

Experimental Study on Task Space Control during Physical Human Robot Interaction

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Abstract—In this paper new approaches for task space control during null space compliance control of a kinematically redundant robot are studied. The approaches are useful for the case where the robot experiences an external interaction on its body, especially in the human environments. The proposed algorithms guarantee safe reaction of the robot during intentional or accidental interaction by exploiting robot's redundancy through null space impedance control. The algorithms do not require joint torque measurements. The performances of the proposed controllers are verified through a variety of experiments on 7R KUKA lightweight robot arm.

Index Terms—Task space control, Human Robot Interaction, Interaction Observer, Null space impedance.

I. INTRODUCTION

THE emerging application of the robots in anthropic environments is growing rapidly. When a robot is supposed to be employed near human, it must be designed with high degree of compliance to ensure safety of any interaction. This compliance is useful for the applications including physical Human-Robot Interaction (pHRI) [1], such as service and medical robotics. In these applications, not only unexpected impacts of robot with humans are likely to happen, but also intentional physical interaction with robot maybe required. To this end, different strategies are possible. The safest approach is to avoid any unwanted Collision. However, it is usually based on exteroceptive sensors such as camera which makes it inappropriate during fast interaction. On the other hand, it is possible to cover the manipulator with a sensitive skin capable of measuring the interaction forces. Alternatively, these forces can be estimated from joint positions or torques by means of suitable observers for fast collision detection and reaction algorithms [2]. In any case the robot compliance must be increased. Compliance can be introduced passively by using elastic decoupling between the actuator and the driven link (variable joint stiffness), or actively by relying on fast control loops [3], [4]. 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 [5], [6]. However, the impedance behavior can be also imposed in the joint space to ensure safe interaction [7]–[9].

Kinematic redundancy has been always one of the interesting topics for robotics community. One approach to deal with the redundant degrees is multi-priority control, that is a well-established framework [10]–[12]. 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. Null space impedance as a result of multi-priority control in acceleration level was presented in [10] and [11]. The approach is motivated by the need of having control over the interaction of the robot body with the environment in the joint space in spite of the task space control. It was shown that, in order to ensure impedance behavior as the secondary task without affecting the main task, the external forces acting on the main task variables must be suitably compensated by the controller. This is possible, e.g., if the external torques are measured or estimated [7], [13]. Notice that the correct execution of the robot's main task during the interaction, subordinated to safety, is also appealing and important.

In [14] a method was presented that enables fast collision detection and safe reaction based on generalized momentum of the robot, without using any torque sensor. 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 [15].

In this paper the problem of controlling a robot manipulator in the task space beside a compliant behavior for the redundant degrees of freedom in the joint space is considered. An example of application scenario is depicted in Fig. 1, where a robot working on a table experiences a contact with a human. The goal is to minimize the induced main task error beside safe interaction through active compliance in the null space of the main task. To this purpose, two control approaches which do not require direct joint torque measurements was proposed in [16], [17] by the authors. The first approach is based on a disturbance observer which estimates the external forces acting on the main task variables on the basis of the task space error. The second approach relies on the momentum of the system. In both cases, the overall stability of the system, with asymptotic convergence of the main task and a desired impedance behavior in the null space of the main task, was proven through a rigorous analysis. In the following, the formulation of momentum-based interaction observer is reintroduced and



Fig. 1. An example scenario: A redundant robot works close to a human and safety of interaction beside task execution is ensured

new stability proof for the task space dynamics is devised. Afterward, several experiments which were performed on a 7DOF KUKA LWR4 robot are reviewed and discussed.

II. PRELIMINARIES

A. System Description

The dynamic model of a n -link robot manipulator can be written as

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

where q is the $(n \times 1)$ joint vector, $M(q)$ is $(n \times n)$ inertia matrix, $C(q, \dot{q})\dot{q}$ is the $(n \times 1)$ vector of Coriolis and centrifugal torques, $g(q)$ is the $(n \times 1)$ vector of the gravitational torques. Furthermore, τ is the $(n \times 1)$ vector of control torques and τ_{ext} is the $(n \times 1)$ vector of external torques resulting from the interaction with the environment. If the manipulator is equipped with torque sensors in its joints or force sensors on the interaction points, these external torques can be directly measured.

B. Joint Space Impedance Control

Impedance control is one of the most adopted methods of controlling the interaction between a manipulator and the environment. While the cartesian or task space impedance control regulates the mechanical impedance of the robot end effector [18], the joint space impedance control imposes a compliant behavior to the robots joints. Namely, the controller tries to realize the following closed-loop equation in the joint space

$$M_d(\ddot{q}_d - \ddot{q}) + B_d(\dot{q}_d - \dot{q}) + K_d(q_d - q) = \tau_{ext}, \quad (2)$$

where $q_d(t)$ is a desired trajectory or simply a rest configuration, while M_d , B_d and K_d are $(n \times n)$ positive definite matrices, representing the desired inertia, damping and stiffness, respectively.

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 robots joints have been performed for example for iCub robot [19] or in [4]. Alternatively, suitable algorithms aimed at estimating

the external torque without using torque sensor can be adopted [14]. Note that, the joint space impedance control can be applied to both redundant and non-redundant manipulators. Moreover, It is clear that any interaction on the robot body will affect the task space.

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 [10], [12]. Using this approach it is possible to control the interaction both on the end effector and on the robot body.

In the case that the measure of the external torque τ_{ext} is available, a null space impedance behavior can be achieved by using the command joint acceleration

$$\ddot{q}_c = J^\dagger(\ddot{x}_c - \dot{J}\dot{q}) + N(\ddot{q}_d + M_d^{-1}(B_d\dot{q} + K_d\tilde{q} - \tau_{ext})), \quad (3)$$

where $\ddot{x}_c$ is the $(m \times 1)$ command acceleration in the task space and N is the null space projection matrix. Once the joint command acceleration is given, for instance, a model-based resolved acceleration control can be used to compute the driving torque

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

Applying above command acceleration, the following task space and null space closed-loop dynamics are derived

$$\ddot{x} = \ddot{x}_c, \quad (5)$$

$$N(\ddot{q} + M_d^{-1}(B_d\dot{q} + K_d\tilde{q} - \tau_{ext})) = 0. \quad (6)$$

By a proper choice of the null space impedance matrices, it is possible to achieve a desired compliant behavior for the robot body, without affecting the task space dynamics. Equation (6) 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

$$\ddot{x} = \ddot{x}_c - JM^{-1}\tau_{ext} \quad (7)$$

$$N(\ddot{q} + M_d^{-1}(B_d\dot{q} + K_d\tilde{q}) - M^{-1}\tau_{ext}) = 0. \quad (8)$$

in place of (5) and (6). Hence, a desired Compliance can be still achieved in the null space, but in view of (7), the external torque affects also the main task.

An important role in the null space dynamics (8) is played by the dynamically consistent generalized inverse [20]:

$$J^\#(q) = M^{-1}J^T(JM^{-1}J^T)^{-1}. \quad (9)$$

In detail, by using $J^\#$ and the corresponding null space projector $N_\# = I - J^\#J$ in the command acceleration (3) (with $M_d = M$ and $\tau_{ext} = 0$), the following equation is achieved in place of (8)

$$N_\#(\ddot{q} + M^{-1}(B_d\dot{q} + K_d\tilde{q} - \tau_{ext})) = 0. \quad (10)$$

If the external interaction happens only at the end effector, i.e., $\tau_{ext} = \mathbf{J}^T \mathbf{F}_{ext}$, the null space closed loop dynamics (8) is not affected by these forces, being $\mathbf{N}_\# \mathbf{M}^{-1} \mathbf{J}^T \mathbf{F}_{ext} = \mathbf{0}$. This is not true when a generic generalized inverse is used.

Equation (10) represents the impedance behavior projected in the null space, with dimension $r = n - m$, through n equations that, therefore, are not all independent. This problem can be overcome by considering a $(n \times r)$ matrix $\mathbf{Z}(\mathbf{q})$, such that $\mathbf{J}\mathbf{Z} = \mathbf{0}$, and introducing a $(r \times 1)$ velocity vector $\boldsymbol{\nu}$, such that

$$\dot{\mathbf{q}}_n = \mathbf{N}\dot{\mathbf{q}} = \mathbf{Z}\boldsymbol{\nu}. \quad (11)$$

In this way it is possible to reformulate the null space behavior using r independent equation As shown in [17].

D. Task Space Control

In view of the task space dynamics (7), it is clear that any interaction on the body of the manipulator may produce deviations from the desired task, depending on the choice of the command acceleration. To track a desired trajectory $\mathbf{x}_d(t)$, a common choice is that usually denoted as task space resolved acceleration control [21]

$$\ddot{\mathbf{x}}_c = \ddot{\mathbf{x}}_d + \mathbf{K}_v \dot{\tilde{\mathbf{x}}} + \mathbf{K}_p \tilde{\mathbf{x}}, \quad (12)$$

with $\tilde{\mathbf{x}} = \mathbf{x}_d - \mathbf{x}$ and positive definite matrices $\mathbf{K}_v$ and $\mathbf{K}_p$, which produces a linear closed-loop dynamics in the absence of interaction.

Another choice is that known as task space passivity-based control, namely

$$\ddot{\mathbf{x}}_c = \ddot{\mathbf{x}}_d + \mathbf{P}\dot{\tilde{\mathbf{x}}} + \boldsymbol{\Lambda}_x^{-1}(\boldsymbol{\mu}_x + \mathbf{K})\mathbf{s}, \quad (13)$$

where $\boldsymbol{\Lambda}_x$ and $\boldsymbol{\mu}_x$ are respectively the inertia matrix and the Coriolis/centrifugal matrix in task space (see [17]). In (13) $\mathbf{s} = \dot{\tilde{\mathbf{x}}} + \mathbf{P}\tilde{\mathbf{x}}$, and $\mathbf{P}$ and $\mathbf{K}$ are positive definite diagonal matrices. This control law preserves the passivity of the robot's dynamics.

A further choice is that known as task space PD+ control, i.e.,

$$\ddot{\mathbf{x}}_c = \ddot{\mathbf{x}}_d + \boldsymbol{\Lambda}_x^{-1}((\boldsymbol{\mu}_x + \mathbf{D})\dot{\tilde{\mathbf{x}}} + \mathbf{K}\tilde{\mathbf{x}}). \quad (14)$$

with symmetric positive definite matrices $\mathbf{K}$, $\mathbf{D}$. In this case, the closed-loop dynamics remains nonlinear as for passivity-based control.

It is worth remarking that the non compensated interaction torques in the task space dynamics (7) produce task space errors that could be reduced by using high gains in the command accelerations (12)–(14). However, a more effective solution is that of estimating and compensating the external torques acting on the task variables. To this aim, an external torque observer is proposed in the following section.

III. MOMENTUM BASED OBSERVER

In order to execute the assigned end effector task during any interaction on the robot body, an interaction observer is proposed here. An estimation of the external interaction is obtained by monitoring the momentum of the system [2], [14]. The basic concepts are the generalized momentum $\mathbf{p}(t) =$

$\mathbf{M}(\mathbf{q})\dot{\mathbf{q}}$ and the n -dimensional residual vector $\mathbf{r}$ which are defined as

$$\mathbf{r}(t) = \mathbf{K}_I \left[\mathbf{p}(t) - \int_0^t (\boldsymbol{\tau} + \mathbf{C}^T(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} - \mathbf{g}(\mathbf{q}) + \mathbf{r}(\sigma)) d\sigma \right], \quad (15)$$

with $\mathbf{r}(0) = \mathbf{0}$, $\mathbf{K}_I$ a diagonal positive matrix and $\mathbf{p}(0) = \mathbf{0}$. These quantities can be computed using measured signal $\mathbf{q}$, $\dot{\mathbf{q}}$ and the commanded torque $\boldsymbol{\tau}$. It can be shown that the dynamics of $\mathbf{r}$ is

$$\dot{\mathbf{r}} = -\mathbf{K}_I \mathbf{r} - \mathbf{K}_I \boldsymbol{\tau}_{ext}. \quad (16)$$

Thus the residual vector is a filtered version of the real external torque, i.e.

$$\mathbf{r}(t) \approx -\boldsymbol{\tau}_{ext}. \quad (17)$$

In the absence of interaction, assuming no noise and unmodeled disturbances, $\mathbf{r}(t) = \mathbf{0}$. As soon as collision occurs, the components of $\mathbf{r}$ will raise exponentially and will reach the value of $-\boldsymbol{\tau}_{ext}$. Therefore, the idea is that of using the residual vector as an estimate of the external torque in the task space control law as detailed in Proposition 3.

Proposition: In the presence of constant (or slowly time-varying) unknown external torque, for positive definite matrices $\mathbf{K}_v$ and $\mathbf{K}_p$, the task space command acceleration

$$\ddot{\mathbf{x}}_c = \ddot{\mathbf{x}}_d + \mathbf{K}_v \dot{\tilde{\mathbf{x}}} + \mathbf{K}_p \tilde{\mathbf{x}} - \mathbf{J}\mathbf{M}^{-1}\mathbf{r}, \quad (18)$$

together with residual dynamics (15), guarantees that $\tilde{\mathbf{x}}$, $\dot{\tilde{\mathbf{x}}}$ and estimation error $\tilde{\mathbf{r}} = \mathbf{r} + \boldsymbol{\tau}_{ext}$, go to zero asymptotically while a desired compliant behavior is imposed in the null space of the main task.

sketch of Proof: From (7) and (16) the closed-loop error dynamics is

$$\ddot{\tilde{\mathbf{x}}} + \mathbf{K}_v \dot{\tilde{\mathbf{x}}} + \mathbf{K}_p \tilde{\mathbf{x}} = \mathbf{J}\mathbf{M}^{-1}\tilde{\mathbf{r}}, \quad (19)$$

$$\dot{\tilde{\mathbf{r}}} + \mathbf{K}_I \tilde{\mathbf{r}} = \dot{\boldsymbol{\tau}}_{ext}. \quad (20)$$

The closed-loop dynamics for the null space is the same as in (10).

The stability analysis is based on a theorem from the stability analysis of the cascade systems (Theorem 3 in [22]). Using this theorem it can be shown that when $\dot{\boldsymbol{\tau}}_{ext}$ is bounded $\tilde{\mathbf{x}}$ is also bounded. Specifically when $\dot{\boldsymbol{\tau}}_{ext} = \mathbf{0}$ the system is asymptotically stable and $\mathbf{x}$ goes to zero.

For complete stability proof, [17] is referred. $\square$

Remark : Despite the task space command (18) is simple and intuitive, experimental tests show that the behavior of the controlled system in the task space is greatly dependent on the joint configuration and can also have large task space errors during fast interaction. The reason is that the residual torque error at the right-hand side of (19) is multiplied by the configuration dependent matrix $\boldsymbol{\Lambda}_x^{-1}$. An alternative control law can be adopted, by using the PD+ controller

$$\ddot{\mathbf{x}}_c = \boldsymbol{\Lambda}_x^{-1}(-(\boldsymbol{\mu}_x + \mathbf{D})\dot{\tilde{\mathbf{x}}} + \mathbf{K}\tilde{\mathbf{x}} + \mathbf{J}^{\#T}\mathbf{r}), \quad (21)$$

leading to the closed-loop equation

$$-\boldsymbol{\Lambda}_x \ddot{\tilde{\mathbf{x}}} - (\boldsymbol{\mu}_x + \mathbf{D})\dot{\tilde{\mathbf{x}}} + \mathbf{K}\tilde{\mathbf{x}} = \mathbf{J}^{\#T}\tilde{\mathbf{r}}, \quad (22)$$

which preserves the robot natural dynamics. The stability of the system can be shown by modifying the proof of Proposition 3 as in the proof of Proposition 2.

IV. EXPERIMENTAL EVALUATION; A REVIEW

The proposed approaches are verified Numerically and experimentally on a 7 DOF KUKA LWR4 lightweight arm ($n = 7$). Control algorithms are executed through Fast Research Interface (FRI) library [23] on a remote PC with Ubuntu operating system. The remote computer is connected to KUKA Robot Controller (KRC) unit through UDP socket with sampling rate of 2 ms.

The experiments are performed for two main categories: without observer, and with interaction observer. A variety of experiments including contact with human on the robot body and on the end effector, contact with wall, different choice of null space impedance matrices and different degrees of redundancy was implemented.

A. Experiment I:

The position of the end effector is assumed as the main task ($m = 3$). Therefore, the robot has 4 degrees of redundancy ($r = 4$). A constant configuration $\mathbf{q}_d = [\pi/4, -\pi/6, 0, -\pi/1.8, \pi/6, -\pi/4, 0]$ is considered, corresponding to the constant desired position of the end effector in the task space $\mathbf{x}_d = [-0.242, -0.133, 0.968]^T$. A human applies force on the whole robot body and the behavior of the robot is studied. The robot body complies with the applied forces and the end effector task error is minimized thanks to the external interaction observer. Different impedance matrices are chosen and verified. The snapshot of this experiments for a nonzero stiffness and zero stiffness are illustrated in Fig. 2 and Fig. 3 respectively. The experiment later on was performed considering position and orientation of the end effector as the main task ($m = 6$), and thus with one degree of redundancy. The results of this experiment is illustrated in accompanying video and in [24].

B. Experiment II:

In this experiment the interaction occurs through an elastic ball (resembling human) of 1200 N/m approximate stiffness at a point of the robot arm close to the fourth joint. In order to have a comparative study and guarantee repeatability, the ball is moved by a position controlled industrial robot with constant speed of 4.5 cm/s along a straight line. While the end effector of KUKA robot is commanded to be in the desired position, the elastic ball comes in contact with the robot, stops for 10 s and finally goes back far from the robot. A snapshot of the experimental setup is depicted in Fig. 4 and in accompanying video. A comparative results is reported in Appendix A. For complete results please see [17], [24].

C. Experiment III:

In the third set of experiments, the performance of the control algorithms are tested in a scenario in which the end effector of the robot follows a trajectory in the task space and

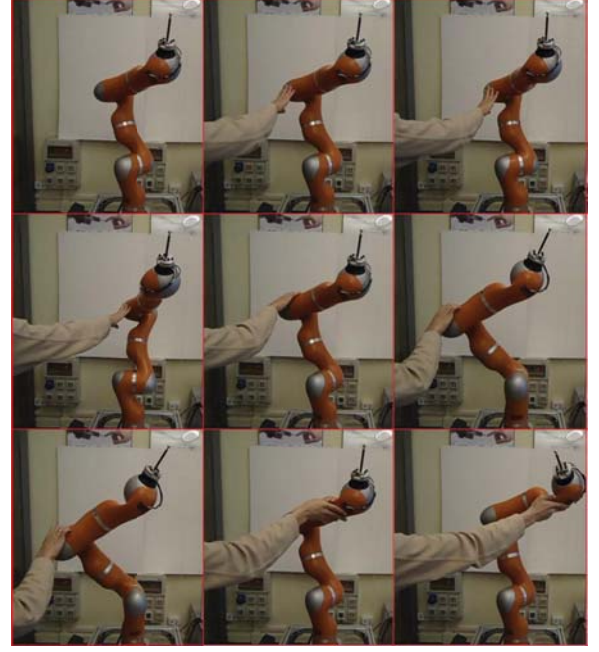


Fig. 2. Experiment I: human in interaction with a KUKA LWR4 arm



Fig. 3. Experiment I: Full compliance (zero stiffness).

the body of the robot experiences a contact with a vertical wall in a point close to the fourth joint, as depicted in Fig. 5 and accompanying video. Clearly, in this case, both task space control and safety during contact are required. To increase safety and protect the body of the robot from any damage during the experiment, the wall is covered with a soft pad.

The trajectory is a straight line motion from $\mathbf{x}_i$ to $\mathbf{x}_f$ and is planned according to a fifth order polynomial of time, with duration 10 s. Then the robot is kept in the final position for other 10 s. A constant configuration $\mathbf{q}_d$, consistent with the initial position $\mathbf{x}_i$, is considered as the desired goal in the null space. The vertical wall is located such that the contact with the wall starts around $t = 4.5$ s.

It can be seen that, the task space error in the the schemes with the observer, has been reduced considerably with respect to the control schemes without observer [17]. Moreover, the robot body complies after contact with the wall so that the external toques remain limited. As in the previous experiment, the time histories of joint external torques as well as those of the joint variables are very similar for different controllers, due to the fact that the null space impedance dynamics is the

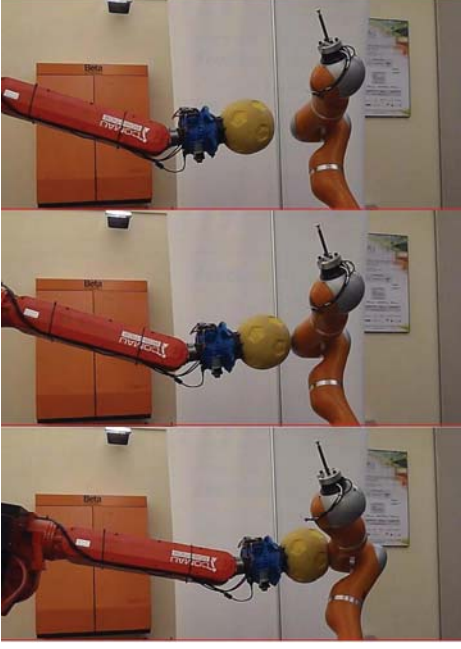


Fig. 4. Experiment II: Repetitive experimental setup



Fig. 5. Experiment III: Snapshot of the KUKA LWR4 robot in contact with a wall.

same for all the controllers.

V. CONCLUSION

A nonlinear controller-observer approach that ensure task space error convergence, besides proper compliant 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 for instance, in human environments and the interaction with the robot body can occur intentionally or accidentally. In these conditions the redundancy of the system is utilized to ensure safe and dependable physical interaction, while the main task is preserved. The proposed approach acts based on the generalized momentum of the system. A series of experiments on a torque controlled KUKA LWR4 robot were surveyed and the theoretical findings were confirmed.

APPENDIX A COMPARATIVE RESULTS OF EXPERIMENT II

The corresponding main task error and the estimated external torques obtained by the torque sensors available on LWR4 robot are shown in Fig. 6. The time interval of interaction is identified by two vertical lines. Note that the torque sensor

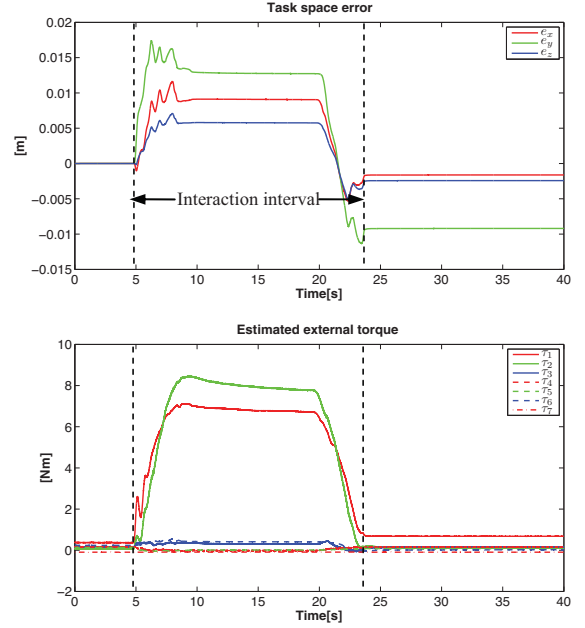


Fig. 6. Experiment II: Task errors and external torques estimation evaluated from torque sensors, without observer, using (12)

information is not used in the controller and here is reported to give an estimation of external applied torques. It can be observed that the task space error components are zero initially but, after the collision with the sphere, they increase and reach constant values when the sphere stops. When the sphere is retreated and contact is lost, the task error components become small but non-null, due to the presence of non negligible joint friction.

During the interaction, the configuration of the robot changes and the redundancy allows the manipulator to comply with the external forces. As soon as the contact is lost, the robot comes back to its desired configuration. The behavior of the arm in the null space can be set by properly choosing the impedance matrices.

The experiment is repeated using the momentum based observer. The results are depicted in Fig. 7. The time history of the residual vector $\mathbf{r}$ is reported in Fig. 8. It can be seen that the controller works very well during the constant phase of the interaction. However when the external torque is not constant, during the first and the third phase of the interaction, the task space error shows high frequency oscillations.

This behavior can be mitigated using the PD+ command acceleration (21) as suggested in Remark. The task space error for this case is reported in Fig. 9. It can be seen that the performance of the system, during the first and third phase of the interaction, is improved. The estimated external torque and the joint space trajectory do not change significantly and are not reported here for brevity.

ACKNOWLEDGMENT

The first author acknowledges the support given by the office of vice chancellor of the research and technology in

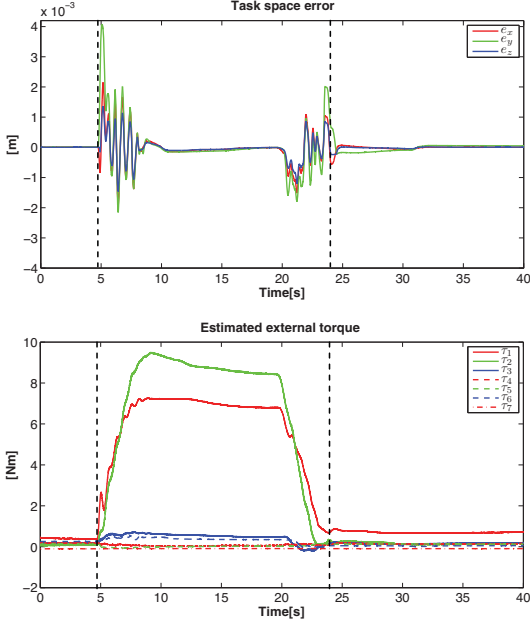


Fig. 7. Experiment II: Task errors and external torques estimation evaluated from torque sensors, using momentum based observer

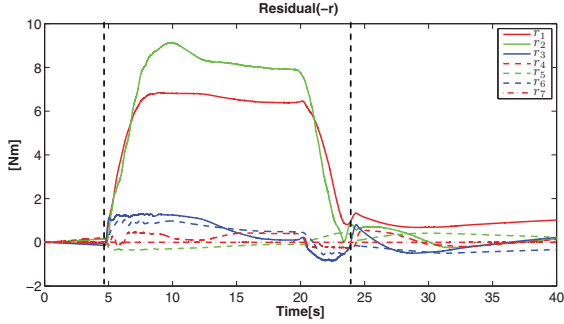


Fig. 8. Experiment II: Residual vector using momentum based observer with command acceleration (21)

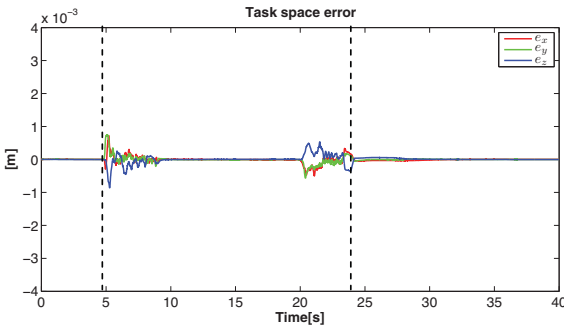


Fig. 9. Experiment II: Task errors using momentum based observer with command acceleration (21)

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University of Isfahan under research project number 930402. This work was also supported in part by the European Community within the FP7 ICT-287513 SAPHARI Project.