Impedance Control based Force-tracking Algorithm for Interaction Robotics Tasks: An Analytically Force Overshoots-free Approach

Loris Roveda, Federico Vicentini, Nicola Pedrocchi and Lorenzo Molinari Tosatti
Institute of Industrial Technologies and Automation (ITIA) of Italian National Research Council (CNR), via Bassini, 15 - 20133 Milan, Italy

Keywords: Force Overshoots Avoidance, Force-tracking Impedance Controls, Interacting Robotics Applications, Compliant Environments.

Abstract: In the presented paper an analytically force overshoots-free approach is described for the execution of robotics interaction tasks involving a compliant (of unknown geometrical and mechanical properties) environment. Based on the impedance control, the aim of the work is to perform force-tracking applications avoiding force overshoots that may result in task failures. The developed algorithm shapes the equivalent stiffness and damping of the closed-loop manipulator to regulate the interaction dynamics deforming the impedance control set-point. The force-tracking performance are obtained defining the control gains analytically based on the estimation of the interacting environment stiffness (performed using an Extended Kalman Filter). The method has been validated in a probing task, showing the avoidance of force overshoots and the achieved target dynamic performance.

1 INTRODUCTION

Robotics applications are increasingly targeted to interaction tasks, requiring high (controlled) compliance in order to ensure safety and adaptability during the task execution.

Interaction tasks are generally referred to either human-robot interaction, where limited energy transfer is needed as major requirement, or to robot machining, where the regulation of the energy transfer is a process requirement. The robot compliance can then be required at either design (e.g. intrinsic safe mechanics, such as Baxter Rethink (2012)) or control level (*e.g.*KUKA LWR Kugi et al. (2008)).

Focused tasks include industrial applications such as (semi-) automatic assembly, cooperative disassembly and handling assistance, where manipulators share the same working area with other manipulators and human operators, while interacting with a compliant and (partially) unknown environment. Specifically, interesting configurations of interacting environments include also machining processes (e.g. surface finishing and forming), where materials, manufacturing and manufacts are either lightweight, elastic, nonlinearly compliant or high-added valued.

Such applications require a fine interaction control in order to preserve the manipulator itself and the surrounding interacting environment. In fact, while interacting with a human operator or a fragile component, even a small force overshoot may cause the failure of the task (*e.g.*, breaking the manipulated component).

Since the milestones of sensor-based

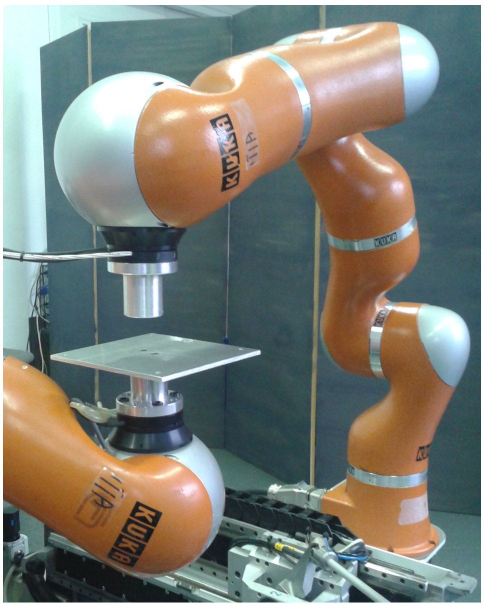

Figure 1: Experimental Set-up.

Roveda L., Vicentini F., Pedrocchi N. and Molinari Tosatti L..
Impedance Control based Force-tracking Algorithm for Interaction Robotics Tasks: An Analytically Force Overshoots-free Approach.
DOI: 10.5220/0005565403860391
In *Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2015), pages 386-391
ISBN: 978-989-758-123-6

force/dynamics control Salisbury (1980); Mason (1981); Raibert and Craig (1981); Yoshikawa (1987); Khatib (1987), impedance control Hogan (1984) has been particularly effective in order to interact with compliant environments, including also non-restrictive assumptions Colgate and Hogan (1989) on the dynamical properties of the interacting environment. In fact, with respect to pure force controllers Lange et al. (2012, 2013), impedance control compounds an easier tunable dynamic balance response for the robot. In addition, particular design of impedance controllers Ott et al. (2010), grants a wide control bandwidth, thanks to a continuous adaptation of the controller.

Nevertheless, some force/deformation regulation requirements are introduced (investigated, designed and validated) in order to improve the robustness and safety of interaction with a dynamic task, especially in the case of a precision-force process Roveda et al. (2013). Although impedance methods are proved to be dynamically equivalent to explicit force controllers Volpe and Khosla (1995) a direct tracking of explicit interaction forces is not straightforwardly allowed.

To overcome this limitation and preserving the properties of the impedance behaviour two different families of methods have been mainly introduced: class (a) force-position tracking impedance controllers and class (b) variable impedance controllers.
Common solutions of class (a) methods is suggested in Villani et al. (1999), where the controlled force is derived from a position control law, scaling the trajectory as a function of the estimated environment stiffness, calculating the time-varying PID gains. Another important approach (Seraji and Colbaugh, 1993, 1997; Jung et al., 2004) involves the generation of a reference motion as a function of the force-tracking error, under the condition that the environment stiffness is variously unknown, *i.e.*estimated as a function of the measured force.
Common solutions of class (b) methods consist on gain-scheduling strategies that select the stiffness and damping parameters from a predefined set (off-line calculated) on the basis of the current target state (Ikeura and Inooka, 1995; Ferraguti et al., 2013). Lee and Buss (2000) varies the controlled robot stiffness on-line to regulate the desired contact force based on the previous force tracking error, without any knowledge of the environment. Yang et al. (2011) presents a human-like learning controller to interact with unknown environments that feedforward adapts force and impedance. Oh et al. (2014a,b) describes a frequency-shaped impedance control method shapes a disturbance observer in the frequency domain so that the impedance is manipulated to achieve both the compliant interaction and reference tracking.

Commonly in class (a) methods, all approaches mantain a constant dynamic behaviour of the controlled robot, so that when the environment stiffness quickly and significantly changes, the bandiwth of the controllers has to be limited for avoiding instability, while in class (b) methods, stationary, known and structured environment are considered. Moreover, no contributions are related to specifically avoid force overshoots during the task execution.

The aim of this work is to combine the main features of such control schemes in order to analytically achieve the force overshoots avoidance goal. Extending the work described in Roveda et al. (2014), that provide an experimental proof of the force overshoots avoidance during the task execution by adapting all the impedance control parameters (*i.e.*, set-point, stiffness and damping), the developed method allows to analytically derive the control gains to obtain a target oscillations-free dynamic behaviour for the force overshoots avoidance based on the estimation of the interacting environment stiffness (performed using an Extended Kalman Filter). The developed algorithm shapes the equivalent stiffness and damping of the closed-loop manipulator deforming the impedance control set-point.
The developed control algorithm has been validated using a KUKA LWR 4+ manipulator in contact with a second impedance controlled KUKA LWR 4 + that simulates an interacting environment (Figure 1), showing the avoidance of force overshoots and the achieved target dynamic performance.

2 PROBLEM FORMULATION

Based on the estimate of the environment stiffness $\widehat{\mathbf{K}}_e$ and the force error $\mathbf{e}_f = \mathbf{f}^d - \mathbf{f}$, where $\mathbf{f}^d$ and $\mathbf{f}$ are the desired and measured robot forces, respectively, the developed controller (Figure 2) defines the set-point $\mathbf{x}_r^0$ of the KUKA LWR 4 + impedance controller in order to shape the stiffness and damping of the closed-loop manipulator while tracking a force reference. In particular, the controller has been derived to have the complete analytical formulation. In such a way, the control parameters (*i.e.*, proportional and derivative gains $\mathbf{K}_p$, $\mathbf{K}_d$ and shaping coeffients $\mathbf{K}_0$, $\mathbf{m}_k$) can be mathematically defined:

$$\mathbf{x}_r^0 = \mathbf{x}_r + \mathbf{K}_r^{-1}\,(\mathbf{e}_f\,\mathbf{m}_k + \mathbf{K}_0)\,\mathbf{K}_p\,\mathbf{f}^d\,\widehat{\mathbf{K}}_e^{-1} - \mathbf{K}_d\,\dot{\mathbf{x}}_r \quad (1)$$

$$\widehat{\mathbf{K}}_e = f(\mathbf{f}_e, \mathbf{x}_e^{eq}, \mathbf{x}_e) \quad (2)$$

where $\mathbf{K}_0$ is the diagonal stiffness matrix of the controlled robot at zero-force error, $\mathbf{m}_K$ is the

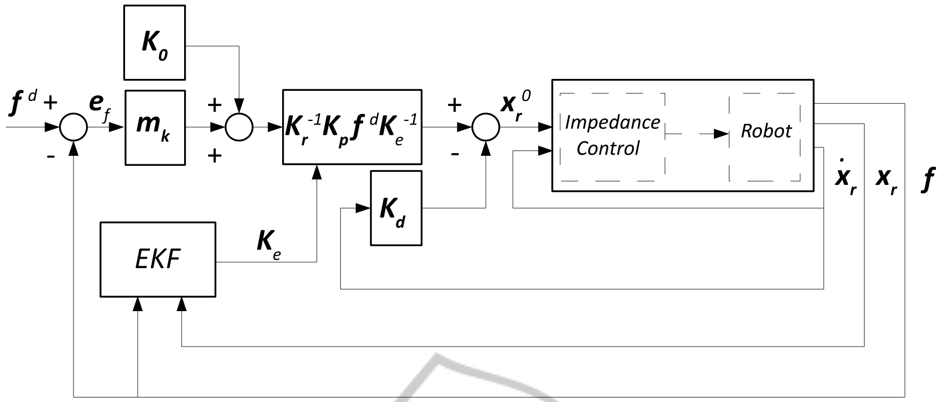

Figure 2: Control scheme, including the environment observer (EKF).

coefficient describing the function of the stiffness matrix with respect to the force error, $\mathbf{K}_p$ is the diagonal proportional gain matrix, $\mathbf{K}_d$ is the diagonal derivative gain matrix that shapes the closed-loop manipulator damping based on the robot velocity $\dot{\mathbf{x}}_r$, $\mathbf{f}_e$ is the force vector acting on the environment, $\mathbf{x}_e$ is the actual position of the environment, $\mathbf{x}_e^{eq}$ is the equilibrium position of the environment.
In order to obtain the desired performance of the controller, proportional and derivative gains $\mathbf{K}_p$, $\mathbf{K}_d$ and shaping coeffitients $\mathbf{K}_0$, $\mathbf{m}_k$ are analytically defined. In particular, by imposing $\mathbf{m}_k < 0$ the closed-loop manipulator behaviour is more robust in the first contact phase, having an equivalent stiffness that becomes stiffer as the target force is achieved.

The main task space impedance loop is performed by the model-based control of the manipulator at a rate of $200\,Hz$, synchronously with the environment estimation (*EKF* in Figure 2). A model of the robot-environment interaction is needed to define the force set-points in (1) through the environemt stiffness $\widehat{\mathbf{K}}_e$, which in turn is estimated through the deformation of the environment and the full state of robot kinematics and exchanged forces. Signals in (1), (2) are updated to the main KUKA LWR control loop, whose remote control mode allows the tuning of all impedance parameters, together with the sampling of force and kinematics state. The remote controller is based on a real-time Linux Xenomai platform with RTNet-patched network interfaces.

3 INTERACTION DYNAMICS

3.1 Closed-Loop Robot Dynamics

The KUKA LWR 4+ enables a task space visco-elastic behavior Albu-Schäffer et al. (2007), with tunable equivalent Cartesian stiffness $\mathbf{K}_r$ and damping $\mathbf{D}_r$. With some experimental identification and practice it is possible to assume a full impedance behavior, considering an inertia matrix $\mathbf{M}_r$ with negligible/ininfluent extra-diagonal coupling terms. Some practice with the KUKA LWR 4 + impedance control suggests the full model

$$\mathbf{M}_r\ddot{\mathbf{x}}_r + \mathbf{D}_r\dot{\mathbf{x}}_r + \mathbf{K}_r\boldsymbol{\Delta}\mathbf{x}_r = \mathbf{f} \quad (3)$$

a good approximation of the real behavior of the robot up to 5 Hz, where $\boldsymbol{\Delta}\mathbf{x}_r = \mathbf{x}_r - \mathbf{x}_r^0$ is the difference between the actual robot pose, $\mathbf{x}_r$ and the desired one $\mathbf{x}_r^0$, and $\mathbf{f}$ is the external interacting force/torque vector. Recall that the control interface of the KUKA LWR 4 + allows a user-defined input $\mathbf{x}_r^0$, *i.e.*, the impedance balance set-point (Figure 3).

3.2 Compliant Environment Dynamics

Denoting $\mathbf{D}_e$ and $\mathbf{K}_e$ as the environment damping and stiffness respectively, a simplified environment dynamics can be modeled as Flügge (1975):

$$\mathbf{f} = -\left(\mathbf{D}_e\dot{\mathbf{x}}_e + \mathbf{K}_e\,\Delta\mathbf{x}_e\right) \quad (4)$$

where $\Delta\mathbf{x}_e = \mathbf{x}_e - \mathbf{x}_e^0$, and $\mathbf{x}_e^0$ is the equilibrium position for the environment. In particular, considering a stable contact point with $\mathbf{x}_e^0 = 0$, the environment position is equal to the robot position (*i.e.*, $\mathbf{x}_e = \mathbf{x}_r$), as in Figure 3.

3.3 Environment Observer

3.3.1 EKF Design

The environment model in (4) is used to implement an Extended Kalman Filter for the environment stiffness estimation. Under the mild hypothesis that the contact is preserved once established and simplification

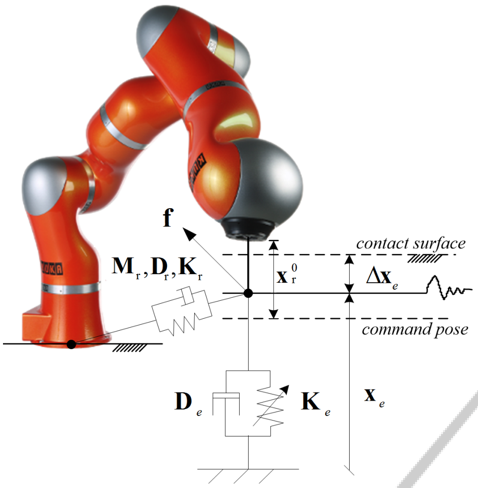

Figure 3: KUKA LWR 4 + interaction model.

hypothesis that the contact(s) are elastic the robot-environment interaction is defined by the filter state, augmented with the environment properties:

$$\boldsymbol{\xi}_e = [\Delta\mathbf{x}_e, \mathbf{K}_e, \mathbf{D}_e, \mathbf{f}_e]^T. \tag{5}$$

Substituting the augmented state (5) in model (4), the filter dynamics result in:

$$\boldsymbol{f}(\boldsymbol{\xi}_e, \boldsymbol{\nu}_e) = \begin{bmatrix} \mathbf{D}_e^{-1}(-\mathbf{K}_e\Delta\mathbf{x}_e + \mathbf{f}_e + \boldsymbol{\nu}_{\mathbf{x}_e}) \\ \boldsymbol{\nu}_{\mathbf{K}_e} \\ \boldsymbol{\nu}_{\mathbf{D}_e} \\ \boldsymbol{\nu}_{\mathbf{f}_e} \end{bmatrix} \tag{6}$$

where the vector $\boldsymbol{\nu}_e = [\boldsymbol{\nu}_{\mathbf{x}_e}, \boldsymbol{\nu}_{\mathbf{K}_e}, \boldsymbol{\nu}_{\mathbf{D}_e}, \boldsymbol{\nu}_{\mathbf{f}_e}]^T$ accounts for uncertainties in models parameters/estimates.
The observer of the augmented state is therefore defined as:

$$\begin{cases} \dot{\boldsymbol{\xi}}_e = \boldsymbol{f}(\boldsymbol{\xi}_e, \boldsymbol{\nu}_e) + \mathbf{K}_{EKF}(\mathbf{y} - \mathbf{C}_a\hat{\boldsymbol{\xi}}_e) \\ \hat{\mathbf{y}} = \boldsymbol{H}(\boldsymbol{\xi}_e, \boldsymbol{w}) \end{cases} \tag{7}$$

where $\hat{\boldsymbol{\xi}}$ are estimates, $\mathbf{K}_{EKF}$ is the gain matrix, $\mathbf{C}_a$ is the observation matrix, $\hat{\mathbf{y}}$ is the measurements vector and $\boldsymbol{H}(\boldsymbol{\xi}_e, \boldsymbol{w})$ is the observation function.
Based on Haykin et al. (2001), the state $\hat{\boldsymbol{\xi}}$ is updated by measurements of $\mathbf{x}_e$ and $\mathbf{f}_e = \mathbf{f}$, providing the environment stiffness $\widehat{\mathbf{K}}_e$ (more details are shown in Roveda et al. (2013)).

3.3.2 EKF Experimental Validation

Characterization, tuning and evaluation of the observer in (7) are performed in real experiments for the estimation of the environment stiffnes $\widehat{K}_e$, after the localization of the environment location $x_{e,eq}$.
The on-line estimation of environment stiffness can be executed using the the 1-DoF formulation of (6) for the filter states update.

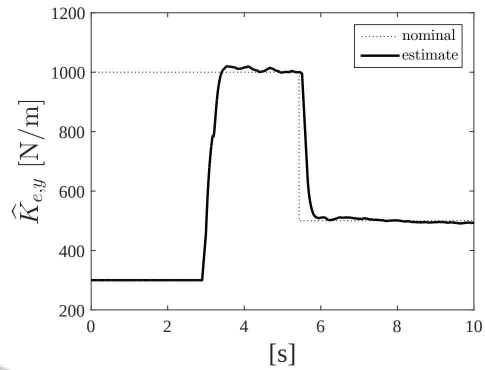

Figure 4: Stiffness estimation in real experiment in 1 DoF, along a horizontal axis.

In Fig. 4 a varing stiffness environment is observed (a companion LWR 4+ in impedance control is used to generate a non-shared reference stiffness) in a real experiment. Experimental results show a delay in the estimation of approximately 0.5 s and a maximum steady state error of less than 1% and 3% w.r.t. the nominal known values.

4 CONTROL APPLICATION

4.1 Control Parameters Calculation

Considering a single DoF (as the impedance control allows to decouple the Cartesian DoF) and substituting the impedance control set-point x_r^0 as defined by (1) and the environment dynamics as defined by (4) in (3), the closed-loop dynamics results:

$$\begin{aligned} M_r\ddot{x}_r + (D_r + D_e + K_r K_d)\dot{x}_r + (K_e + m_k f^d K_p)x_r \\ = K_p f^d K_e^{-1}(m_k f^d + K_0) \end{aligned} \tag{8}$$

Considering the static term of (8) and $x_r^d = \dfrac{f^d}{K_e}$, it is easy to define the proportional gain K_p as:

$$K_p = \frac{K_e}{K_0} \tag{9}$$

in order to have a zero-steady-state-error.

Considering the eigenvalues of (8), it is easy to define the derivstive gain K_d as:

$$K_d = \frac{\sqrt{4M_r(K_p m_k f^d + K_e)}}{K_r} \tag{10}$$

in order to avoid force overshoots.

4.2 Validation Test

The developed control algorithm has been validated using a KUKA LWR 4+ manipulator in contact in the vertical Z direction with a second impedance controlled KUKA LWR 4 + that simulates an interacting environment (Figure 1). The second KUKA LWR 4 + stiffness is not known to the controller and it is estimated using the implemented EKF.

During the experimental tests, the environment stiffness is $K_e \cong 20000 N/m$. The impedance control stiffness is $K_r = 5000 N/m$ and the adimensional impedance control damping is $h_r = 0.3$ in order to test the capabilities of the defined controller to avoid force overshoots, even considering a low-damped behaviour.

Figure 5 shows the measured and target interaction forces during the task execution. The obtained dynamics is able to avoid any force overshoot during the task execution. The selection of the control parameters m_k and K_0 allows to regulate the dynamic performance of the closed-loop manipulator.

5 CONCLUSIONS

The presented paper presents an analytically force overshoots-free approach based on the impedance control. Shaping the equivalent stiffness and damping of the closed-loop manipulator through the impedance control set-point, the described algorithm allows to mathematically define the control parameters in order to avoid force overshoots while interacting with a compliant and unknown environment, estimating the environment stiffness using an Extended Kalman Filter.

The effectiveness of the method has been proven

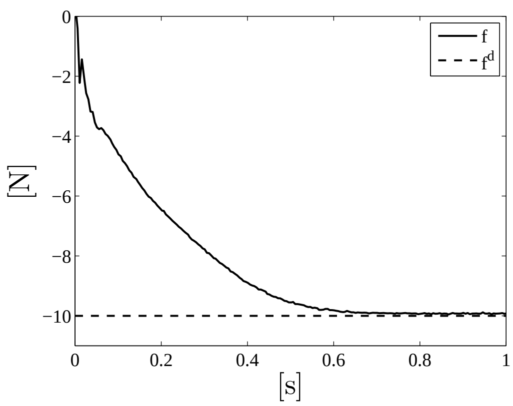

Figure 5: Measured and target interaction forces during the task execution.

in a probing task, showing the force overshoots avoidance without any loss of bandwidth. Future work will apply the defined algorithm to more challenging tasks (*e.g.*, assembly task) and will extend the algorithm to the compliant robot base case.

ACKNOWLEDGEMENTS

The work has been developed within the project FourByTHree, funded from European Unions Horizon 2020 research and innovation programme under grant agreement $n°$ 637095.

REFERENCES

Albu-Schäffer, A., Ott, C., and Hirzinger, G. (2007). A unified passivity-based control framework for position, torque and impedance control of flexible joint robots. *The International Journal of Robotics Research*, 26(1):23–39.

Colgate, E. and Hogan, N. (1989). An analysis of contact instability in terms of passive physical equivalents. In *Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on*, pages 404–409.

Ferraguti, F., Secchi, C., and Fantuzzi, C. (2013). A tank-based approach to impedance control with variable stiffness. In *Proceedings of the 2013 International Conference on Robotics and Automation (ICRA)*.

Flügge, W. (1975). *Viscoelasticity*. Springer New York.

Haykin, S. S. et al. (2001). *Kalman filtering and neural networks*. Wiley Online Library.

Hogan, N. (1984). Impedance control: An approach to manipulation. In *American Control Conference, 1984*, pages 304–313.

Ikeura, R. and Inooka, H. (1995). Variable impedance control of a robot for cooperation with a human. In *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*, volume 3, pages 3097–3102. IEEE.

Jung, S., Hsia, T., and Bonitz, R. (2004). Force tracking impedance control of robot manipulators under unknown environment. *Control Systems Technology, IEEE Transactions on*, 12(3):474–483.

Khatib, O. (1987). A unified approach for motion and force control of robot manipulators: The operational space formulation. *Robotics and Automation, IEEE Journal of*, 3(1):43–53.

Kugi, A., Ott, C., Albu-Schäffer, A., and Hirzinger, G. (2008). On the passivity-based impedance control of flexible joint robots. *Robotics, IEEE Transactions on*, 24(2):416–429.

Lange, F., Bertleff, W., and Suppa, M. (2013). Force and trajectory control of industrial robots in stiff contact. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 2927–2934. IEEE.

Lange, F., Jehle, C., Suppa, M., and Hirzinger, G. (2012). Revised force control using a compliant sensor with a position controlled robot. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 1532–1537. IEEE.

Lee, K. and Buss, M. (2000). Force tracking impedance control with variable target stiffness. *The Intern. Federation of Automatic Control*, 16(1):6751–6756.

Mason, M. T. (1981). Compliance and force control for computer controlled manipulators. *Systems, Man and Cybernetics, IEEE Transactions on*, 11(6):418–432.

Oh, S., Woo, H., and Kong, K. (2014a). Frequency-shaped impedance control for safe human–robot interaction in reference tracking application.

Oh, S., Woo, H., and Kong, K. (2014b). Stability and robustness analysis of frequency-shaped impedance control for reference tracking and compliant interaction. In *World Congress*, volume 19, pages 3557–3562.

Ott, C., Mukherjee, R., and Nakamura, Y. (2010). Unified impedance and admittance control. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 554–561. IEEE.

Raibert, M. and Craig, J. (1981). Hybrid position/force control of manipulators. *Journal of Dynamic Systems, Measurement, and Control*, 103(2):126–133.

Rethink (2012). Baxter research robot (visited january 2015).

Roveda, L., Vicentini, F., Pedrocchi, N., and Tosatti, Francesco Braghin, L. M. (2014). Impedance shaping controller for robotic applications in interaction with compliant environments. In *International Conference on Informatics in Control (ICINCO)*.

Roveda, L., Vicentini, F., and Tosatti, L. M. (2013). Deformation-tracking impedance control in interaction with uncertain environments. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 1992–1997. IEEE.

Salisbury, J. K. (1980). Active stiffness control of a manipulator in cartesian coordinates. In *Decision and Control including the Symposium on Adaptive Processes, 1980 19th IEEE Conference on*, volume 19, pages 95–100.

Seraji, H. and Colbaugh, R. (1993). Adaptive force-based impedance control. In *Intelligent Robots and Systems' 93, IROS'93. Proceedings of the 1993 IEEE/RSJ International Conference on*, volume 3, pages 1537–1544. IEEE.

Seraji, H. and Colbaugh, R. (1997). Force tracking in impedance control. *The International Journal of Robotics Research*, 16(1):97–117.

Villani, L., Canudas de Wit, C., and Brogliato, B. (1999). An exponentially stable adaptive control for force and position tracking of robot manipulators. *Automatic Control, IEEE Transactions on*, 44(4):798–802.

Volpe, R. and Khosla, P. (1995). The equivalence of second-order impedance control and proportional gain explicit force control. *The International journal of robotics research*, 14(6):574–589.

Yang, C., Ganesh, G., Haddadin, S., Parusel, S., Albu-Schaeffer, A., and Burdet, E. (2011). Human-like adaptation of force and impedance in stable and unstable interactions. *Robotics, IEEE Transactions on*, 27(5):918–930.

Yoshikawa, T. (1987). Dynamic hybrid position/force control of robot manipulators–description of hand constraints and calculation of joint driving force. *Robotics and Automation, IEEE Journal of*, 3(5):386–392.