

Null-space Impedance Control with Disturbance Observer

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Abstract—In this paper a new approach for the null-space impedance control of a kinematically redundant robot is proposed. The approach is useful for the case where the robot experience an external interaction on the body, especially in the presence of humans. The proposed algorithm guarantees safe and dependable physical interaction of the robot body with the environment, thanks to the null-space impedance control. At the same time, the correct execution of the task assigned to the end effector is ensured by a disturbance observer. The algorithm does not require joint torque measurements. The performance of the proposed controller is verified through simulations on 7R KUKA lightweight robot arm.

I. INTRODUCTION

One of the current trends in robotics is to develop new robots and control algorithms for doing daily life applications. While the industrial robots are stiff with high impedance, the robots used in dynamic environments (human environments) must be designed with high degree of safety and compliance. This compliance is useful for the applications including physical Human-Robot Interaction (pHRI) [1,2], such as service and medical robotics. In these applications not only unexpected impacts between robot and humans are likely to happen, but also intentional physical interaction with robot maybe required. To this end, different strategies may be thought. Collision avoidance is the safest approach. However, it is usually based on exteroceptive sensors such as camera which makes it inappropriate during fast interaction. Nevertheless, fast collision detection algorithms based on suitable observers also exists [3]. Alternatively, the other approach is to increase the robot compliance. Compliance can be introduced passively by using elastic decoupling between the actuator and the driven link (variable joint stiffness) [4], or actively by relying on fast control loops [5]. Note that, correct execution of the operational task during interaction is also appealing and important.

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 given to the operational task to control the interaction of the end effector [6]. However, the impedance behavior can be imposed also in the joint space to ensure safe interaction [7-9].

Recently, problems and solutions related to kinematic redundancy have obtained new interest because of the application of robotic systems with high degree of freedom, such as humanoid and dual-arm robots. One approach to deal with this redundant degrees is multi-priority control, that is a well-established framework and can be performed both in kinematic [10,11] and dynamic level [12,13]. With this formulation for instance it is possible to control the behavior of several interaction points on the body of the robot, if the contact points are known a priori.

The Cartesian impedance control for torque controlled lightweight robots was investigated in [6]. Later in [14], the impedance control problem accompanied with the null-space stiffness implementation for DLR 7DOF flexible joint arm, based on singular perturbation approach, was addressed.

Multi-priority Cartesian impedance control has been investigated in [15], where several impedances in the Cartesian space are realized with a specified order of priority. Recently in [16] the multi-priority control has been considered for a case where the second priority joint space impedance operates in the null-space of the first priority Cartesian impedance of the end effector.

In [3,17] an efficient method was presented that enables fast collision detection and safe reaction based on generalized momentum of the robot, without using any torque sensor. Later in [18], safety issues were considered and several reaction strategies were presented and validated by experiments. Also 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 [19].

The problem of force sensor-less disturbance rejection was investigated in [20] for robot manipulators. A force estimator is used to compensate external force disturbance that is applied on the end effector. The method later has been extended to the case where parametric uncertainties also exist despite the unknown external disturbance on the end effector [21].

Null-space impedance as a result of multi-priority control in acceleration level was presented in [13]. The approach was motivated by the idea of having control over the interaction of the robot body with the environment in the joint space in spite of the task space control by exploiting

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robot redundancy. It was shown that if the estimation of the external torque applied to the robot is available, both the main task and the null-space impedance are perfectly realized. However, when the external torque information is not available, any external force applied to the body of the robot affects the main task (end effector task) while the null-space impedance yet can be realized under some circumstances.

This paper pursues the idea of exploiting kinematic redundancy for safe interaction of the robot body with the environment without using joint torque sensors. While the null-space impedance is realized in the null-space of the main task, the asymptotic convergence of the main task tracking error is also ensured by introducing suitable observer on the task space. 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 operational task of the robot if active joint compliance is used to ensure safe interaction. Our approach allows to minimize the error in the task space while it ensures compliance in the null-space.

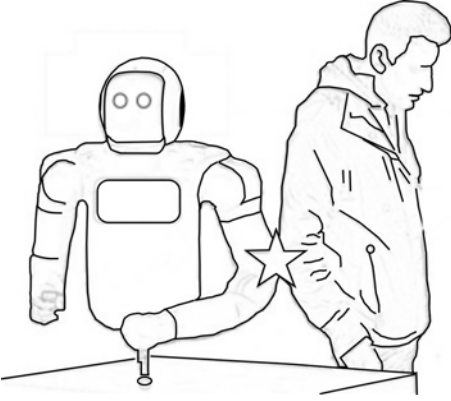


Fig 1. Robot in interaction with human environment

The paper is organized as follows; The joint impedance and null-space impedance concepts are reviewed in Section II. The main results of the paper including the disturbance observer are proposed in Section III. In Section IV the performance of the proposed scheme is evaluated by some simulations. The paper is concluded in section V.

II. PROBLEM STATEMENTS

A. System Description

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

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

where $\mathbf{q} \in \mathbb{R}^n$ is the vector of joint variables, $\mathbf{M}(\mathbf{q})$ is the inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}}$ contains Coriolis/centrifugal terms and $\mathbf{g}(\mathbf{q})$ is the vector of gravitational torque. In (1), $\boldsymbol{\tau}$ is the input torque while $\boldsymbol{\tau}_{ext}$ 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, this external torque can be directly measured or estimated.

B. Joint Impedance Control

Impedance control is one of the most efficient methods of controlling the interaction between a manipulator and the environment. While the task space impedance control regulates the mechanical impedance of the robot at the end effector [22], the joint space impedance control imposes a compliant behavior to the robot joints. Namely, the controller tries to realize the following closed-loop equation in the joint space

$$\mathbf{M}_d(\ddot{\mathbf{q}}_d - \ddot{\mathbf{q}}) + \mathbf{B}_d(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_d(\mathbf{q}_d - \mathbf{q}) = \boldsymbol{\tau}_{ext}, \quad (2)$$

where $\mathbf{M}_d$, $\mathbf{B}_d$ and $\mathbf{K}_d$ are respectively the inertia, damping and stiffness matrices and $\mathbf{q}_d$ is the rest position or desired trajectory. Notice that the joint space impedance control can be used for both redundant and non-redundant manipulators, since it is realized in the joint space. To implement the above algorithm, usually a measure of external torque is required. Attempts to build and integrate high precision torque sensors in robot joints have been performed for example for iCub robot [23] or in [7]. Alternatively, suitable algorithms aimed at estimating the external torque without using torque sensor can be adopted [18].

C. Null-space Impedance Control

For a redundant manipulator, redundancy lets us to have some kind of joint impedance and traditional task space impedance simultaneously. Actually the so-called null-space impedance can be realized in the joint space despite the main task mission. This impedance is performed in the null-space of the main task and has been proposed as a result of multi-priority redundancy resolution [13]. Using this approach it is possible to control the interaction both at the end effector and on the robot body. For the null-space impedance control, the command joint acceleration $\ddot{\mathbf{q}}_c$ is given by

$$\ddot{\mathbf{q}}_c = \mathbf{J}^\dagger(\ddot{\mathbf{x}}_c - \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{N}[\ddot{\mathbf{q}}_d + \mathbf{M}_d^{-1}(\mathbf{B}_d\dot{\mathbf{q}} + \mathbf{K}_d\tilde{\mathbf{q}} - \boldsymbol{\tau}_{ext})]. \quad (3)$$

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 configuration in the joint space, $\mathbf{J}(\mathbf{q})$ is the Jacobian matrix, $\mathbf{N} = (\mathbf{I} - \mathbf{J}^\dagger\mathbf{J})$ is the null-space projection matrix, and $\mathbf{M}_d$, $\mathbf{B}_d$ and $\mathbf{K}_d$ are the impedance matrices. Once the joint command acceleration $\ddot{\mathbf{q}}_c$ is given, for instance, a model-based resolved acceleration control can be used to compute the driving torques

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}_c + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{ext}, \quad (4)$$

which ends to the task space and null-space closed-loop behavior as follows

$$\begin{aligned} \ddot{\mathbf{x}} &= \ddot{\mathbf{x}}_c, \\ \mathbf{N}[\ddot{\mathbf{q}} + \mathbf{M}_d^{-1}(\mathbf{B}_d\dot{\mathbf{q}} + \mathbf{K}_d\tilde{\mathbf{q}}) - \mathbf{M}_d^{-1}\boldsymbol{\tau}_{ext}] &= \mathbf{0}. \end{aligned} \quad (5)$$

Thus, the joint space impedance is realized in the null-space of the main task space. By a proper choice of the null-space impedance matrices, it is possible to achieve a desired compliant behavior for the system.

Equation (5) was obtained for the case where the external torque acting on the manipulator is directly measured or estimated. When the external torque information is not available, the closed-loop behavior is obtained as

$$\begin{aligned} \ddot{\mathbf{x}}_c - \ddot{\mathbf{x}} &= \mathbf{J} \mathbf{M}^{-1} \boldsymbol{\tau}_{ext} \\ \mathbf{N} [\ddot{\mathbf{q}} + \mathbf{M}_d^{-1} (\mathbf{B}_d \dot{\mathbf{q}} + \mathbf{K}_d \tilde{\mathbf{q}}) - \mathbf{M}^{-1} \boldsymbol{\tau}_{ext}] &= \mathbf{0}. \end{aligned} \quad (6)$$

Note that by using the dynamically consistent generalized inverse $\mathbf{J}^\# = \mathbf{M}^{-1} \mathbf{J}^T (\mathbf{J} \mathbf{M}^{-1} \mathbf{J}^T)^{-1}$ in the above formulation and choosing $\mathbf{M}_d = \mathbf{M}$, the following equation for the null-space can be derived

$$\mathbf{N}_\#^T [\mathbf{M} \ddot{\mathbf{q}} + \mathbf{B}_d \dot{\mathbf{q}} + \mathbf{K}_d \tilde{\mathbf{q}} - \boldsymbol{\tau}_{ext}] = \mathbf{0}, \quad (7)$$

where the equality $\mathbf{M} \mathbf{N}_\# = \mathbf{N}_\#^T \mathbf{M}$ with $\mathbf{N}_\# = (\mathbf{I} - \mathbf{J}^\# \mathbf{J})$, has been used.

Hence, a desired impedance can be still achieved in the null-space, but in view of (6), the external torque also affects the operational task.

III. DISTURBANCE OBSERVER

In order to develop our method, we need to project the joint space dynamics (1) into the task space, by multiplying both sides of (1) by the transpose of the dynamically consistent generalized inverse, $\mathbf{J}^{\#T} = \mathbf{A} \mathbf{J} \mathbf{M}^{-1}$. This produces

$$\mathbf{A}(\ddot{\mathbf{x}} - \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{A} \mathbf{J} \mathbf{M}^{-1} [\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q})] + \mathbf{F}_{ext} = \mathbf{F}, \quad (8)$$

where $\mathbf{A} = (\mathbf{J} \mathbf{M}^{-1} \mathbf{J}^T)^{-1}$ is the task inertia matrix and $\mathbf{F}_{ext} = \mathbf{J}^{\#T} \boldsymbol{\tau}_{ext}$ is the equivalent end effector force corresponding to the external torque applied to the robot body. Using (8), the following theorem can be established.

Theorem: Let us denote with $\hat{\boldsymbol{\tau}}$ the estimated external torque and with $\tilde{\boldsymbol{\tau}} = \boldsymbol{\tau}_{ext} - \hat{\boldsymbol{\tau}}$ 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, under assumption of constant unknown external torque (or slowly time-varying one, such that, $\dot{\tilde{\boldsymbol{\tau}}} \approx \dot{\hat{\boldsymbol{\tau}}}$), for selected constant diagonal positive definite matrix $\mathbf{K}$ and constant positive definite matrix $\boldsymbol{\Gamma}_f$, the control law

$$\begin{aligned} \boldsymbol{\tau} &= \mathbf{J}^T \mathbf{A}(\ddot{\mathbf{x}}_d + \mathbf{P} \dot{\tilde{\mathbf{x}}} - \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{J}^T (\frac{1}{2} \dot{\mathbf{A}} + \mathbf{K}) \mathbf{s} + \mathbf{J}^T \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}} \\ &+ \mathbf{M} \mathbf{N}_\# [\ddot{\mathbf{q}}_d + \mathbf{M}_d^{-1} (\mathbf{B}_d \dot{\mathbf{q}} + \mathbf{K}_d \tilde{\mathbf{q}})] + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}), \end{aligned} \quad (9)$$

with the disturbance observer

$$\dot{\tilde{\boldsymbol{\tau}}} = -\boldsymbol{\Gamma}_f^{-T} \mathbf{J}^\# \mathbf{s}, \quad (10)$$

guarantees that the $\tilde{\mathbf{x}}$ and $\dot{\tilde{\mathbf{x}}}$ go to zero asymptotically while the null-space impedance behavior is imposed in the null-space of the main task. Moreover, the estimated external torques remain bounded and the closed-loop system is stable.

Proof: Applying the above control law to the system (1) we have

$$\begin{aligned} \ddot{\mathbf{q}} + \mathbf{M}^{-1} \boldsymbol{\tau}_{ext} &= \mathbf{M}^{-1} \mathbf{J}^T \mathbf{A}(\ddot{\mathbf{x}}_d + \mathbf{P} \dot{\tilde{\mathbf{x}}} - \dot{\mathbf{J}}\dot{\mathbf{q}}) \\ &+ \mathbf{M}^{-1} \mathbf{J}^T (\frac{1}{2} \dot{\mathbf{A}} + \mathbf{K}) \mathbf{s} + \mathbf{M}^{-1} \mathbf{J}^T \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}} \\ &+ \mathbf{N}_\# [\ddot{\mathbf{q}}_d + \mathbf{M}_d^{-1} (\mathbf{B}_d \dot{\mathbf{q}} + \mathbf{K}_d \tilde{\mathbf{q}})]. \end{aligned} \quad (11)$$

By multiplying both sides of the above equation by $\mathbf{A} \mathbf{J}$

$$\begin{aligned} \mathbf{A} \mathbf{J} \ddot{\mathbf{q}} + \mathbf{A} \mathbf{J} \mathbf{M}^{-1} \boldsymbol{\tau}_{ext} &= \mathbf{A}(\ddot{\mathbf{x}}_d + \mathbf{P} \dot{\tilde{\mathbf{x}}} - \dot{\mathbf{J}}\dot{\mathbf{q}}) \\ &+ (\frac{1}{2} \dot{\mathbf{A}} + \mathbf{K}) \mathbf{s} + \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}}, \end{aligned} \quad (12)$$

and substituting for $\ddot{\mathbf{x}} = \mathbf{J} \ddot{\mathbf{q}} + \dot{\mathbf{J}}\dot{\mathbf{q}}$ and $\dot{\mathbf{s}} = \dot{\tilde{\mathbf{x}}} + \mathbf{P} \dot{\tilde{\mathbf{x}}}$, the closed-loop behavior of the robot in the task space is given by

$$\begin{aligned} \mathbf{J}^{\#T} \tilde{\boldsymbol{\tau}} &= \tilde{\mathbf{F}} = \mathbf{A} \dot{\mathbf{s}} + (\frac{1}{2} \dot{\mathbf{A}} + \mathbf{K}) \mathbf{s}, \\ \tilde{\mathbf{F}} &= \mathbf{F}_{ext} - \hat{\mathbf{F}}. \end{aligned} \quad (13)$$

where $\hat{\mathbf{F}} = \mathbf{J}^{\#T} \hat{\boldsymbol{\tau}}$ is the estimation of $\mathbf{F}_{ext}$. Also, the closed-loop dynamics for the null-space is obtained by multiplying both sides of (11) by $\mathbf{N}_\#$,

$$\mathbf{N}_\# [\ddot{\mathbf{q}} + \mathbf{M}_d^{-1} (\mathbf{B}_d \dot{\mathbf{q}} + \mathbf{K}_d \tilde{\mathbf{q}}) - \mathbf{M}^{-1} \boldsymbol{\tau}_{ext}] = \mathbf{0}. \quad (14)$$

It can be seen that this behavior is the same as the null-space closed-loop in (6), thanks to the use of dynamically consistent generalized inverse that decouples the end effector dynamics from the null-space dynamics.

Let us define a lower bounded, nonnegative function as

$$V = \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \tilde{\mathbf{x}} + \frac{1}{2} \mathbf{s}^T \mathbf{A} \mathbf{s} + \frac{1}{2} \tilde{\boldsymbol{\tau}}^T \boldsymbol{\Gamma}_f \tilde{\boldsymbol{\tau}}. \quad (15)$$

The time derivative of (15) along the system trajectories is

$$\dot{V} = 2 \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \dot{\tilde{\mathbf{x}}} + \mathbf{s}^T \mathbf{A} \dot{\mathbf{s}} + \frac{1}{2} \mathbf{s}^T \dot{\mathbf{A}} \mathbf{s} + \tilde{\boldsymbol{\tau}}^T \boldsymbol{\Gamma}_f \dot{\tilde{\boldsymbol{\tau}}}. \quad (16)$$

Using (13), (10) yields

$$\begin{aligned} \dot{V} &= 2 \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \dot{\tilde{\mathbf{x}}} + \mathbf{s}^T (\mathbf{J}^{\#T} \tilde{\boldsymbol{\tau}} - (\frac{1}{2} \dot{\mathbf{A}} + \mathbf{K}) \mathbf{s}) \\ &+ \frac{1}{2} \mathbf{s}^T \dot{\mathbf{A}} \mathbf{s} - \mathbf{s}^T \mathbf{J}^{\#T} \tilde{\boldsymbol{\tau}}, \end{aligned} \quad (17)$$

which further gives

$$\dot{V} = 2 \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \dot{\tilde{\mathbf{x}}} - \mathbf{s}^T \mathbf{K} \mathbf{s}. \quad (18)$$

Finally, by replacing $\mathbf{s} = \dot{\tilde{\mathbf{x}}} + \mathbf{P} \tilde{\mathbf{x}}$ in (18), we obtain

$$\dot{V} = -\dot{\tilde{\mathbf{x}}}^T \mathbf{K} \tilde{\mathbf{x}} - \tilde{\mathbf{x}}^T \mathbf{P}^T \mathbf{K} \mathbf{P} \tilde{\mathbf{x}} \leq 0. \quad (19)$$

Equations (15) and (19) imply that $\tilde{\mathbf{x}}$, $\mathbf{s}$ and $\tilde{\boldsymbol{\tau}}$ are bounded. The Barbalat's lemma can be used to show the convergence of the signals. It is easy to see that $\dot{V}$ is given by

$$\ddot{V} = -2 \dot{\tilde{\mathbf{x}}}^T \mathbf{K} \dot{\tilde{\mathbf{x}}} + 2 \dot{\tilde{\mathbf{x}}}^T \mathbf{K} \mathbf{P} \dot{\tilde{\mathbf{x}}} - 2 \dot{\tilde{\mathbf{x}}}^T \mathbf{P}^T \mathbf{K} \mathbf{P} \dot{\tilde{\mathbf{x}}}. \quad (20)$$

From the closed-loop dynamics, it can be deduced that $\dot{\tilde{\mathbf{x}}}$ and $\tilde{\mathbf{x}}$ are also bounded (as we will show in the following). Thus, $\ddot{V}$ remains bounded and Barbalat's lemma indicates that $\dot{V} \rightarrow 0$ and consequently $\tilde{\mathbf{x}}, \mathbf{s} \rightarrow 0$ as $t \rightarrow \infty$.

We only have to show that $\dot{\tilde{\mathbf{x}}}$ and $\dot{\mathbf{s}}$ are bounded. Given the expression $\mathbf{s} = \dot{\tilde{\mathbf{x}}} + \mathbf{P} \tilde{\mathbf{x}}$, this implies that $\dot{\tilde{\mathbf{x}}}$ is bounded for

bounded signal $\tilde{x}$ and s . Also notice that the impedance behavior (14) ensures the boundedness of internal motion of the redundant system and thus $\dot{q}$ is bounded because of the boundedness of x and the desired trajectory. Finally closed-loop dynamic equation (13) shows that (assuming no singularity and by positive semi-definiteness of A which implies that A^{-1} exists and is bounded) $\dot{s}$ is bounded.

Remark 1: The controller (9) can be written in a useful form as

$$\begin{aligned} \tau = & J^T A(\ddot{x}_d + P\dot{x} - \dot{J}\dot{q}) + J^T(\mu + K)s + J^T J^{*T} \tilde{\tau} \\ & + MN_{\#}[\ddot{q}_d + M_d^{-1}(B_d\dot{q} + K_d\tilde{q})] + C(q, \dot{q})\dot{q} + g(q), \end{aligned} \quad (21)$$

where μ is chosen in such a way that $\dot{A} - 2\mu$ is skew-symmetric. It can be shown that the above theorem still holds.

Remark 2: Equation (14) gives (7), when $M_d = M$.

Remark 3: While the force estimation error $\tilde{F} = J^{*T} \tilde{\tau}$ goes to zero, the torque estimation error $\tilde{\tau}$ converges to zero only for the non-redundant robots.

IV. SIMULATION

The proposed approach for a scenario depicted in Fig. 1 is verified in simulation on a 7 DOF KUKA lightweight arm, neglecting the presence of joint elasticity and dissipative effects. The simulation is performed for two cases. In both cases the position trajectory of the end effector is assumed as the main task. By this choice the robot has 4 degrees of redundancy. The end effector orientation and a constant desired joint configuration is considered as the desired task for the null-space. To this end, based on second-order inverse kinematic algorithm, the joint space desired trajectory is computed and is fed as the desired trajectory for the null-space impedance.

Case I - Interaction control without disturbance observer: The end effector task is selected as a linear position trajectory from x_i to x_f with constant rotation matrix R_i

$$\begin{aligned} x_i &= [0, -0.39, 0.61]^T, \\ x_f &= [0.085, -0.085, 0.597]^T, \\ R_i &= \begin{pmatrix} -0.866 & -0.5 & 0 \\ 0.5 & -0.866 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \end{aligned} \quad (22)$$

In the first simulation, the resolved acceleration controller (4) with the command acceleration given by (3), without external torque information, is used. It is assumed that a constant external torque $\tau_{ext} = [-10, -10, -5, 5, 0, 0, 0]^T$ is applied to the joints during the interval $t \in [3, 10]$ s. The position tracking errors are depicted in Fig. 2.

The proportional and derivative gains for the main task are chosen as $K_p = 50I$, $K_d = 15I$, while the null-space impedance matrices are chosen as $M_d = M$, $B_d = 7I$, $K_d = 9I$.

From the simulation results, it can be realized that during the time interval that there is no external torque, the controller

guarantees that the initial errors go to zero. However, when the external torque is applied, the manipulator body complies as expected but the main task undergoes errors.

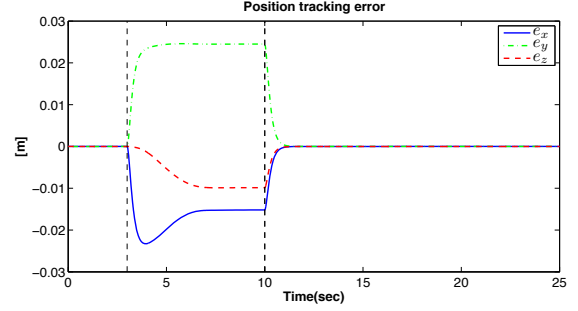


Fig 2. Position errors when a constant external torque is applied to the arm without disturbance observer

The second simulation considers the contact of the manipulator with an obstacle (human) during its maneuver. The interaction is modeled based on elastic contact between a moving obstacle with the stiffness of 1000 N/m and the fourth joint of the robot arm. The control gains and the trajectories are the same as the first simulation. The corresponding position errors are shown in Fig. 3. Having hit to the obstacle, the task error is not null anymore as expected.

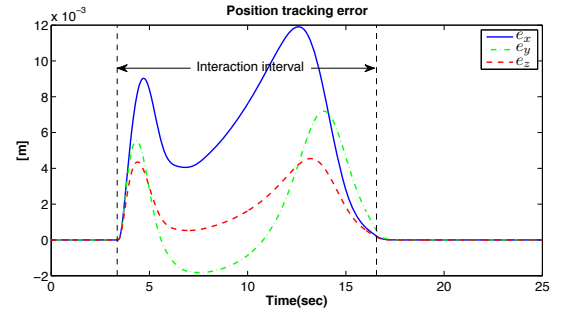


Fig 3. Task errors during contact with an elastic obstacle without disturbance observer

Case II - Interaction control with disturbance observer: In the next two simulations the proposed controller (9) with the disturbance observer (10) is used to minimize the task space error while realizing the proper impedance law in the null-space. These two simulations, illustrated in Fig. 4 and Fig. 5, are the counterparts of the Fig. 2 and Fig. 3.

The parameters of the controller are chosen as $P = 15I$, $K = 50I$, $\Gamma_f = 0.025I$, while the impedance gains are same as before.

Fig. 4 shows the position errors (task errors), orientation errors (based on unit quaternion extracted from mutual rotation matrix) and joint torques, for the case where a constant external torque is applied to the manipulator body. It can be seen that after applying the external torque, the proposed controller keeps the task errors bounded and pushes them to zero.

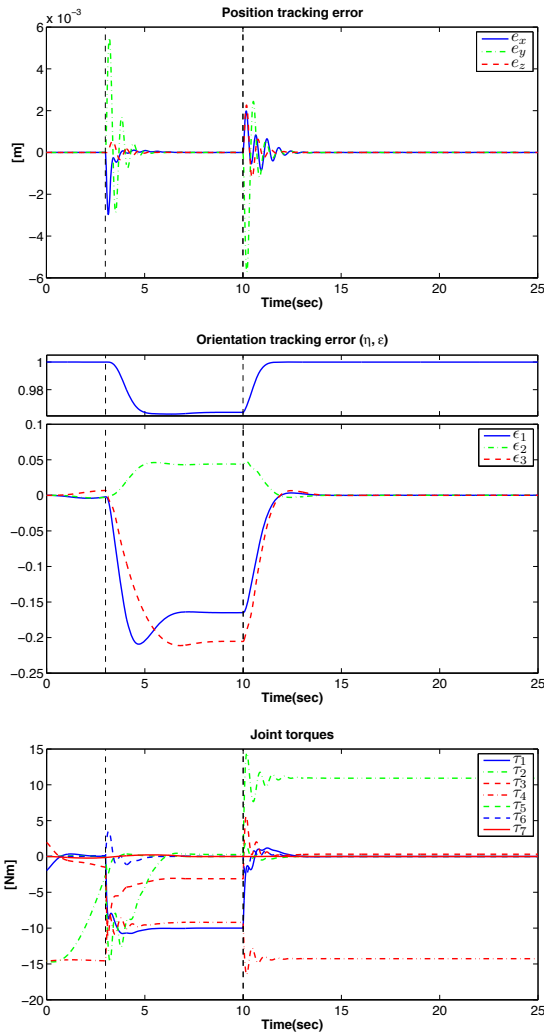


Fig 4. Position errors, orientation errors and joint torques when a constant external torque is applied to the arm with disturbance observer

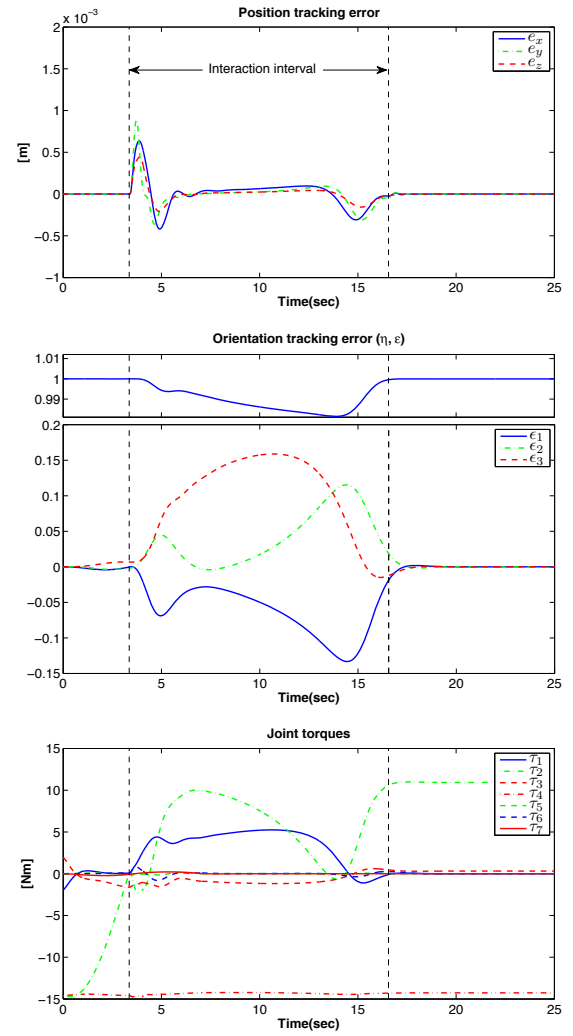


Fig 5. Position errors, orientation errors and joint torques during contact with moving elastic obstacle with disturbance observer

In Fig. 5 the performance of the controller is analyzed for the case where the body of the robot experiences an elastic contact with moving obstacle. Although the external torque τ_{ext} is not constant during the contact, the controller performs very well and minimizes the main task error during the contact while the control torque remains bounded. It is worth to remark that the estimated external torque does not necessarily converge to the actual value as remarked previously.

Notice that during interaction, the orientation of the manipulator experiences errors since it is performed in the lower priority level as the desired trajectory for the null-space impedance. Furthermore, by this algorithm the robot does not leave the collision area but it has a physical interaction with obstacle. As soon as the obstacle leaves the robot's working area, the orientation errors go to zero and the arm comes back to its desired configuration.

The video clip of the above analysis for the case of interaction with elastic obstacle is shown in attachment. The snapshot of the system is depicted in Fig. 6.

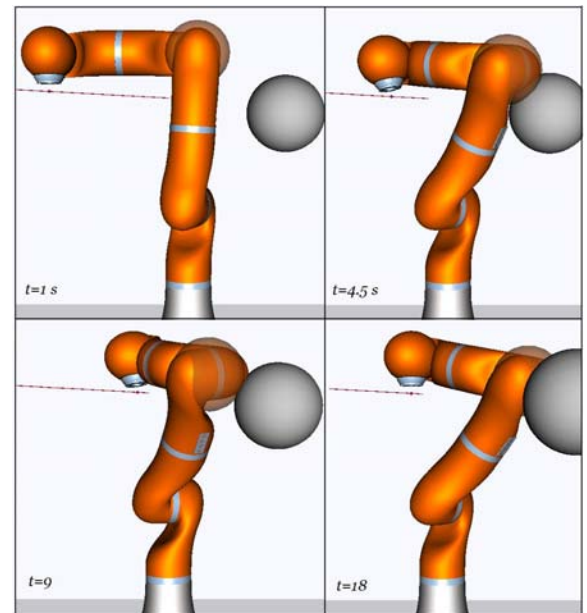


Fig 6. Snapshots of the system during contact with moving elastic obstacle

V. CONCLUSION

A nonlinear control algorithm with the ability to ensure the task space tracking error convergence, besides proper impedance behavior in the null-space was developed. The controller does not need torque sensors and can be used for the case where the redundant robot, for instance, works in the presence of the humans and interaction (intentionally or accidentally) may occur. In this condition, the redundancy of the system is exploited for safe physical interaction beside correct task execution. The simulation results confirm the effectiveness of the proposed approach.

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