

Null-Space Impedance Control for Physical Human-Robot Interaction

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Abstract In this paper two approaches for the correct task execution during null-space impedance control of a kinematically redundant robot are presented. The algorithms guarantee safe and dependable reaction of the robot during deliberate or accidental interaction with the environment, thanks to null-space impedance control. Moreover, the correct execution of the task assigned to the end-effector is ensured by control laws relying on two different observers. One is based on task space information and the other on the generalized momentum of the robot. The performance of the proposed control is verified through numerical simulations on 7R KUKA lightweight robot arm.

1 Introduction

New applications where robots work near humans are growing rapidly. Unlike the industrial robots which are stiff with high impedance, the robots working with humans must be designed with high degree of compliance and safety. In these applications, not only unexpected impacts of robots with humans are likely to happen, but also intentional physical Human-Robot Interaction (pHRI) may be required (De Santis et al., 2008). To cope with these situations, different strategies are possible. For example, the manipulator can be covered with a sensitive skin (Lumelsky and Cheung, 2001) capable of measuring the interaction forces. Alternatively, these forces can be estimated from joint positions or torques by means of suitable observers (Haddadin et al., 2008). In any case, suitable control strategies must be adopted to increase robot's compliance (Yoshikawa and Khatib, 2008). Passive compliance can be also introduced by using elastic decoupling between the actuator and the driven link (Bicchi and Tonietti, 2004).

Impedance control represents a very suitable framework for controlling robots in contact with an unknown environment. The problem of impedance control has been extensively studied in the literature. The compliant behavior usually is realized in the task space to control the interaction of the end-effector (Ott, 2008). However, an impedance behavior can be imposed also in the joint space to ensure safety.

A complete theoretical and empirical evaluation of different operational space control techniques for redundant manipulators has been investigated by Nakanishi et al. (2008). One approach to deal with this redundant degrees of freedom is multi-priority control, that can be performed both in kinematic (Siciliano and Slotine, 1991) and dynamic level (Khatib et al., 2004).

De Luca and Ferrajoli (2008) presented a method for fast collision detection and safe reaction based on generalized momentum of the robot, without using any torque sensor. The redundancy of the robot was exploited to preserve as much as possible the execution of the end-effector task by projecting the reaction torques into the null space of the main task.

This paper investigates the null-space impedance control previously presented in (Sadeghian et al., 2011) for robots that do not have joint torque sensors. A new nonlinear control scheme is introduced to estimate the applied external torque on the body of the robot by using a suitable task-based observer. Asymptotic convergence of the main task tracking error is ensured, while at the same time, the joint space impedance is realized in the null space of the main task. Furthermore, the same goal also is pursued by means of a momentum based observer. An example of the application scenario is depicted in Fig. 1, where a redundant robot working on a table experiences a contact with a human. This contact may produce error on the main task of the robot if active compliance is used to ensure safe interaction. Our approach allows to minimize the error in the task space while ensuring compliance in the null space.

2 Null-Space Impedance Control

Dynamic model of a n -link robot manipulator can be expressed by

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) + \tau_{ext} = \tau, \quad (1)$$

with standard notation. In this model, τ is the input vector torque while τ_{ext} is the torque resulting from external interaction. If the manipulator is equipped with torque sensors in its joints or force sensors on the interaction points, the external torque can be measured or estimated. In this paper, we assume that these sensors are not available. The well-known model-based

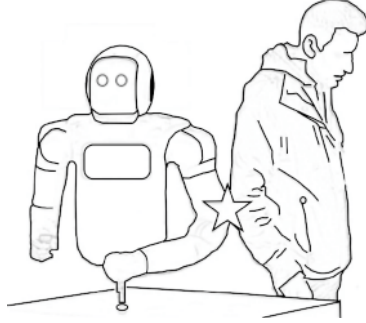


Figure 1. Robot in interaction with a human.

resolved acceleration control can be adopted to compute the driving torques

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}_c + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}), \quad (2)$$

where $\ddot{\mathbf{q}}_c$ is the joint command acceleration to be suitably designed.

For a redundant manipulator, redundancy lets us to have some kind of joint impedance and task space control simultaneously. The so-called null-space impedance can be realized in the null space of the main task to control the interaction on the robot's body. The corresponding command joint acceleration in (2) is given by

$$\ddot{\mathbf{q}}_c = \mathbf{J}^\dagger(\ddot{\mathbf{x}}_c - \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{N}(\ddot{\mathbf{q}}_d + \mathbf{M}_d^{-1}(\mathbf{B}_d\dot{\mathbf{q}} + \mathbf{K}_d\tilde{\mathbf{q}})), \quad (3)$$

which produces the task space and null-space closed-loop behavior respectively as follows

$$\begin{aligned} \ddot{\mathbf{x}}_c - \ddot{\mathbf{x}} &= \mathbf{J}\mathbf{M}^{-1}\boldsymbol{\tau}_{ext}, \\ \mathbf{N}(\ddot{\mathbf{q}} + \mathbf{M}_d^{-1}(\mathbf{B}_d\dot{\mathbf{q}} + \mathbf{K}_d\tilde{\mathbf{q}}) - \mathbf{M}^{-1}\boldsymbol{\tau}_{ext}) &= \mathbf{0}. \end{aligned} \quad (4)$$

Here $\ddot{\mathbf{x}}_c$ is the command acceleration in the task space, $\tilde{\mathbf{q}} = \mathbf{q}_d - \mathbf{q}$ where $\mathbf{q}_d$ is the desired trajectory or a rest configuration in the joint space, $\mathbf{J}^\dagger$ is any (weighted) right pseudo-inverse of the task space Jacobian matrix $\mathbf{J}$, $\mathbf{N} = (\mathbf{I} - \mathbf{J}^\dagger\mathbf{J})$ is the null-space projection matrix, and $\mathbf{M}_d$, $\mathbf{B}_d$ and $\mathbf{K}_d$ are the impedance matrices. This choice of $\ddot{\mathbf{q}}_c$ allows the joint space impedance in the null-space of the main task to be realized, provided that the desired inertia matrix is chosen as $\mathbf{M}_d = \mathbf{M}(\mathbf{q})$. On the other hand, the main task experiences errors as a result of the external torques that are applied on the robot's body. It can be easily shown that an arbitrary $\mathbf{M}_d$

can be set only if the measurement of τ_{ext} is available to the controller; in this case, also the influence of τ_{ext} on the main task can be cancelled out.

3 Task-Based Observer

The following theorem is given for correct execution of the main task, while ensuring a compliant behaviour of the robot's body.

Theorem: Let us denote with $\hat{\tau}$ the estimated external torque and with $\tilde{\tau} = \tau_{ext} - \hat{\tau}$ the estimation error. Also, define the error $\mathbf{s} = \dot{\tilde{\mathbf{x}}} + \mathbf{P}\tilde{\mathbf{x}}$, where $\mathbf{P}$ is a positive definite diagonal matrix and $\tilde{\mathbf{x}} = \mathbf{x}_d - \mathbf{x}$. Then, for selected constant diagonal positive definite matrix $\mathbf{K}$ and constant positive definite matrix $\mathbf{\Gamma}_f$, the control law

$$\begin{aligned} \boldsymbol{\tau} = & \mathbf{J}^T \boldsymbol{\Lambda} (\ddot{\mathbf{x}}_d + \mathbf{P}\dot{\tilde{\mathbf{x}}} - \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{J}^T \left(\frac{1}{2} \dot{\boldsymbol{\Lambda}} + \mathbf{K} \right) - \mathbf{J}^T \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}} \\ & + \mathbf{M} \mathbf{N}_{\#} (\ddot{\mathbf{q}}_d + \mathbf{M}^{-1} (\mathbf{B}_d \dot{\tilde{\mathbf{q}}} + \mathbf{K}_d \tilde{\mathbf{q}})) + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}), \end{aligned} \quad (5)$$

with the disturbance observer

$$\dot{\tilde{\boldsymbol{\tau}}} = -\mathbf{\Gamma}_f^T \mathbf{J}^{\#} \mathbf{s}, \quad (6)$$

guarantee that the $\tilde{\mathbf{x}}$ and $\dot{\tilde{\mathbf{x}}}$ go to zero asymptotically while the null-space impedance behavior is imposed. Moreover, the estimated disturbance remains bounded and the closed-loop system is stable $\square$

In (5), $\boldsymbol{\Lambda} = (\mathbf{J} \mathbf{M}^{-1} \mathbf{J}^T)^{-1}$ is task inertia matrix, $\mathbf{J}^{\#} = \mathbf{M}^{-1} \mathbf{J}^T \boldsymbol{\Lambda}$ is the dynamically consistent generalized inverse (Khatib et al., 2004) and $\mathbf{N}_{\#} = (\mathbf{I} - \mathbf{J}^{\#} \mathbf{J})$.

Applying the above control law to the system (1) the closed-loop behavior of the robot in the task space is given by

$$\begin{aligned} \mathbf{J}^{\#T} \dot{\tilde{\boldsymbol{\tau}}} = \tilde{\mathbf{f}} = & \boldsymbol{\Lambda} \dot{\mathbf{s}} + \left(\frac{1}{2} \dot{\boldsymbol{\Lambda}} + \mathbf{K} \right) \mathbf{s}, \\ \tilde{\mathbf{f}} = & \mathbf{f}_{ext} - \hat{\mathbf{f}}, \end{aligned} \quad (7)$$

where $\hat{\mathbf{f}} = \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}}$ is the estimation of $\mathbf{f}_{ext} = \mathbf{J}^{\#T} \boldsymbol{\tau}_{ext}$. The closed-loop dynamics for the null-space is

$$\mathbf{N}_{\#} (\ddot{\tilde{\mathbf{q}}} + \mathbf{M}^{-1} (\mathbf{B}_d \dot{\tilde{\mathbf{q}}} + \mathbf{K}_d \tilde{\mathbf{q}}) - \mathbf{M}^{-1} \boldsymbol{\tau}_{ext}) = \mathbf{0}, \quad (8)$$

corresponding to an impedance behavior in the null-space of the main task.

The proof is based on the following Lyapunov-like function:

$$V = \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \tilde{\mathbf{x}} + \frac{1}{2} \mathbf{s}^T \boldsymbol{\Lambda} \mathbf{s} + \frac{1}{2} \tilde{\boldsymbol{\tau}}^T \mathbf{\Gamma}_f \tilde{\boldsymbol{\tau}}. \quad (9)$$

Notice that, while the force estimation error $\tilde{\mathbf{f}} = \mathbf{J}^{\#T} \tilde{\boldsymbol{\tau}}$ goes to zero, the torque estimation error $\tilde{\boldsymbol{\tau}}$ converges to zero only for non-redundant robots.

4 Momentum-Based Observer

Another method to ensure the correct execution of the main task during interaction is based on the collision detection algorithm presented by De Luca and Ferrajoli (2008). The basic concept is the computation of the n -dimensional residual vector

$$\mathbf{r}(t) = \mathbf{K}_I \left(\mathbf{p}(t) - \int_0^t (\boldsymbol{\tau} + \mathbf{C}^T(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} - \mathbf{g}(\mathbf{q}) + \mathbf{r}(\sigma)) d\sigma \right), \quad (10)$$

where $\mathbf{p}(t) = \mathbf{M}(\mathbf{q}) \dot{\mathbf{q}}$ is the robot generalized momentum and $\mathbf{K}_I$ is a positive definite diagonal matrix. This vector can be computed using the measured signals $\mathbf{q}$ and $\dot{\mathbf{q}}$, and the commanded torque $\boldsymbol{\tau}$, with initial conditions $\mathbf{r}(0) = \mathbf{0}$ and $\mathbf{p}(0) = \mathbf{0}$. The dynamics of $\mathbf{r}$ is

$$\dot{\mathbf{r}} = -\mathbf{K}_I \mathbf{r} - \mathbf{K}_I \boldsymbol{\tau}_{ext}, \quad (11)$$

corresponding to a filtered version of the real external torques, i.e. $\mathbf{r}(t) = \boldsymbol{\tau}_{ext}$. In the absence of interaction, assuming no noise and unmodeled disturbances, $\mathbf{r}(t) = \mathbf{0}$. As soon as interaction occurs, the components of $\mathbf{r}$ will raise exponentially and will reach to the value of $-\boldsymbol{\tau}_{ext}$.

A control algorithm similar to the one that was given by (5), using $\mathbf{r}$ in place of $\tilde{\boldsymbol{\tau}}$, is adopted

$$\begin{aligned} \boldsymbol{\tau} = & \mathbf{J}^T \boldsymbol{\Lambda} (\ddot{\mathbf{x}}_d + \mathbf{K}_D \dot{\tilde{\mathbf{x}}} + \mathbf{K}_p \tilde{\mathbf{x}} - \dot{\mathbf{J}} \dot{\mathbf{q}}) - \mathbf{J}^T \mathbf{J}^{\#T} \mathbf{r} \\ & + \mathbf{M} \mathbf{N}_{\#} [\ddot{\mathbf{q}}_d + \mathbf{M}_d^{-1} (\mathbf{B}_d \dot{\tilde{\mathbf{q}}} + \mathbf{K}_d \tilde{\mathbf{q}})] + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}), \end{aligned} \quad (12)$$

By defining the estimation error $\tilde{\mathbf{r}} = \mathbf{r} + \boldsymbol{\tau}_{ext}$, the closed-loop task dynamics is

$$\begin{aligned} \ddot{\tilde{\mathbf{x}}} + \mathbf{K}_D \dot{\tilde{\mathbf{x}}} + \mathbf{K}_p \tilde{\mathbf{x}} &= \mathbf{J} \mathbf{M}^{-1} \tilde{\mathbf{r}} \\ \dot{\tilde{\mathbf{r}}} &= -\mathbf{K}_I \tilde{\mathbf{r}} + \dot{\boldsymbol{\tau}}_{ext}. \end{aligned} \quad (13)$$

while the closed-loop dynamics for the null-space is the same as in (8). From the stability properties of the cascade systems (Panteley and Loria, 1998) it can be shown that when $\|\dot{\boldsymbol{\tau}}_{ext}\|$ is bounded, $\tilde{\mathbf{x}}$ is also bounded and specifically when $\dot{\boldsymbol{\tau}}_{ext} = 0$ the system is asymptotically stable and $\tilde{\mathbf{x}}, \dot{\tilde{\mathbf{x}}} \rightarrow \mathbf{0}$.

5 Numerical Simulation

The proposed approaches are verified in simulation on a 7 DOF KUKA lightweight arm, neglecting the presence of joint elasticity and dissipative

effects. The position of the end-effector is assumed as the main task. Therefore, the robot has 4 degrees of redundancy. A second-order inverse kinematics algorithm is used to compute the joint space desired trajectory for the null-space impedance, assuming a desired trajectory also for the end-effector orientation.

The main end-effector task is set as a straight line of about 1 m length. It is assumed that the manipulator hits an obstacle during its maneuver. The obstacle is moving with a constant speed of 2 cm/s. The interaction is modeled as an elastic contact with stiffness 1000 Nm/rad and happens at the fourth joint of the robot arm. A snapshot of the system during contact is reported on Fig 2.

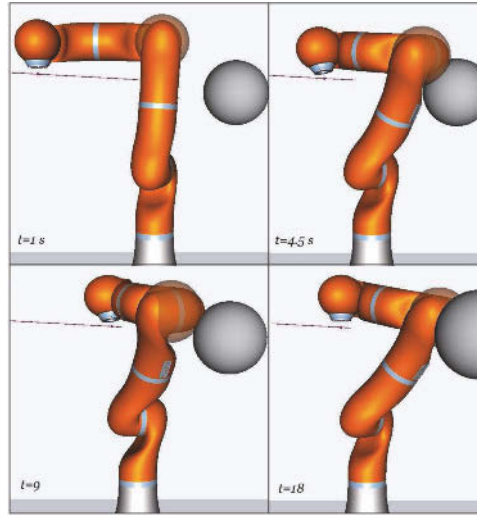


Figure 2. Snapshots of the system during interaction with an elastic sphere.

The position errors for the main task are reported in Fig. 3. It can be observed that the position errors are significantly reduced (of about one order of magnitude) when the observers are used. Notice that, during interaction, the end-effector orientation experiences errors since the orientation trajectory is assigned in the lower priority level as the desired trajectory for the null-space impedance. Thus the manipulator arm does not escape from the collision area and the redundancy allows to comply by keeping the position trajectory. As soon as the arm loses the contact with the obstacle, the orientation error disappears and the arm comes back to the desired configuration.

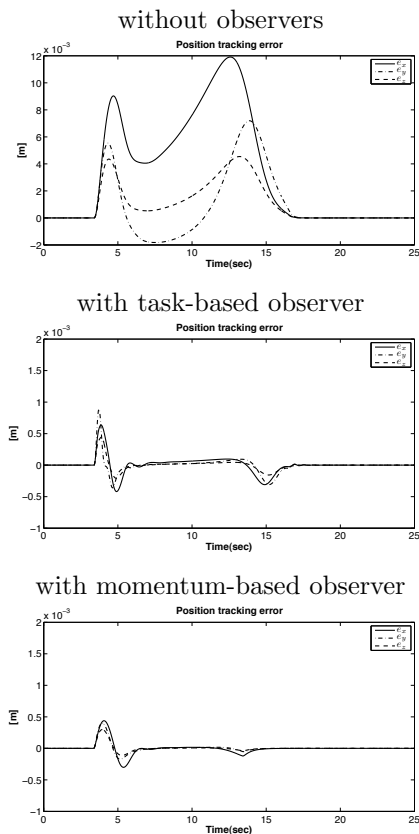


Figure 3. Position errors for the main task.

6 Conclusion

Two nonlinear control algorithms that ensure task space tracking error convergence, besides proper impedance behavior in the null-space, have been presented. The controllers do not need torque sensors and can be used for the case where the robot works close to humans and physical interaction occurs. The redundancy of the system is exploited to ensure safe and dependable physical interaction. The simulation results confirm the effectiveness of the proposed approach.¹

¹This work was partially funded by the European Community, within the FP7 ICT-287513 SAPHARI project and by the Italian Ministry of University and Research

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