{\alpha}_n = (\boldsymbol{I} - \boldsymbol{J}^{\dagger}\boldsymbol{J})\left(\dot{\boldsymbol{\beta}} - \dot{\boldsymbol{J}}^{\dagger}\boldsymbol{J}(\boldsymbol{\beta} - \dot{\boldsymbol{q}}) + \boldsymbol{B}^{-1}(\boldsymbol{K}_n\boldsymbol{e}_n + \boldsymbol{C}\boldsymbol{e}_n)\right)$$

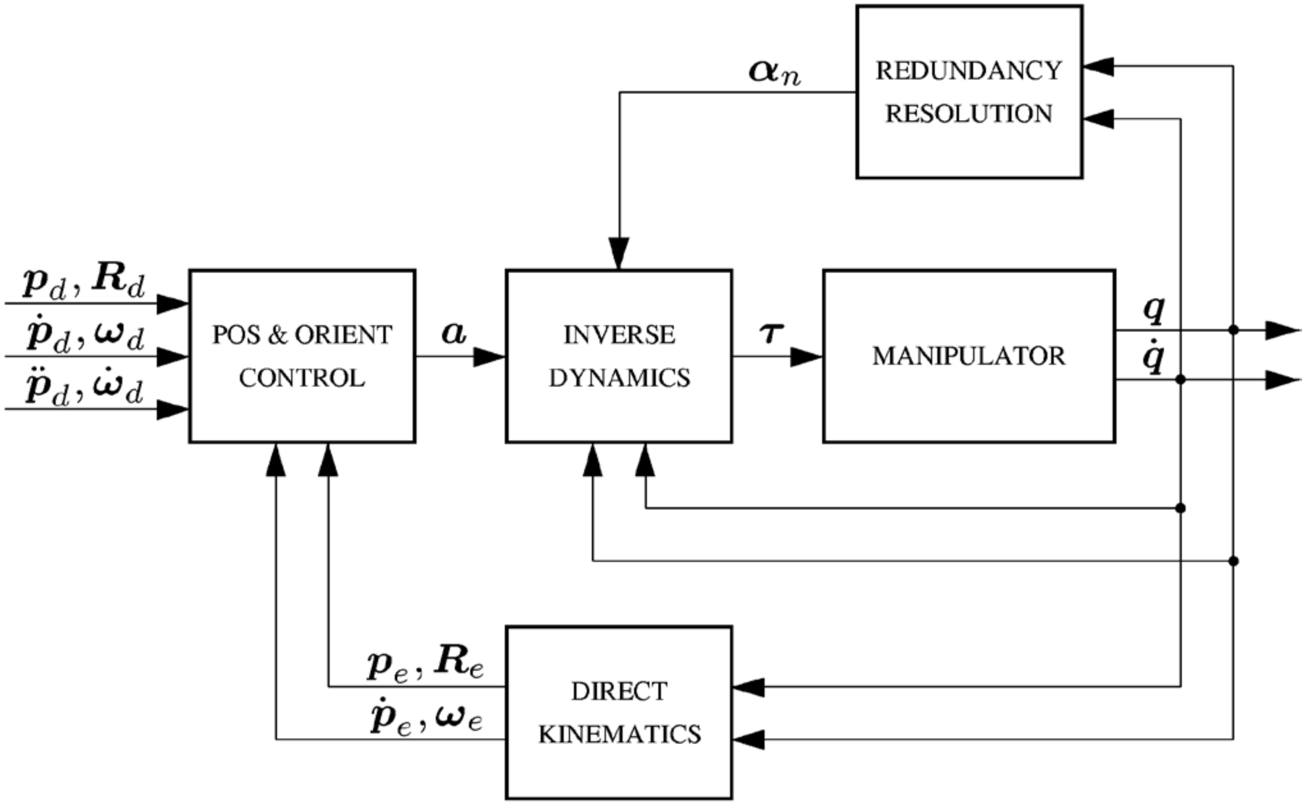
$$\boldsymbol{e}_n = \left(\boldsymbol{I} - \boldsymbol{J}^{\dagger}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})\right)(\boldsymbol{\beta} - \dot{\boldsymbol{q}}) \qquad \boldsymbol{\beta} = k_{\beta}\boldsymbol{B}^{-1}\left(\frac{\partial w(\boldsymbol{q})}{\partial \boldsymbol{q}}\right)$$

  - Stability via Lyapunov argument

$$\mathcal{V} = \frac{1}{2}\boldsymbol{e}_n^{\mathrm{T}}\boldsymbol{B}(\boldsymbol{q})\boldsymbol{e}_n$$

Redundancy Resolution

- Inverse dynamics control with redundancy resolution



- PD control with gravity compensation

$$\boldsymbol{\tau} = \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{q}) \begin{bmatrix} \gamma_p \\ \gamma_o \end{bmatrix} - \boldsymbol{K}_D \dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$$

  - Position control

$$\gamma_p = \boldsymbol{K}_{Pp} \Delta \boldsymbol{p}_{de}$$

  - Orientation control

γ_o ⇒ Euler angles, Angle/axis, Quaternion

- Euler angles

$$\gamma_o = \boldsymbol{T}^{-\mathrm{T}}(\boldsymbol{\varphi}_e)\boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{de}$$

- Alternative Euler angles

$$\gamma_o = \boldsymbol{T}_e^{-\mathrm{T}}(\boldsymbol{\varphi}_{de})\boldsymbol{K}_{Po}\boldsymbol{\varphi}_{de}$$

- Angle/axis

$$\gamma_o = \boldsymbol{K}_{Po}\boldsymbol{o}'_{de}$$

- Quaternion

$$\gamma_o = \boldsymbol{K}_{Po}\boldsymbol{R}_e{}^{e}\boldsymbol{\epsilon}_{de}$$

  - For all … stability via Lyapunov arguments $\mathcal{V} = \frac{1}{2}\dot{\boldsymbol{q}}^{\mathrm{T}}\boldsymbol{B}(\boldsymbol{q})\dot{\boldsymbol{q}} + \mathcal{U}_p + \mathcal{U}_o$

Constrained Motion

- Motion control vs. force control
  - Object manipulation or surface operation requires control of interaction between robot manipulator and environment
  - Use of purely motion control strategy is candidate to fail (task planning accuracy)
  - Control of contact force (compliant behaviour)
  - Use of force/torque sensor (interfaced with robot control unit)
- Indirect vs. direct force control
  - Indirect force control: force control via motion control (w/out explicit closure of force feedback loop)
  - Direct force control: force controlled to desired value (w/ closure of force feedback loop)

Indirect Force Control

- Compliance control
  - Active compliance
  - Experiments
- Impedance control
  - Active impedance
  - Inner motion control
  - Three-DOF impedance control
  - Experiments
  - Six-DOF impedance control
  - Experiments

- Active vs. passive compliance

$$\gamma = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{T}(\boldsymbol{\varphi}_e) \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{K}_{Pp} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{K}_{Po} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{p}_{de} \\ \Delta \boldsymbol{\varphi}_{de} \end{bmatrix}$$

$$\Delta \boldsymbol{p}_{de} = \boldsymbol{K}_{Pp}^{-1} \boldsymbol{f}$$

$$\Delta \boldsymbol{\varphi}_{de} = \boldsymbol{K}_{Po}^{-1} \boldsymbol{T}^{\mathrm{T}}(\boldsymbol{\varphi}_e) \boldsymbol{\mu}$$

$$\boldsymbol{f} = \boldsymbol{K}_f (\boldsymbol{p}_e - \boldsymbol{p}_0)$$

  - At steady state (position/force)

$$\boldsymbol{p}_{e,\infty} = \left(\boldsymbol{I} + \boldsymbol{K}_{Pp}^{-1} \boldsymbol{K}_f\right)^{-1} \left(\boldsymbol{p}_d + \boldsymbol{K}_{Pp}^{-1} \boldsymbol{K}_f \boldsymbol{p}_o\right)$$

$$\boldsymbol{f}_{\infty} = \left(\boldsymbol{I} + \boldsymbol{K}_f \boldsymbol{K}_{Pp}^{-1}\right)^{-1} \boldsymbol{K}_f (\boldsymbol{p}_d - \boldsymbol{p}_o)$$

Experiments

- Set-up
  - COMAU Smart 3-S robot
  - Open control architecture
- PD control with gravity compensation
  - Large proportional gains
  - Small proportional gains

- Programmable mass-damping-stiffness at the end-effector

$$\boldsymbol{\tau} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\alpha} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{h}$$

$$\boldsymbol{\alpha} = \boldsymbol{J}^{-1}(\boldsymbol{q})\left(\begin{bmatrix}\boldsymbol{a}_p \\ \boldsymbol{a}_o\end{bmatrix} - \dot{\boldsymbol{J}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\right)$$

force/torque sensor

$$\boldsymbol{a}_p = \ddot{\boldsymbol{p}}_d + \boldsymbol{K}_{Mp}^{-1}(\boldsymbol{K}_{Dp}\Delta\dot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Pp}\Delta\boldsymbol{p}_{de} - \boldsymbol{f})$$

$$\boldsymbol{a}_o = \boldsymbol{T}(\boldsymbol{\varphi}_e)(\ddot{\boldsymbol{\varphi}}_d + \boldsymbol{K}_{Mo}^{-1}(\boldsymbol{K}_{Do}\Delta\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{de} - \boldsymbol{T}^{\mathrm{T}}(\boldsymbol{\varphi}_e)\boldsymbol{\mu})) + \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_e,\dot{\boldsymbol{\varphi}}_e)\dot{\boldsymbol{\varphi}}_e$$

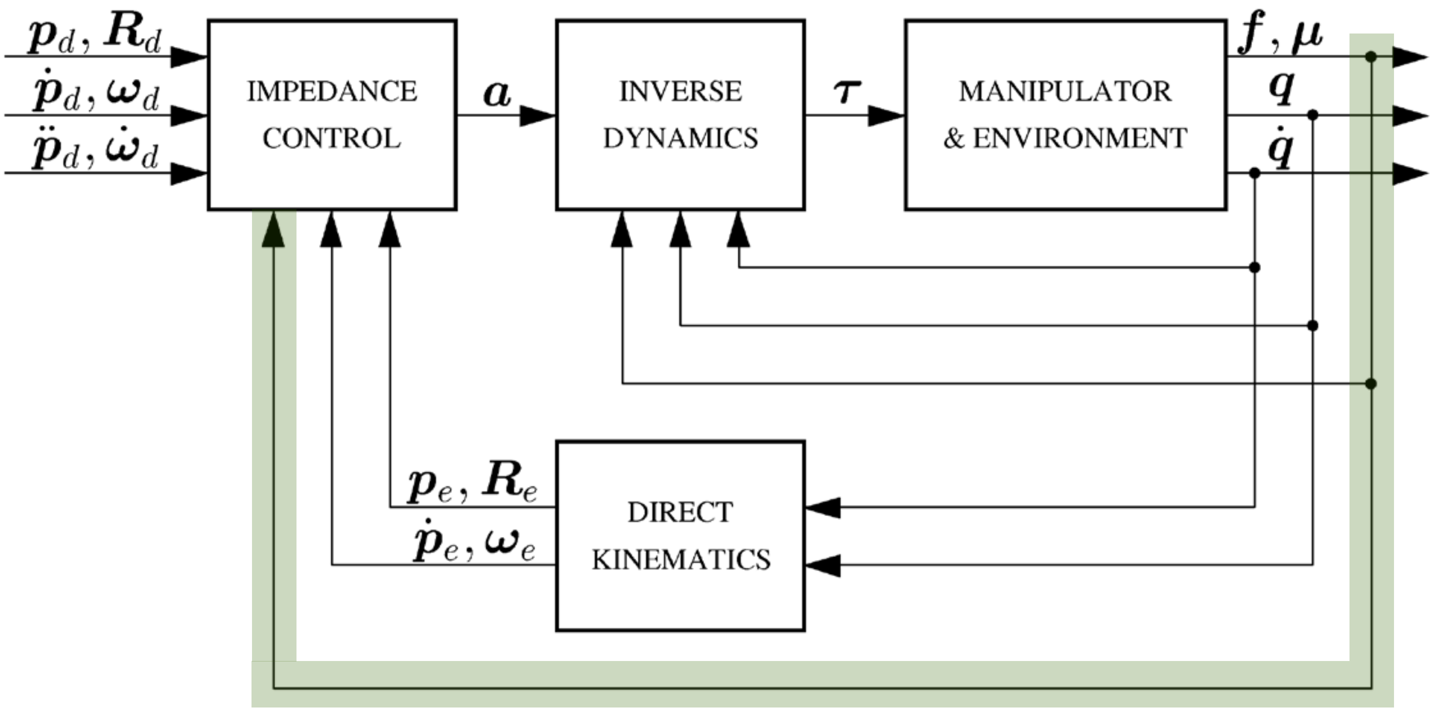
$$\Downarrow$$

$$\boldsymbol{K}_{Mp}\Delta\ddot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Dp}\Delta\dot{\boldsymbol{p}}_{de} + \boldsymbol{K}_{Pp}\Delta\boldsymbol{p}_{de} = \boldsymbol{f}$$

$$\boldsymbol{K}_{Mo}\Delta\ddot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Do}\Delta\dot{\boldsymbol{\varphi}}_{de} + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{de} = \boldsymbol{T}^{\mathrm{T}}(\boldsymbol{\varphi}_e)\boldsymbol{\mu}$$

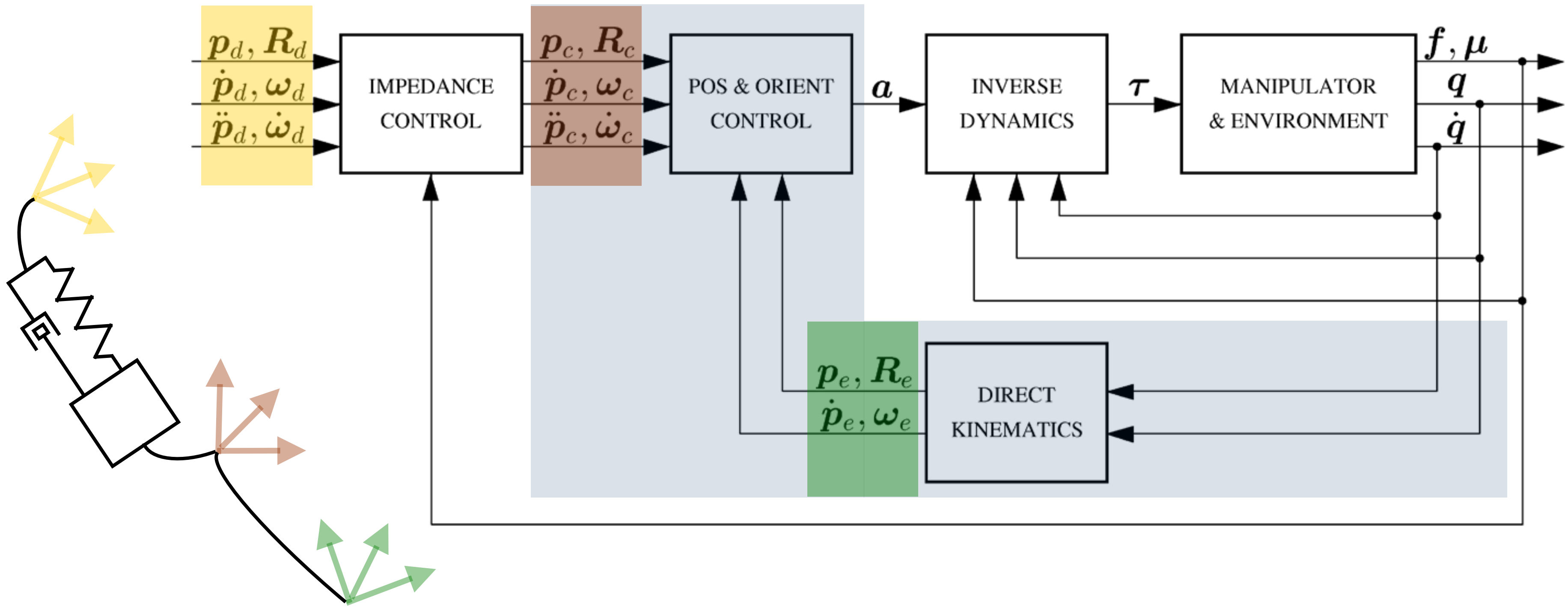
Active Impedance

- Impedance control
  - Force/torque measurements



Inner Motion Control

- Compliant frame between desired and end-effector frame
  - Enhanced disturbance rejection



- Translational impedance

$$\boldsymbol{M}_p \Delta\ddot{\boldsymbol{p}}_{dc} + \boldsymbol{D}_p \Delta\dot{\boldsymbol{p}}_{dc} + \boldsymbol{K}_p \Delta\boldsymbol{p}_{dc} = \boldsymbol{f}$$

$$\Delta\boldsymbol{p}_{dc} = \boldsymbol{p}_d - \boldsymbol{p}_c$$

- Linear acceleration (inner motion loop)

$$\boldsymbol{a}_p = \ddot{\boldsymbol{p}}_c + \boldsymbol{K}_{Dp} \Delta\dot{\boldsymbol{p}}_{ce} + \boldsymbol{K}_{Pp} \Delta\boldsymbol{p}_{ce}$$

$$\Delta\boldsymbol{p}_{ce} = \boldsymbol{p}_c - \boldsymbol{p}_e$$

Experiments

- ATI force/torque sensor
- 3-DOF impedance control
  - Effects of mass, damping and stiffness
  - Contact with unknown surface

- Rotational impedance
  - Euler angles

$$\boldsymbol{M}_o \Delta\ddot{\boldsymbol{\varphi}}_{dc} + \boldsymbol{D}_o \Delta\dot{\boldsymbol{\varphi}}_{dc} + \boldsymbol{K}_o \Delta\boldsymbol{\varphi}_{dc} = \boldsymbol{T}^{\mathrm{T}}(\boldsymbol{\varphi}_c)\boldsymbol{\mu}$$

$$\Delta\boldsymbol{\varphi}_{dc} = \boldsymbol{\varphi}_d - \boldsymbol{\varphi}_c$$

    - Infinitesimal orientation displacement

$$\boldsymbol{\mu}_E = \boldsymbol{T}^{-\mathrm{T}}(\boldsymbol{\varphi}_c)\boldsymbol{K}_o \boldsymbol{T}^{-1}(\boldsymbol{\varphi}_c)\Delta\boldsymbol{\omega}_{dc}\mathrm{d}t$$

task geometric inconsistency

  - Angular acceleration (inner motion loop)

$$\boldsymbol{a}_o = \boldsymbol{T}(\boldsymbol{\varphi}_e)\left(\ddot{\boldsymbol{\varphi}}_c + \boldsymbol{K}_{Do}\Delta\dot{\boldsymbol{\varphi}}_{ce} + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{ce}\right) + \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_e, \dot{\boldsymbol{\varphi}}_e)\dot{\boldsymbol{\varphi}}_e$$

$$\Delta\boldsymbol{\varphi}_{ce} = \boldsymbol{\varphi}_c - \boldsymbol{\varphi}_e$$

- Rotational impedance
  - Alternative Euler angles

$$\boldsymbol{M}_o\ddot{\boldsymbol{\varphi}}_{dc} + \boldsymbol{D}_o\dot{\boldsymbol{\varphi}}_{dc} + \boldsymbol{K}_o\boldsymbol{\varphi}_{dc} = \boldsymbol{T}^{\mathrm{T}}(\boldsymbol{\varphi}_{dc})^c\boldsymbol{\mu}$$

$${}^c\boldsymbol{R}_d = \boldsymbol{R}_c^{\mathrm{T}}\boldsymbol{R}_d \implies \boldsymbol{\varphi}_{dc}$$

    - Infinitesimal orientation displacement

$$\begin{aligned}{}^c\boldsymbol{\mu}_E &\simeq \boldsymbol{T}^{-\mathrm{T}}(\mathbf{0})\boldsymbol{K}_o\boldsymbol{T}^{-1}(\mathbf{0})\Delta{}^c\boldsymbol{\omega}_{dc}\mathrm{d}t \\ &= \boldsymbol{K}_o\Delta{}^c\boldsymbol{\omega}_{dc}\mathrm{d}t\end{aligned}$$

task geometric consistency
(XYZ Euler angles + diagonal stiffness)

  - Angular acceleration (inner motion loop)

$$\begin{aligned}\boldsymbol{a}_o = {}&\dot{\boldsymbol{\omega}}_d - \dot{\boldsymbol{T}}_e(\boldsymbol{\varphi}_{de},\dot{\boldsymbol{\varphi}}_{de})\dot{\boldsymbol{\varphi}}_{de} \\ &-\boldsymbol{T}_e(\boldsymbol{\varphi}_{de})\left(\ddot{\boldsymbol{\varphi}}_{dc} + \boldsymbol{K}_{Do}(\dot{\boldsymbol{\varphi}}_{dc} - \dot{\boldsymbol{\varphi}}_{de}) + \boldsymbol{K}_{Po}(\boldsymbol{\varphi}_{dc} - \boldsymbol{\varphi}_{de})\right)\end{aligned}$$

- Rotational impedance
  - Angle/axis

$$\boldsymbol{M}_o \Delta^c\dot{\boldsymbol{\omega}}_{dc} + \boldsymbol{D}_o \Delta^c\boldsymbol{\omega}_{dc} + \boldsymbol{K}'_o\,{}^c\boldsymbol{o}_{dc} = {}^c\boldsymbol{\mu}$$

$${}^c\boldsymbol{o}_{dc} = f(\vartheta_{dc})\,{}^c\boldsymbol{r}_{dc} \qquad \boldsymbol{K}'_o = 2\psi\boldsymbol{\Omega}^{\mathrm{T}}({}^c\boldsymbol{r}_{dc}, \vartheta_{dc})\boldsymbol{K}_o$$

$${}^c\dot{\boldsymbol{o}}_{dc} = \boldsymbol{\Omega}({}^c\boldsymbol{r}_{dc}, \vartheta_{dc})\Delta^c\boldsymbol{\omega}_{dc}$$

    - Infinitesimal orientation displacement

$${}^c\boldsymbol{\mu}_E \simeq 2\psi\,(f'(0))^2\,\boldsymbol{K}_o\Delta^c\boldsymbol{\omega}_{dc}\mathrm{d}t \qquad \psi = 1/2(f'(0))^2$$

$$= \boldsymbol{K}_o\Delta^c\boldsymbol{\omega}_{dc}\mathrm{d}t$$

task geometric consistency

  - Angular acceleration (inner motion loop)

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_c + \boldsymbol{K}_{Do}\Delta\boldsymbol{\omega}_{ce} + \boldsymbol{K}_{Po}\boldsymbol{o}'_{ce}$$

$$\boldsymbol{o}'_{ce} = \frac{1}{2}\left(\boldsymbol{S}(\boldsymbol{n}_e)\boldsymbol{n}_c + \boldsymbol{S}(\boldsymbol{s}_e)\boldsymbol{s}_c + \boldsymbol{S}(\boldsymbol{a}_e)\boldsymbol{a}_c\right)$$

Six-DOF Impedance Control

- Rotational impedance
  - Quaternion

$$\boldsymbol{M}_o \Delta {}^c\dot{\boldsymbol{\omega}}_{dc} + \boldsymbol{D}_o \Delta {}^c\boldsymbol{\omega}_{dc} + \boldsymbol{K}'_o {}^c\boldsymbol{\epsilon}_{dc} = {}^c\boldsymbol{\mu}$$

$${}^c\boldsymbol{R}_d = \boldsymbol{R}_c^{\mathrm{T}} \boldsymbol{R}_d \implies {}^c\boldsymbol{\epsilon}_{dc}$$

$$\boldsymbol{K}'_o = 2\boldsymbol{E}^{\mathrm{T}}(\eta_{dc}, {}^c\boldsymbol{\epsilon}_{dc})\boldsymbol{K}_o$$

$$\boldsymbol{E}(\eta, \boldsymbol{\epsilon}) = \eta \boldsymbol{I} - \boldsymbol{S}(\boldsymbol{\epsilon})$$

    - Infinitesimal orientation displacement

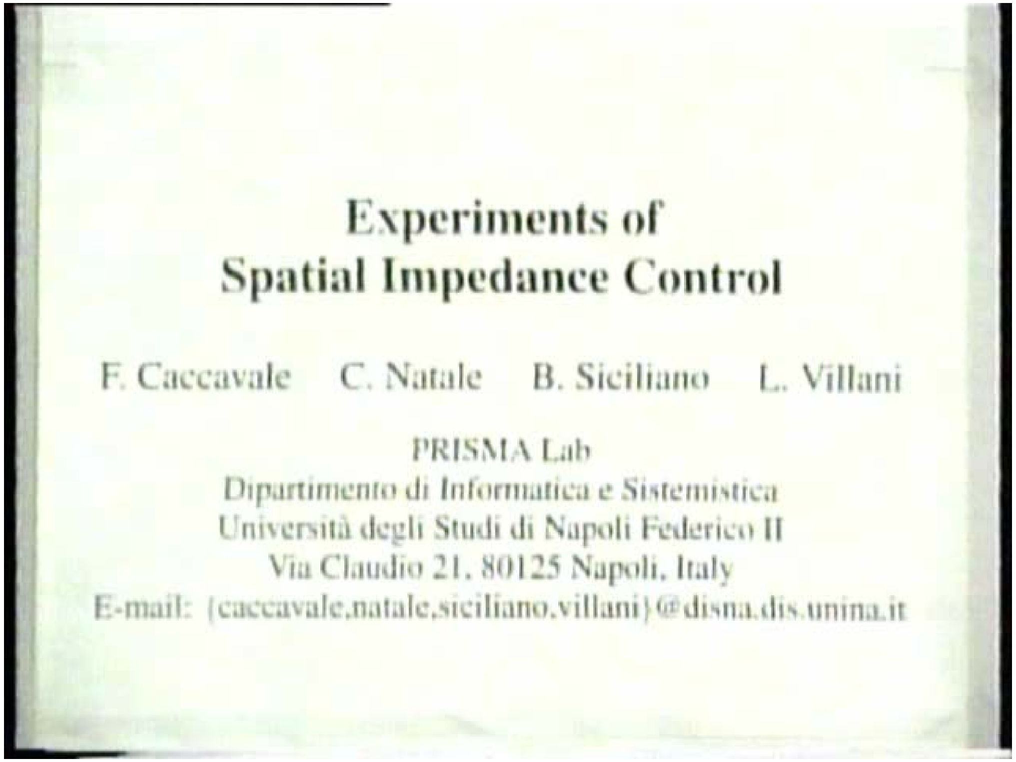
$$\begin{aligned} {}^c\boldsymbol{\mu}_E &\simeq 2\psi \left(f'(0)\right)^2 \boldsymbol{K}_o \Delta {}^c\boldsymbol{\omega}_{dc} \mathrm{d}t \\ &= \boldsymbol{K}_o \Delta {}^c\boldsymbol{\omega}_{dc} \mathrm{d}t \end{aligned}$$

task geometric consistency

  - Angular acceleration (inner motion loop)

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_c + \boldsymbol{K}_{Do} \Delta \boldsymbol{\omega}_{ce} + \boldsymbol{K}_{Po} \boldsymbol{R}_e {}^e\boldsymbol{\epsilon}_{ce}$$

- 6-DOF impedance control
  - Accommodation of both force and moment
  - Operational space approach (Euler angles)
  - Geometrically consistent approach



- Regulation of force and moment to desired values

$$\gamma_p = K_{Pp} \Delta p_{ce} + f_d$$
$$\gamma_o = T^{-\mathrm{T}}(\varphi_e) K_{Po} \Delta\varphi_{ce} + \mu_d$$

  - PI control

$$p_c = K_{Pp}^{-1}\left(K_{Fp}\Delta f + K_{Ip}\int_0^t \Delta f \,\mathrm{d}\varsigma\right) \qquad \Delta f = f_d - f$$
$$\varphi_c = K_{Po}^{-1}\left(K_{Fo}\Delta\mu + K_{Io}\int_0^t \Delta\mu \,\mathrm{d}\varsigma\right) \qquad \Delta\mu = \mu_d - \mu$$

    - At steady state

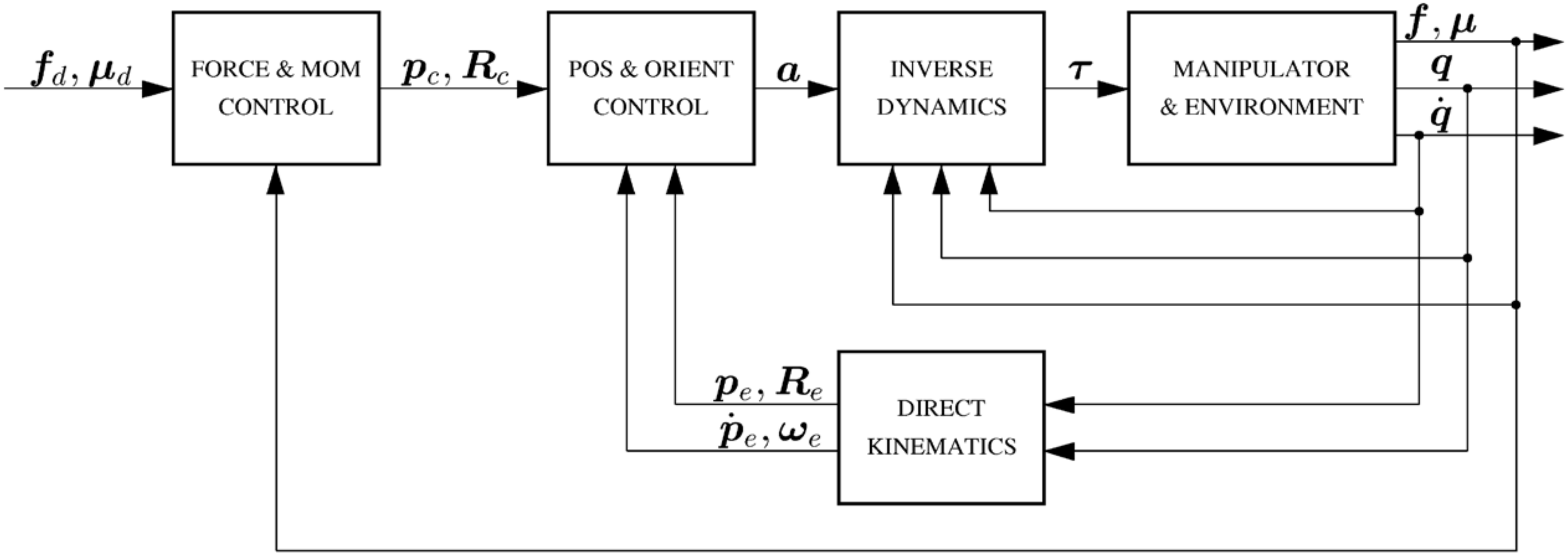
$$f_\infty = f_d \qquad \mu_\infty = \mu_d$$

Dynamic Model-Based Compensation

- Force and moment control with inner motion control loop
  - Linear and angular accelerations

$$\boldsymbol{a}_p = -\boldsymbol{K}_{Dp}\dot{\boldsymbol{p}}_e + \boldsymbol{K}_{Pp}\Delta\boldsymbol{p}_{ce}$$

$$\boldsymbol{a}_o = \boldsymbol{T}(\boldsymbol{\varphi}_e)\left(-\boldsymbol{K}_{Do}\dot{\boldsymbol{\varphi}}_e + \boldsymbol{K}_{Po}\Delta\boldsymbol{\varphi}_{ce}\right) + \dot{\boldsymbol{T}}(\boldsymbol{\varphi}_e, \dot{\boldsymbol{\varphi}}_e)\dot{\boldsymbol{\varphi}}_e$$



- Force control
  - Regulation to zero force
  - Inner position vs. velocity control loop

- Force and motion control
  - Regulation of force but loss of motion control
  - Recover motion control along unconstrained directions while ensuring force control along constrained directions

↓

Parallel control strategy

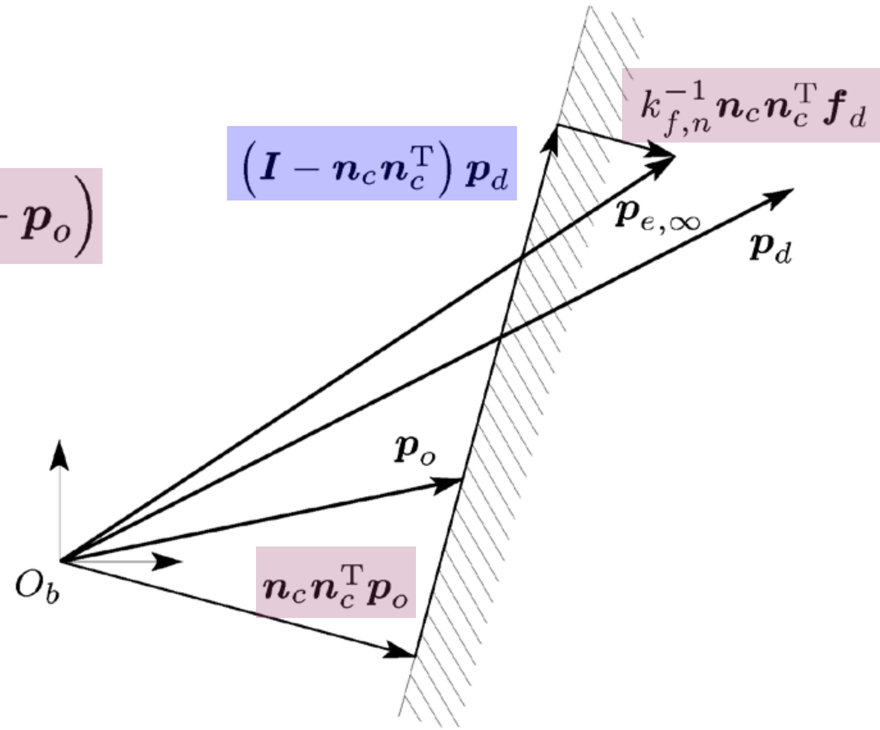
- PD motion control with gravity compensation + force control

$$\boldsymbol{\tau} = \boldsymbol{J}_p^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{K}_{Pp}(\boldsymbol{p}_r - \boldsymbol{p}_e) + \boldsymbol{f}_d - \boldsymbol{K}_D\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) \qquad \boldsymbol{p}_r = \boldsymbol{p}_c + \boldsymbol{p}_d$$

  - At steady state

$$\boldsymbol{p}_{e,\infty} = \left(\boldsymbol{I} - \boldsymbol{n}_c\boldsymbol{n}_c^{\mathrm{T}}\right)\boldsymbol{p}_d + \boldsymbol{n}_c\boldsymbol{n}_c^{\mathrm{T}}\left(k_{f,n}^{-1}\boldsymbol{f}_d + \boldsymbol{p}_o\right)$$

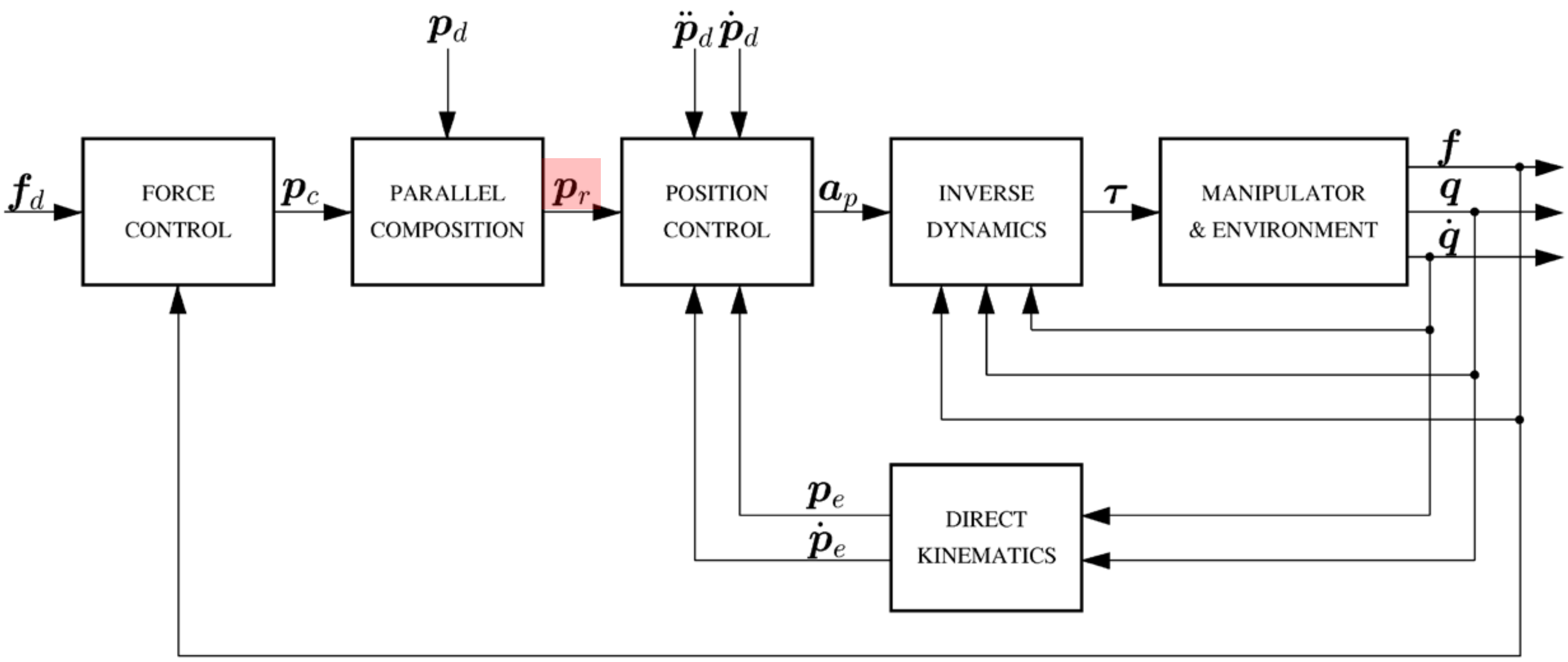
$$\boldsymbol{f}_\infty = k_{f,n}\boldsymbol{n}_c\boldsymbol{n}_c^{\mathrm{T}}(\boldsymbol{p}_{e,\infty} - \boldsymbol{p}_o) = \boldsymbol{f}_d$$



Force and Position Control

- Parallel force/position control
  - Linear acceleration

$$\boldsymbol{a}_p = \ddot{\boldsymbol{p}}_d + \boldsymbol{K}_{Dp}(\dot{\boldsymbol{p}}_d - \dot{\boldsymbol{p}}_e) + \boldsymbol{K}_{Pp}(\boldsymbol{p}_r - \boldsymbol{p}_e)$$



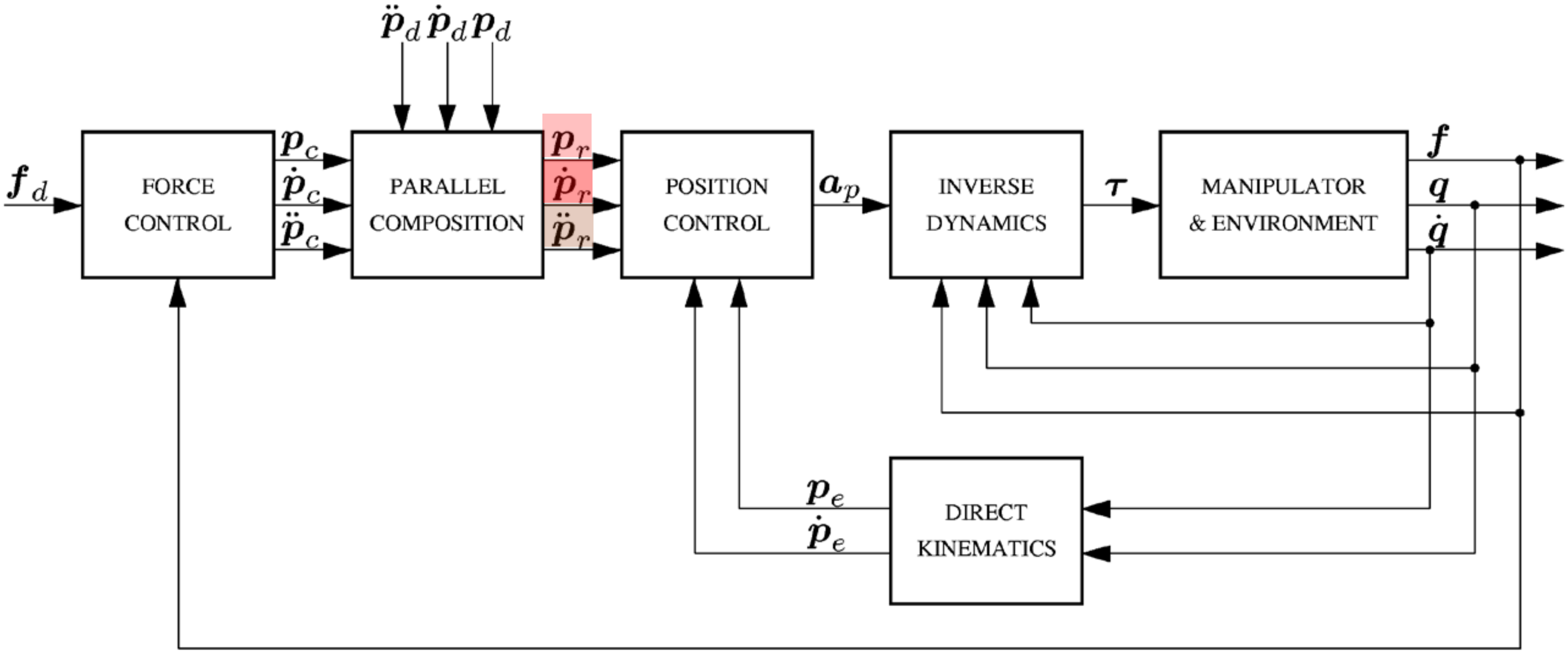
Force and Position Control

- Force/position control with full parallel composition
  - Linear acceleration

$$\boldsymbol{a}_p = \ddot{\boldsymbol{p}}_r + \boldsymbol{K}_{Dp}(\dot{\boldsymbol{p}}_r - \dot{\boldsymbol{p}}_e) + \boldsymbol{K}_{Pp}(\boldsymbol{p}_r - \boldsymbol{p}_e)$$

$$\dot{\boldsymbol{p}}_r = \dot{\boldsymbol{p}}_c + \dot{\boldsymbol{p}}_d$$

$$\ddot{\boldsymbol{p}}_r = \ddot{\boldsymbol{p}}_c + \ddot{\boldsymbol{p}}_d$$



- Parallel force/position control
  - Regulation to zero force with position tracking
  - PD+ position control with PI force control

Moment and Orientation Control

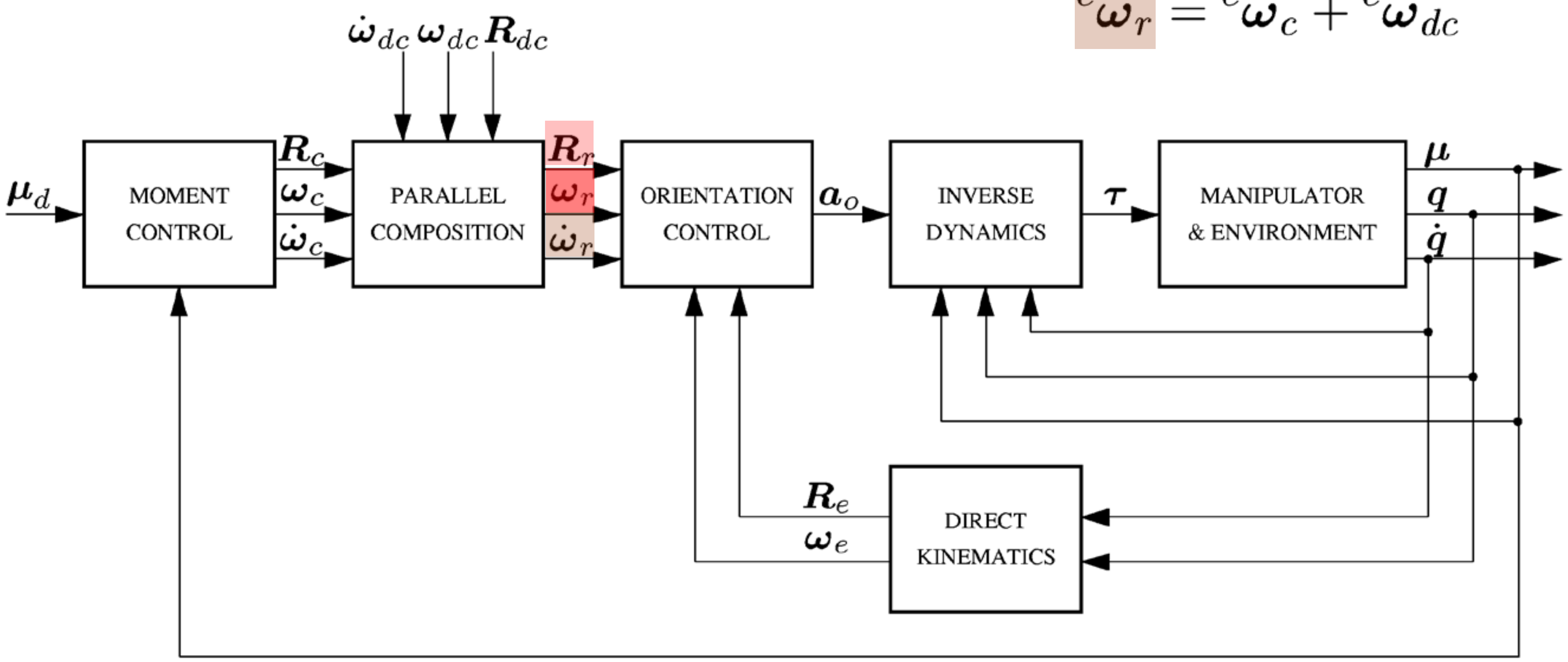
- Moment/orientation control with full parallel composition
  - Linear acceleration

$$\boldsymbol{a}_o = \dot{\boldsymbol{\omega}}_r + \boldsymbol{K}_{Do}(\boldsymbol{\omega}_r - \boldsymbol{\omega}_e) + \boldsymbol{K}_{Po}\boldsymbol{R}_e\, {}^e\boldsymbol{\epsilon}_{re}$$

$$\mathcal{Q}_r = \mathcal{Q}_c * \mathcal{Q}_{dc}$$

$${}^c\boldsymbol{\omega}_r = {}^c\boldsymbol{\omega}_c + {}^c\boldsymbol{\omega}_{dc}$$

$${}^c\dot{\boldsymbol{\omega}}_r = {}^c\dot{\boldsymbol{\omega}}_c + {}^c\dot{\boldsymbol{\omega}}_{dc}$$



- Tracking of time-varying force
  - Full parallel composition

$$\boldsymbol{K}_{Ap}\ddot{\boldsymbol{p}}_c + \boldsymbol{K}_{Vp}\dot{\boldsymbol{p}}_c = \boldsymbol{\phi}$$

$$\boldsymbol{\phi} = k_{f,n}^{-1}\boldsymbol{f}_c$$

$$\boldsymbol{f}_c = \boldsymbol{K}_{Ap}\ddot{\boldsymbol{f}}_d + \boldsymbol{K}_{Vp}\dot{\boldsymbol{f}}_d + \Delta\boldsymbol{f}$$

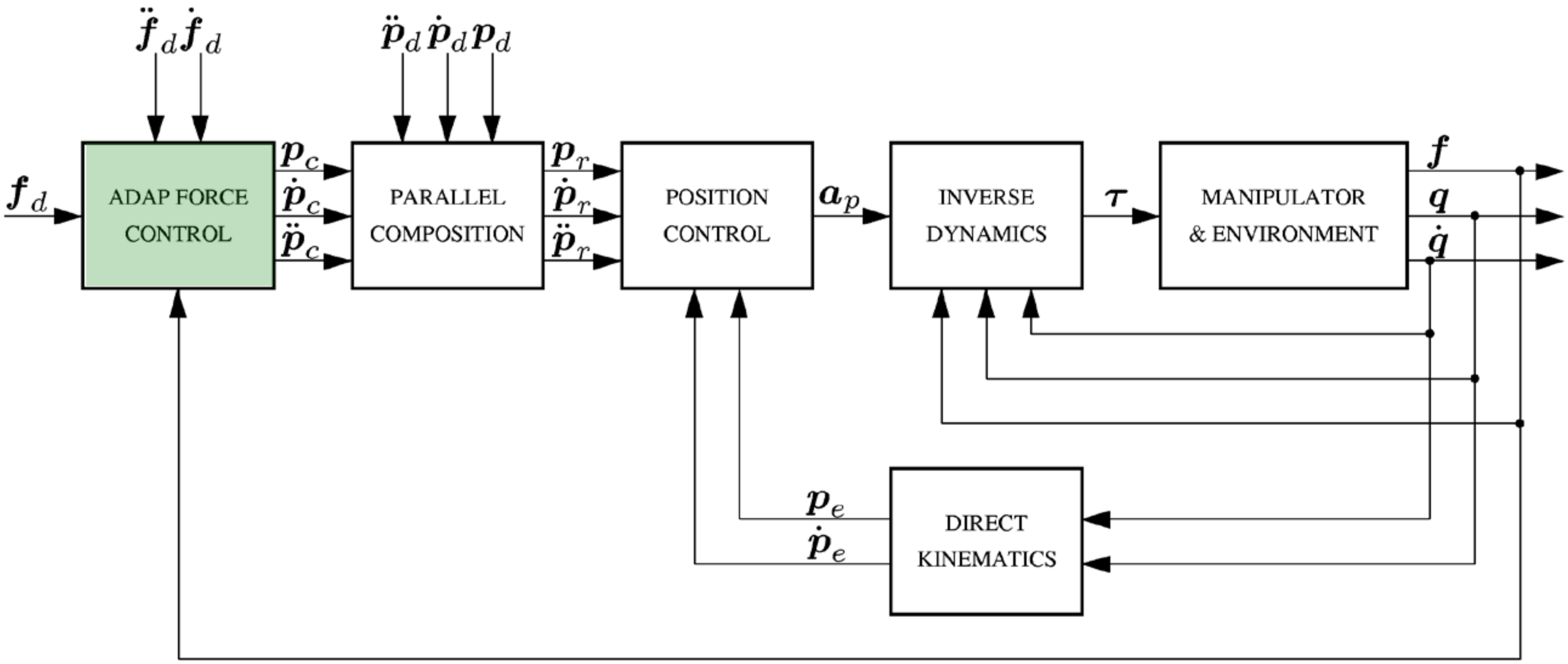
    - Tracking if $k_{f,n}$ exactly known

Force Tracking

- Contact stiffness adaptation ($\varepsilon = k_{f,n}^{-1}$)

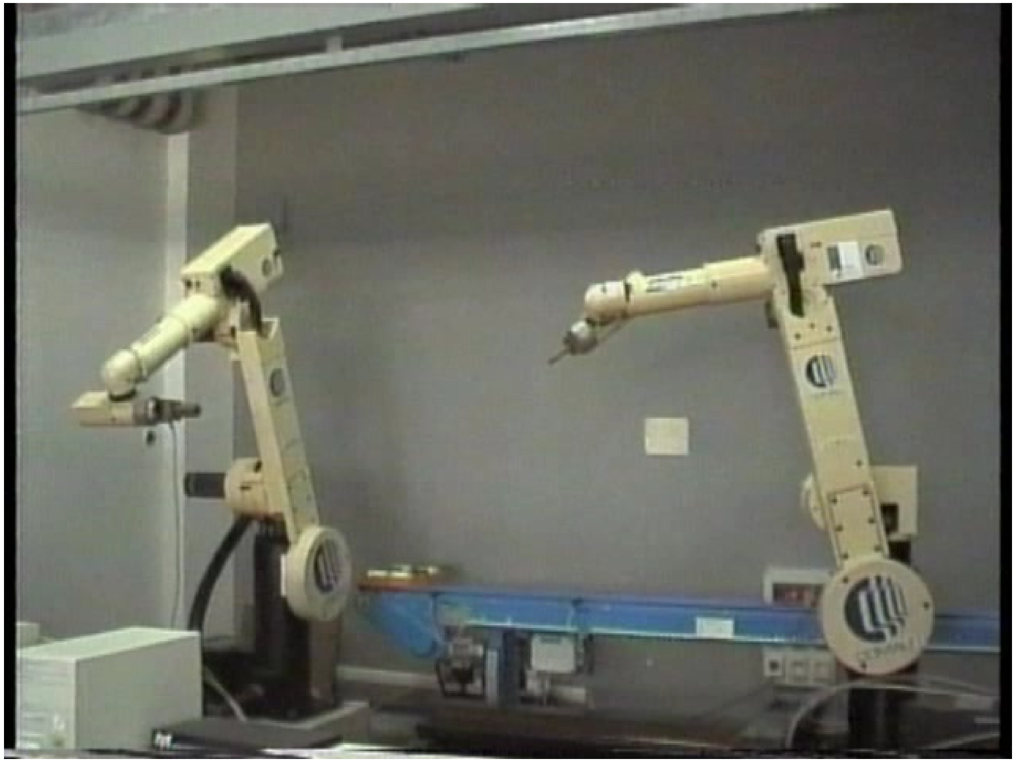
$$\phi = \hat{\varepsilon} \boldsymbol{f}_c + \dot{\hat{\varepsilon}} \psi$$

$$\dot{\psi} + \lambda \psi = \boldsymbol{f}_c \qquad \dot{\hat{\varepsilon}} = \gamma \psi^{\mathrm{T}} \Delta \boldsymbol{f}$$



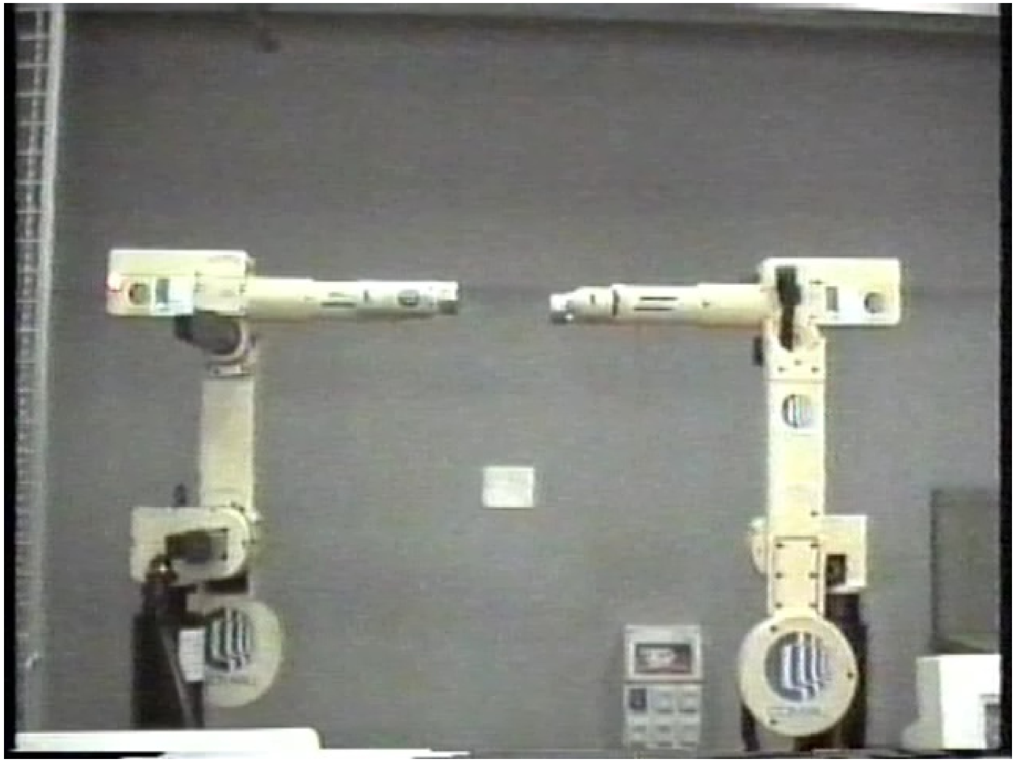
Further Experiments

- Extension to dual-robot system (loose cooperation)
  - Typical peg-in-hole assembly task
  - Robot holding the hole controlled as 6-DOF impedance
  - Robot holding the peg programmed in PDL-2
  - Accommodation of misalignment and overshoot



Further Experiments

- Tight cooperation
  - Two arms tightly grasping a rigid object
  - Control of the object position
  - Control of the internal forces

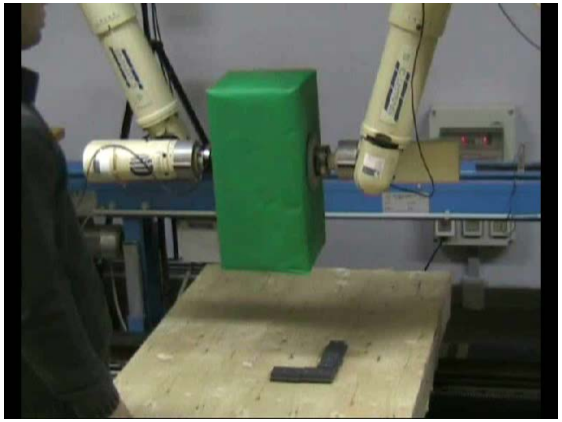


Further Experiments

- Dual-arm impedance control

absolute & relative impedance

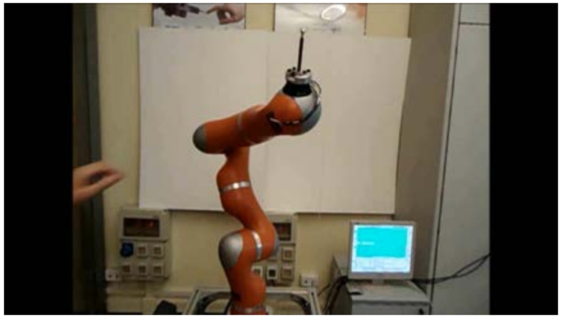
absolute impedance



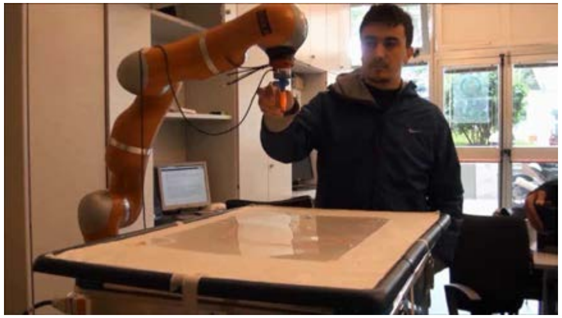
human-object interaction

Further Experiments

- Human−robot interaction



null-space impedance control

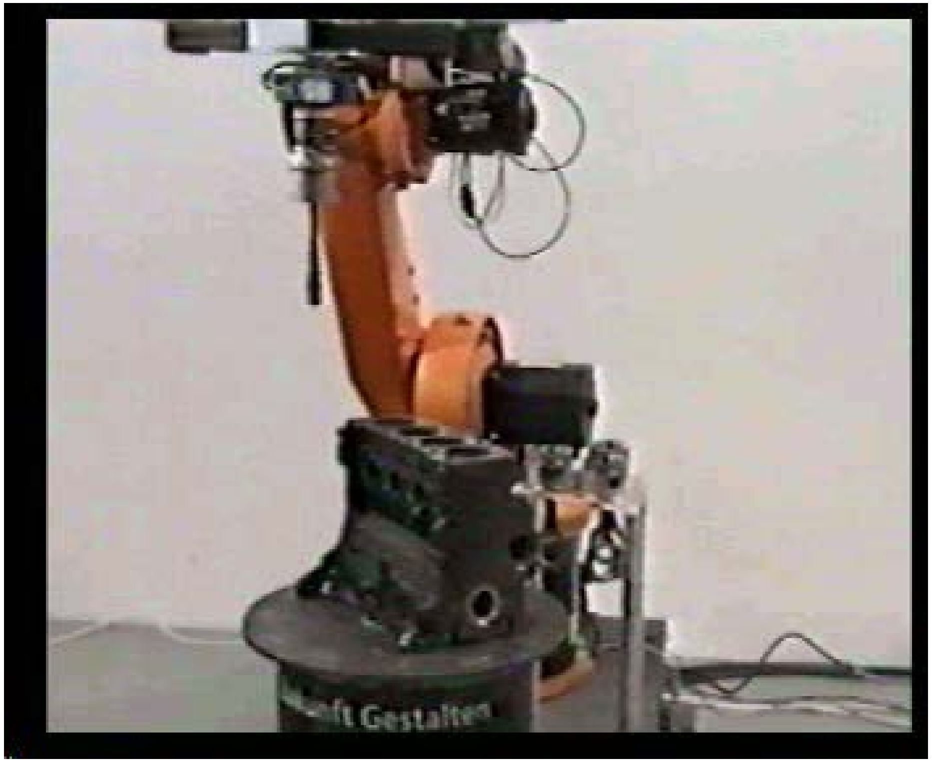


variable impedance control

safe efficient pHRI

Further Experiments

- Set-up @ DLR, Germany
  - KUKA robot with force sensor and camera embedded in the gripper
- Integration of vision and force
  - Visual feedback in gross motion
  - Force feedback in fine motion

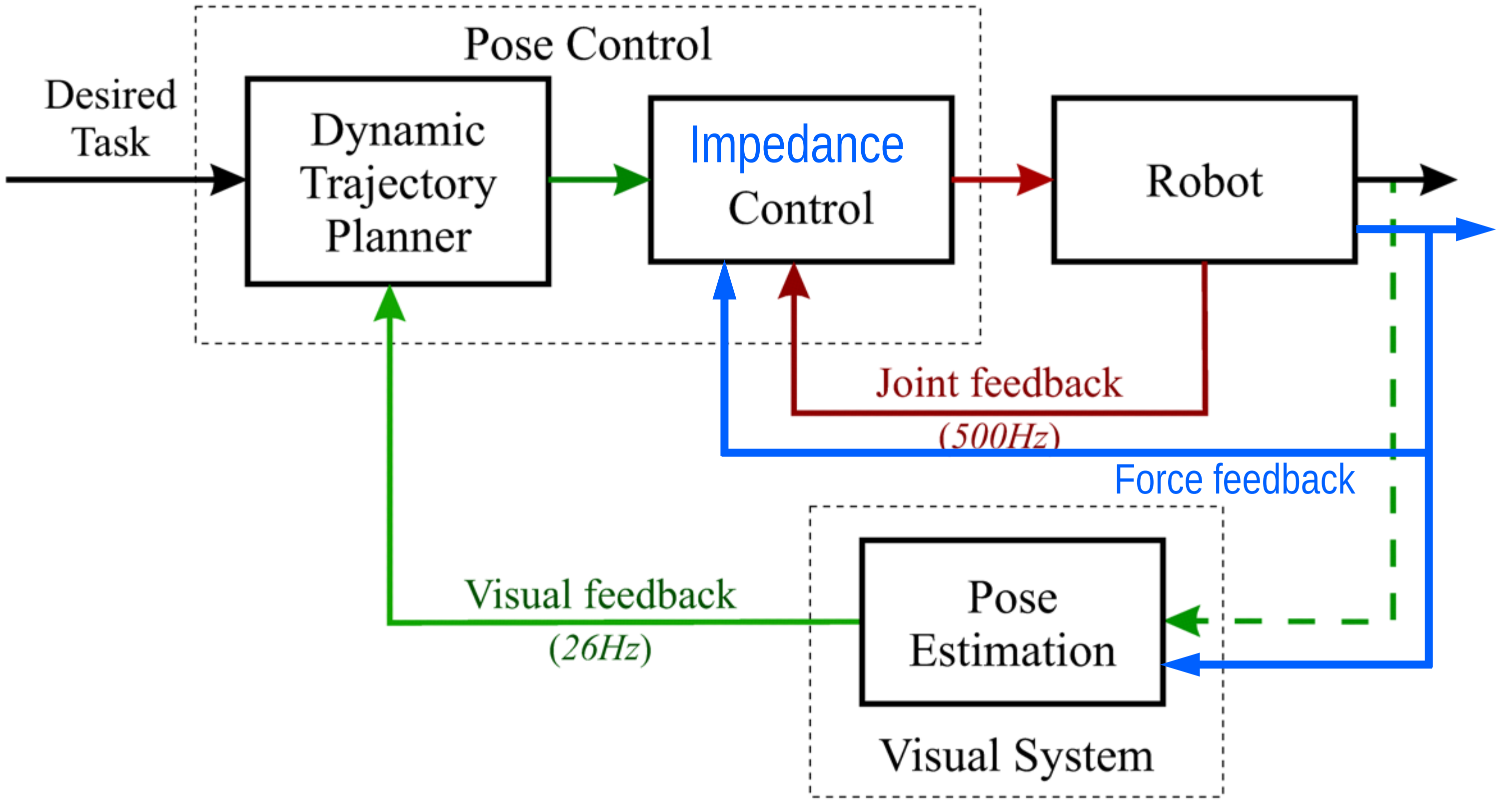


- Problem
  - Control interaction of a robot manipulator with a rigid object of known geometry but unknown position and orientation

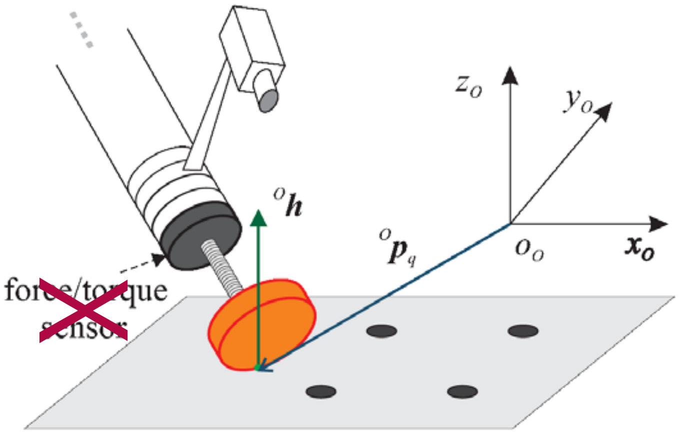
$$\varphi({}^{o}\boldsymbol{p}) = 0 \qquad \{\boldsymbol{o}_o, \boldsymbol{R}_o\} \rightarrow \boldsymbol{x}_o$$

- Solution
  - When robot is far from object
    - Position-based visual servoing is adopted
    - The relative pose of the robot with respect to the object is estimated recursively using only vision
  - When robot is in contact with object
    - Any kind of interaction control strategy can be adopted (impedance control, parallel force/position control)
    - The relative pose of the robot with respect to the object is estimated recursively using vision, force and joint position measurements

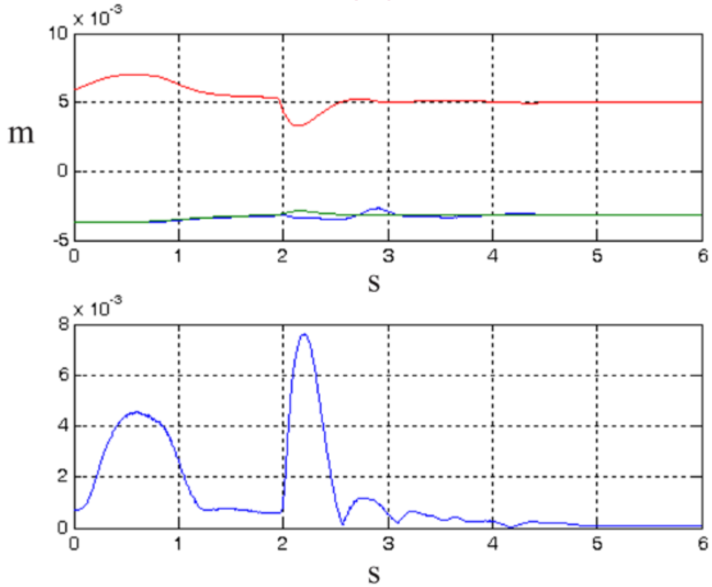
- Position-based visual impedance



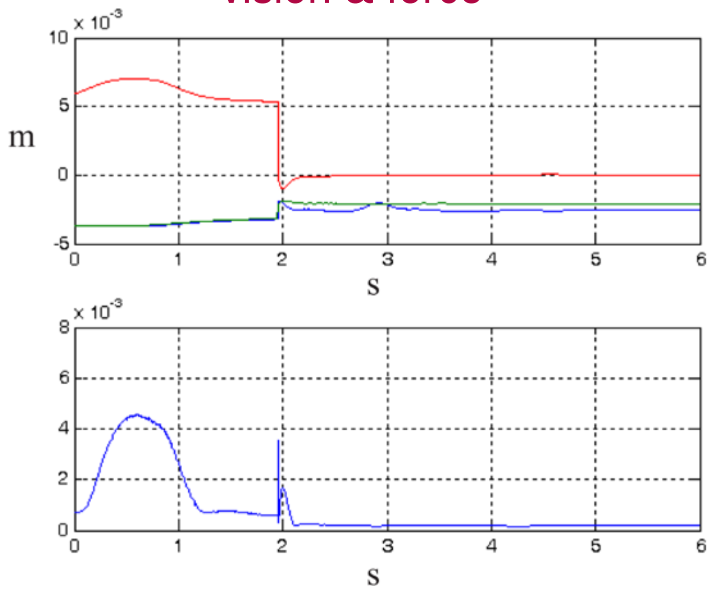
- Pose estimation errors



vision



vision & force

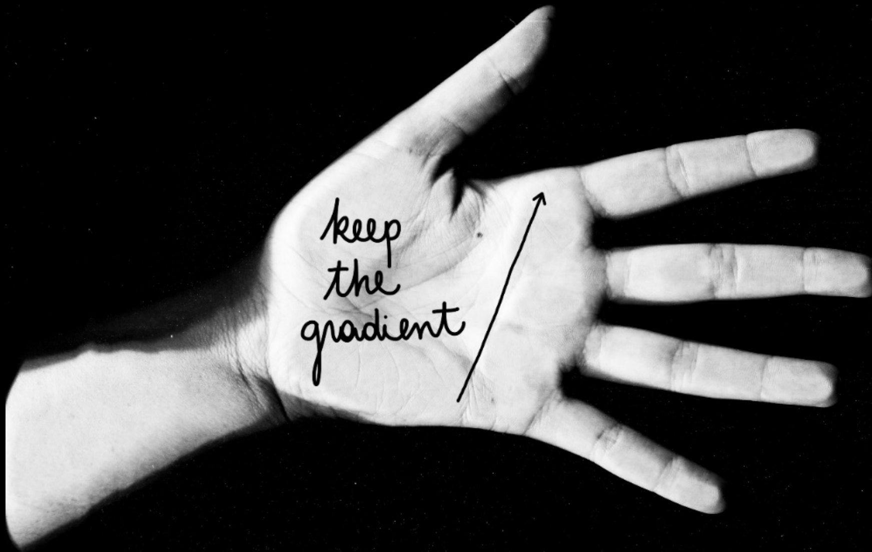


Additional References

- F. Caccavale, C. Natale, B. Siciliano, L. Villani, "Resolved-acceleration control of robot manipulators: A critical review with experiments", *Robotica*, 16, 565–573, 1998
- F. Caccavale, C. Natale, B. Siciliano, L. Villani, "Six-DOF impedance control based on angle/axis representations", *IEEE Transactions on Robotics and Automation*, 15, 289–300, 1999
- F. Caccavale, C. Natale, B. Siciliano, L. Villani, "Achieving a cooperative behaviour in a dual-arm robot system via a modular control structure", *Journal of Robotic Systems*, 18, 691–700, 2001
- F. Caccavale, C. Natale, B. Siciliano, L. Villani, "Integration for the next generation: Embedding force control into industrial robots", *IEEE Robotics and Automation Magazine*, 12(3), 53–64, 2005
- F. Caccavale, B. Siciliano, L. Villani, "Robot impedance control with nondiagonal stiffness", *IEEE Transactions on Automatic Control*, 44, 1943–1946, 1999

Additional References[2]

- S. Chiaverini, L. Sciavicco, "The parallel approach to force/position control of robotic manipulators", *IEEE Transactions on Robotics and Automation*, 9, 361–373, 1993
- S. Chiaverini, B. Siciliano, L. Villani, "Force/position regulation of compliant robot manipulators", *IEEE Transactions on Automatic Control*, 39, 647–652, 1994
- S. Chiaverini, B. Siciliano, L. Villani, "A survey of robot force control schemes with experimental comparison", *IEEE/ASME Transactions on Mechatronics*, 4, 273–285, 1999
- V. Lippiello, B. Siciliano, L. Villani, "A position-based visual impedance control for robot manipulators", *2007 IEEE Int. Conf. on Robotics and Automation*, Rome, I
- C. Natale, *Interaction Control of Robot Manipulators. Six-degrees-of-freedom Tasks*, Springer, Heidelberg, D, 2003
- B. Siciliano, L. Villani, *Robot Force Control*, Kluwer, Boston, MA, 1999



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