Cooperative Multi-Robot Manipulation under Kinematic Uncertainty

Sebastian Erhart   Sandra Hirche

Institute for Information-Oriented Control
Technische Universität München

Applications of adaptive control in robotics, 06/02/2014

Why cooperative manipulation?

Benefits

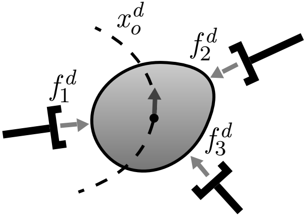
- Load distribution between manipulators
- Increase of manipulation dexterity
- Integration of different team member skills

Cooperative Mobile Manipulation

S. Erhart D. Sieber T. Nierhoff T. Fritzsch S. Hirche

Manipulation task specification

- Accurate tracking of the desired object trajectory $x_o^d(t)$
- Maintaining the desired end effector forces $f_i^d(t)$



Cooperative control objective

$$\lim_{t\to\infty} x_o(t) \to x_o^d(t) \quad \text{and} \quad \lim_{t\to\infty} f_i(t) \to f_i^d(t)$$

Manipulator & object dynamics

- Manipulator dynamics [Craig 1989]

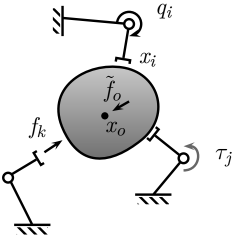
$$M_i(q_i)\ \ddot{q}_i + C_i(q_i, \dot{q}_i) = \tau_i + J_i^T(q_i) f_i$$

- Rigidity constraint

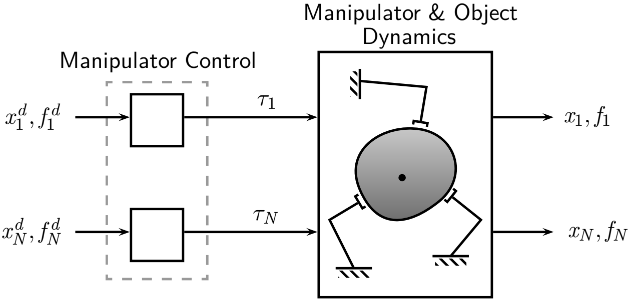
$$\|x_j - x_i\| = \text{const.}$$

- Augmented object dynamics [Chang et al. 2000]

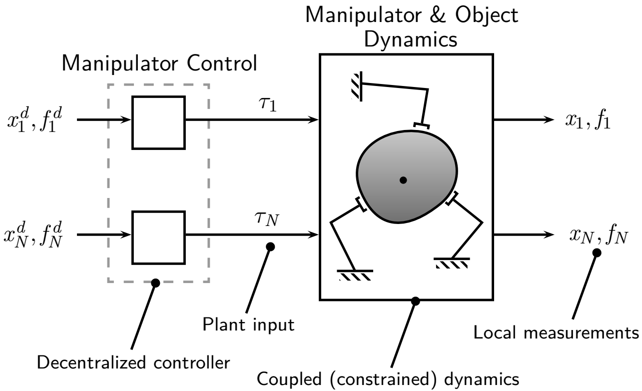
$$\Lambda(x_o)\ddot{x}_o + \mu(x_o, \dot{x}_o) = \tilde{f}_o + \sum_i f_i$$



Control setup



Control setup



Trade-off for manipulator coordination

Manipulation performance $\leftrightarrow$ Communication complexity

Outline

Introduction

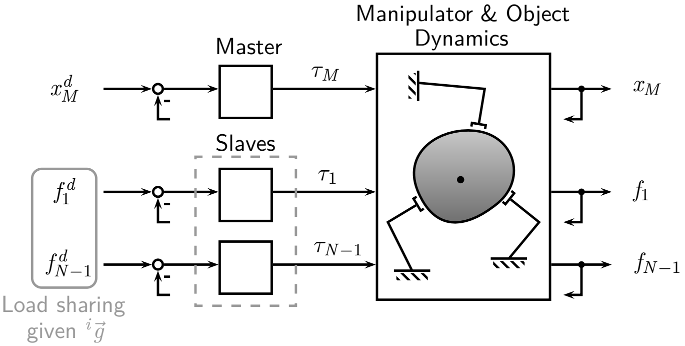
Cooperative control

Kinematic Uncertainty

Cooperative adaptive control

Summary

Master/slave control scheme [Kim and Zheng 1989]

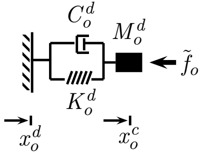


- ⊕ Implicit communication through interaction force
- ⊖ No asymptotic tracking for $x_M^d(t) \neq$ const.

No compliance when interacting with environment

Impedance control [Hogan 1985]

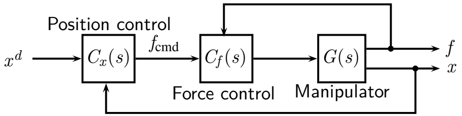
- Desired compliant behaviour



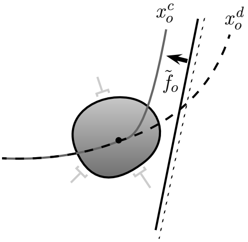
$$M_o^d\Delta\ddot{x}_o + C_o^d\Delta\dot{x}_o + K_o^d\Delta\dot{x}_o = \tilde{f}_o$$

with $\Delta x_o = x_i^c - x_o^d$

- Equivalent control structure [Volpe and Khosla 1994]



Proportional gain force control with feedforward reference force

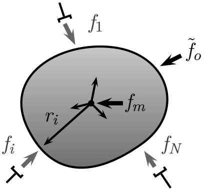


Need to estimate external force $\tilde{f}_o$

How to estimate external force? [Walker et al. 1991]

- Resulting force due to manipulator interaction

$$f_m = \underbrace{\begin{bmatrix} I & 0 & \cdots & I & 0 \\ r_1\times & I & \cdots & r_N\times & I \end{bmatrix}}_{W} \cdot \underbrace{\begin{pmatrix} f_1 \\ \vdots \\ f_N \end{pmatrix}}_{f}$$



- External force estimation (based on object dynamics)

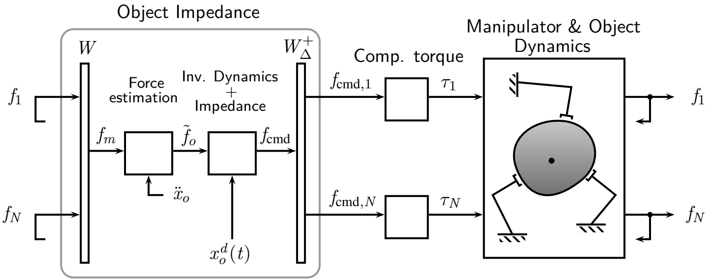
$$M\ddot{x}_o + C(x_o, \dot{x}_o) = \tilde{f}_o + f_m$$

- Manipulator force decomposition, i.e. $f = f_{\text{ext}} + f_{\text{int}}$ with

$$f_{\text{ext}} = W_\Delta^+ \; W \; f \qquad\qquad f_{\text{int}} = (I - W_\Delta^+ W)\; f$$

$\boxed{\text{Force estimation requires centralized computation}}$

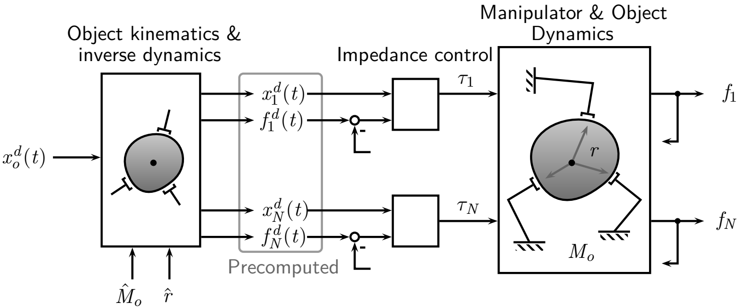
Object impedance control scheme [Schneider et al. 1992]



- ⊕ Force/position tracking for ideal object & manipulator model
- ⊕ Tunable compliance for variety of interaction tasks
- ⊖ Centralized force estimation in real-time

Explicit communication required for manipulator coordination

Distributed impedance control scheme [Szewczyk et al. 2002]



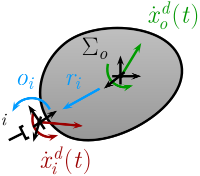
- ⊕ Force/position tracking for ideal object & manipulator model
- ⊕ No explicit communication in real-time needed

No force/position tracking for uncertain kinematic parameters

Uncertain kinematic object model

Given a desired object motion $\dot{x}_o^d \in se(3)$ the compatible end effector motion is

$$\begin{aligned} \dot{x}_i^d(t) &= \begin{bmatrix} R(\hat{o}_i) & 0 \\ 0 & R(\hat{o}_i) \end{bmatrix} \begin{bmatrix} I & 0 \\ r_i\times & I \end{bmatrix} \dot{x}_o^d(t) \\ &= RG_i^* \ \dot{x}_o^d(t) \ + \ \underbrace{\Delta RG_i}_{\text{e.g. slippage} \approx 5\text{cm}/10\text{deg}} \ \dot{x}_o^d(t) \end{aligned}$$



Individual desired end effector trajectory

$$x_i^d(t) = x_i^{d^*}(t) + \underbrace{\int_0^t T(x_i^d)\Delta RG_i \ \dot{x}_o^d(s) \ \mathrm{d}s}_{\Delta x_i(t)}$$

Trajectory error Δx_i correlates with size of workspace

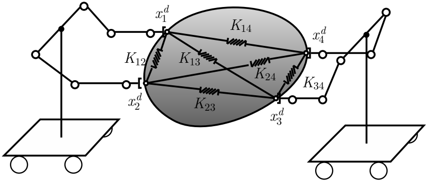
Interaction force
[Erhart, Sieber and Hirche 2013]

Desired relative displacement

$$\Delta x_{ji}^d(t) = \int_0^t T(\Delta x_{ji}^d)\ [\dot{x}_j^d(s) - \dot{x}_i^d(s)]\ \mathrm{d}s$$

Kinematic constraint

$$\|x_j - x_i\| = \text{const.}$$



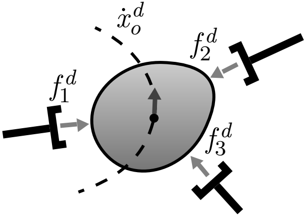
Internal force model

$$f_{ji,\text{int}}(t) \approx K_{ji}\ \Delta x_{ji}^d(t)$$

Interaction force depends on kinematic errors and control parameters

Recap: Manipulation task specification

- Accurate tracking of the desired object *velocity* $\dot{x}_o^d$
- Maintaining the desired end effector forces f_i^d



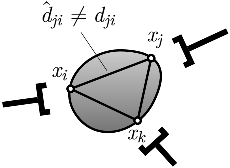
Cooperative control objective

$$\lim_{t\to\infty} \dot{x}_o(t) \to \dot{x}_o^d(t) \quad \text{and} \quad \lim_{t\to\infty} f_i(t) \to f_i^d$$

Kinematic constraints

- Object rigidity introduces kinematic constraints

$$
\begin{aligned}
\|x_j - x_i\|^2 &= d_{ji}^2 \qquad \Big| \frac{d}{dt} \\
(x_j - x_i)^T (v_j^r - v_i^r) &= 0
\end{aligned}
$$



- Manipulator reference velocities v_i^r have to meet constraints

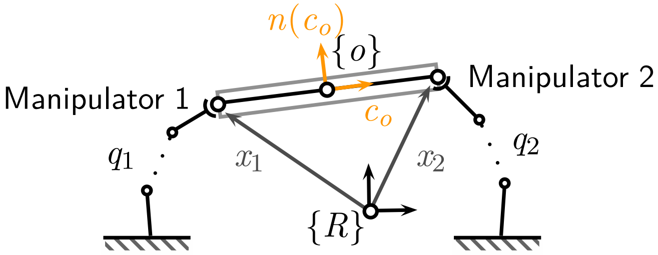
$$
v_i^r = v_i^d(\dot{x}_o^d) + v_i^f \underbrace{(f_i - f_i^d)}_{\Delta f_i}
$$

Impact of uncertain kinematic parameters

Biased estimates $\hat{d}_{ji}$ for control lead to $\Delta f_i \neq 0$

Manipulation task model

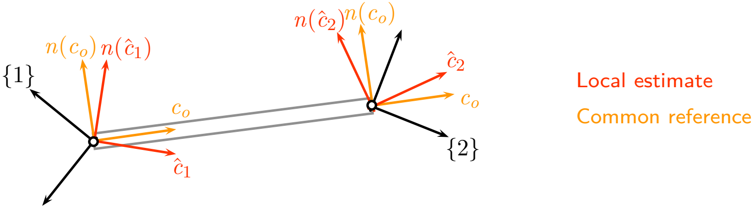
- Desired object motion $\dot{x}_o^d$ given in body-fixed frame $\{o\}$



$$c_o = \frac{x_2 - x_1}{\|x_2 - x_1\|} \quad , \quad \{o\} = \{c_o, n(c_o)\}$$

Kinematic manipulator coordination

- Each manipulator has its own estimate $\hat{c}_i$ of object frame c_o



- Manipulator **feed-forward** velocity

$$
\begin{aligned}
v_1^d &= n(\hat{c}_1) \cdot v_o^d - n(\hat{c}_1)\frac{\hat{d}}{2} \cdot \dot{\varphi}_o^d \\
v_2^d &= n(\hat{c}_2) \cdot v_o^d + n(\hat{c}_2)\frac{\hat{d}}{2} \cdot \dot{\varphi}_o^d \\
\dot{\hat{c}}_i &= n(\hat{c}_i) \cdot \dot{\varphi}_o^d
\end{aligned}
$$

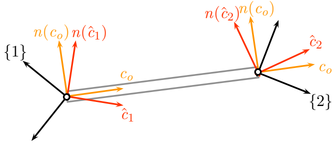
Kinematic manipulator coordination (contd.)

- Manipulator **force feedback** velocity

$$v_i^f = \hat{c}_i \; k_{p,i} \; \Delta\hat{f}_i$$

with

$$\Delta\hat{f}_1 = \hat{c}_1^T \cdot \vec{f}_1 - f^d$$
$$\Delta\hat{f}_2 = \hat{c}_2^T \cdot \vec{f}_2 + f^d$$



- Measured forces $\vec{f}_i$ assumed to produce no net object motion

Internal force assumption

$$\vec{f}_1 = -\vec{f}_2 = -f \; c_o$$

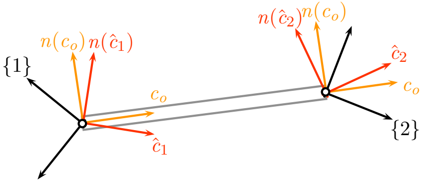
Interaction force computation

Solving the constraint equation

$$c_o^T \cdot (v_2^r - v_1^r) = 0$$

for the emerging interaction force $f \in \mathbb{R}$ with $f^d = 0$ yields

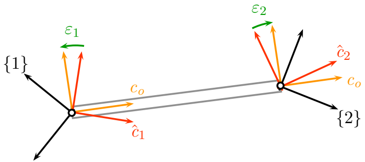
$$\boxed{f = -\frac{c_o^T\left[n(\hat{c}_2) + n(\hat{c}_1)\right]\frac{\hat{d}}{2} \cdot \dot{\varphi}_o^d + c_o^T\left[n(\hat{c}_2) - n(\hat{c}_1)\right] \cdot v_o^d}{c_o^T\left[k_{p,2}(\hat{c}_2^T c_o)\ \hat{c}_2 + k_{p,1}(\hat{c}_1^T c_o)\ \hat{c}_1\right]}}$$



Kinematic error analysis

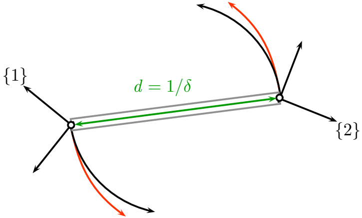
- Angular errors

$$\cos \varepsilon_i = c_o^T \hat{c}_i$$



- Object kinematics

$$\begin{aligned} \dot{\varphi}_o &= \frac{n(c_o)^T \cdot (v_2^r - v_1^r)}{d} \\ &= \delta \; \psi(\varepsilon_i, \hat{\delta}, \dot{x}_o^d) \end{aligned}$$



Rotational motion $\dot{\varphi}_o^d > 0$

Adaptive controller

Kinematic model $\square$

$$
\begin{aligned}
\dot{\hat{\varphi}}_1 &= \dot{\varphi}_o^d + u_{\varphi_1} \\
\dot{\hat{\varphi}}_2 &= \dot{\varphi}_o^d + u_{\varphi_2} \\
\dot{\hat{\delta}} &= u_\delta
\end{aligned}
$$

Controller $\triangle$

$$
\begin{aligned}
u_{\varphi_1} &= -\dot{\varphi}_o^d + \hat{\delta}\ \psi(\varepsilon_i, \hat{\delta}, \dot{x}_o^d) - k_{\varepsilon_1}\varepsilon_1 \\
u_{\varphi_2} &= -\dot{\varphi}_o^d + \hat{\delta}\ \psi(\varepsilon_i, \hat{\delta}, \dot{x}_o^d) - k_{\varepsilon_2}\varepsilon_2 \\
u_\delta &= -\ k_\delta\ (\varepsilon_1 + \varepsilon_2)\ \psi(\varepsilon_i, \hat{\delta}, \dot{x}_o^d)
\end{aligned}
$$

Proposition

The control law $\triangle$ stabilizes the system $\square$ asymptotically in the sense of Lyapunov about the equilibrium point

$$[\varepsilon_1, \varepsilon_2, \hat{\delta}]^T = [0, 0, \delta]^T$$

for $k_{\varepsilon_1}, k_{\varepsilon_2} > 0$ and $k_\delta = 1$.

Adaptive controller - Stability proof

Lyapunov-like analysis

$$V(\varepsilon_1, \varepsilon_2, \hat{\delta}) = \frac{1}{2}\left(\varepsilon_1^2 + \varepsilon_2^2 + \left[\hat{\delta} - \delta\right]^2\right)$$

Computing the time derivative yields

$$\dot{V}(\varepsilon_1, \varepsilon_2, \hat{\delta}) = \ldots = -k_{\varepsilon_1}\varepsilon_1^2 - k_{\varepsilon_2}\varepsilon_2^2 \leq 0$$

$\rightarrow$ Boundedness of $\varepsilon_1, \varepsilon_2$ and $[\hat{\delta} - \delta]$

$\boxed{\text{How to proof (at least asymptotic) convergence?}}$

Adaptive controller - Stability proof (contd.)

Application of Barbalat's Lemma

Boundedness of

$$\ddot{V}(\varepsilon_1, \varepsilon_2, \hat{\delta}) = -2k_{\varepsilon_1}\varepsilon_1\dot{\varepsilon}_1 - 2k_{\varepsilon_2}\varepsilon_2\dot{\varepsilon}_2$$

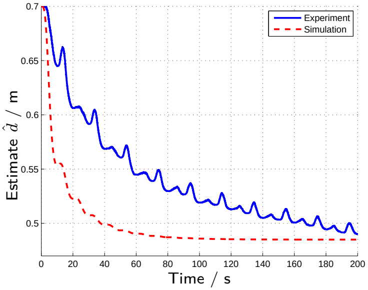
implies $\dot{V} \to 0$ and thus $\varepsilon_i \to 0$ as $t \to \infty$.

Substituting this result into the system dynamics yields

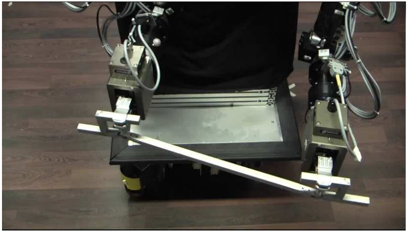
$$(1 - \frac{\delta}{\hat{\hat{\delta}}})\dot{\varphi}_o^d = 0$$

which can only hold true if $\hat{\delta} \to \delta$ for $\dot{\varphi}_o^d \neq 0$.

Experimental evaluation



Object length estimate for $\hat{d}(0) = 0.7m$

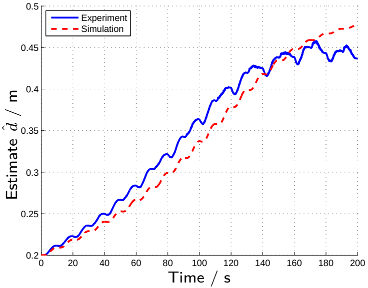


Experimental run for
$\hat{d} = 0.70\text{m} > d = 0.48\text{m}$

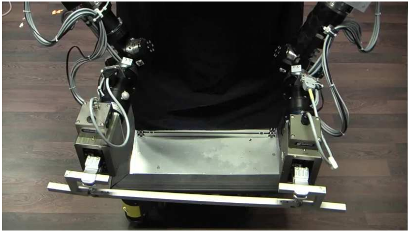
- Desired motion/excitation signal: $\dot{\varphi}_o^d(t) = 3.5\frac{\text{deg}}{\text{s}}\sin(\frac{2\pi}{20\text{s}}t)$

Biased estimate converges to actual value

Experimental evaluation (contd.)



Object length estimate for $\hat{d}(0) = 0.2\text{m}$



Experimental run for

$\hat{d} = 0.20\text{m} < d = 0.48\text{m}$

- Desired motion/excitation signal: $\dot{\varphi}_o^d(t) = 3.5\frac{\text{deg}}{\text{s}}\sin(\frac{2\pi}{20\text{s}}t)$

$\boxed{\text{Biased estimate converges to actual value}}$

Summary & conclusion

- Cooperative manipulation schemes involving centralized force estimation problem
- Manipulation task model under kinematic uncertainty
- Adaptive control law for manipulating an object of uncertain length

- ⊕ Uncertain kinematic parameters counteract control goal
- ⊕ Identification algorithm required to achieve asymptotic force/velocity tracking
- ⊕ Relevance for dynamic/precise/uncertain manipulation tasks

References I

Farhad Aghili. **Self-tuning cooperative control of manipulators with position/orientation uncertainties in the closed-kinematic loop**.
In: *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*. 2011, pp. 4187 –4193. DOI: 10.1109/IROS.2011.6094470.

C.O. Alford and S.M. Belyeu. **Coordinated control of two robot arms**.
In: *Robotics and Automation, Proceedings of the IEEE Internation Conference on* (1984), pp. 468–473.

R.G. Bonitz and T.C. Hsia. **Internal force-based impedance control for cooperating manipulators**.
In: *Robotics and Automation, IEEE Transactions on* 12.1 (1996), pp. 78–89. ISSN: 1042-296X. DOI: 10.1109/70.481752.

K.-S. Chang, R. Holmberg, and O. Khatib.
The augmented object model: cooperative manipulation and parallel mechanism dynamics.
In: *Robotics and Automation, 2000. Proceedings. ICRA '00. IEEE International Conference on*. Vol. 1. 2000, 470–475 vol.1. DOI: 10.1109/ROBOT.2000.844099.

C.C. Cheah, C. Liu, and J.J.E. Slotine. **Adaptive Jacobian tracking control of robots with uncertainties in kinematic, dynamic and actuator models**.
In: *Automatic Control, IEEE Transactions on* 51.6 (2006), pp. 1024 –1029. ISSN: 0018-9286. DOI: 10.1109/TAC.2006.876943.

John J. Craig. **Introduction to Robotics: Mechanics and Control**. 2nd.
Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1989. ISBN: 0201095289.

Frederik Deroo, Michael Ulbrich, Brian Anderson, and Sandra Hirche.
Accelerated iterative distributed controller synthesis with a Barzilai-Borwein step size.
In: *Decision and Control (CDC), 2012 IEEE 51st Annual Conference on*. IEEE. 2012, pp. 4864–4870.

References II

S. Erhart, D. Sieber, and S. Hirche.
An impedance-based control architecture for multi-robot cooperative dual-arm mobile manipulation.
In: *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. 2013.

Sebastian Erhart and Sandra Hirche. **Adaptive Force/Velocity Control for Multi-Robot Cooperative Manipulation under Uncertain Kinematic Parameters**.
In: *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2013.

Neville Hogan. **Impedance Control: An Approach to Manipulation: Part I - Theory**.
In: *Journal of Dynamic Systems, Measurement, and Control* 107.1 (1985), pp. 1–7.
DOI: 10.1115/1.3140702.

Y. Karayiannidis, C. Smith, F.E. Viña, P. Ogren, and D. Kragic.
Open sesame! Adaptive Force/Velocity Control for Opening Unknown Doors.
In: *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. 2012, pp. 4040–4047. DOI: 10.1109/IROS.2012.6385835.

Kab I. Kim and Yuan F. Zheng.
Two strategies of position and force control for two industrial robots handling a single object.
In: *Robotics and Autonomous Systems* 5.4 (1989), pp. 395 –403. ISSN: 0921-8890.
DOI: http://dx.doi.org/10.1016/0921-8890(89)90023-7.

G. Montemayor and J.T. Wen. **Multiple robot force control with delayed force measurements**.
In: *Control Applications, 2004. Proceedings of the 2004 IEEE International Conference on*. Vol. 1. 2004, 327–332 Vol.1. DOI: 10.1109/CCA.2004.1387232.

V. Perdereau and M. Drouin. **Hybrid external control for two robot coordinated motion**.
In: *Robotica* 14 (1996), pp. 141–153.

References III

S.A. Schneider and Jr. Cannon R.H.
Object impedance control for cooperative manipulation: theory and experimental results.
In: *Robotics and Automation, IEEE Transactions on* 8.3 (1992), pp. 383 –394. ISSN: 1042-296X.
DOI: 10.1109/70.143355.

D. Sieber, F. Deroo, and S. Hirche.
Formation-based approach for cooperative manipulation based on iterative optimal controller design. In: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). 2013.

D. Sieber, F. Deroo, and S. Hirche. **Iterative optimal feedback controller design under relaxed rigidity constraints for cooperative manipulation**. In: Proc. IEEE/CSS CDC. 2013.

Jérôme Szewczyk, Frédéric Plumet, and Philippe Bidaud.
Planning and controlling cooperating robots through distributed impedance.
In: *Journal of Robotic Systems* 19.6 (2002), pp. 283–297. ISSN: 1097-4563. DOI: 10.1002/rob.10041.

M. Uchiyama and P. Dauchez.
A symmetric hybrid position/force control scheme for the coordination of two robots.
In: *Robotics and Automation, 1988. Proceedings., 1988 IEEE International Conference on*. 1988, 350–356 vol.1. DOI: 10.1109/ROBOT.1988.12073.

Richard Volpe and Pradeep Khosla.
On The Equivalence of Second Order Impedance Control and Proportional Gain Explicit Force Control.
1994.

Ian D. Walker, Robert A. Freeman, and Steven I. Marcus.
Analysis of Motion and Internal Loading of Objects Grasped by Multiple Cooperating Manipulators.
In: *The International Journal of Robotics Research* 10.4 (1991), pp. 396–409.
DOI: 10.1177/027836499101000408.
eprint: http://ijr.sagepub.com/content/10/4/396.full.pdf+html.