Safe Robot-Environment Interaction via Optimal Admittance

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***Resumen*— This paper proposes an optimal admittance controller for safe robot-environment interaction. The aim of the approach is to control the position of the robot end effector reactively according to force feedback. The sensors used are simple and provide only limited and immediate information, nonetheless they allow to reactively correct the applied force to guarantee safe robot-environment interaction. The method considers a dynamic optimization problem in the context of admittance control, which is solved via the standard gradient flow approach. As a remarkable feature, the solution of the optimization problem yields a free of dynamical robot model admittance controller. A stability proof is given while experimental results show the effectiveness of our approach.**
Key words: Admittance, Optimization, Interaction, Safety, Manipulator.

I. Introduction

Everyday human necessities are looking forward for robots to work cooperatively with humans as well as in some industrial applications, in order to improve life quality and manufacturing processes. To achieve this, the robot must interact physically in a safe manner with the environment, which is a challenging problem in robotics research. Therefore, researchers have developed mechanical devices (Van Ham et. al., 2009), planning algorithms (Sacks, 2003; Lefebvre et. al., 2005) and control schemes, (Natale, 1998), to successfully execute complex tasks in which robot-environment interaction force is present. We refer the reader to (De Schutter, 1997),(Zeng and Hemami, 1997) and (Lefebvre et. al., 2005) for a review of the literature in robot force control.

From the theoretical point of view, two well known approaches are distinguished to deal with robot-environment force control. In the first approach it is assumed that, during robot-environment interaction, a set of geometric constraints arise on the robot paths; this is known as constrained motion. The second approach is the impedance/admittance control, which can be viewed as unconstrained motion from the geometric point of view. Nonetheless, dynamic constraints are imposed on the robot-environment interaction. It is well known impedance/admittance equivalence, thus here we consider the admittance approach. The idea in the admittance control approach is to on-line modify the desired trajectory in order to achieve some desired force in some direction.

Despite of the success of the impedance/admittance approaches, most of the proposed solutions require *a priori* knowledge of robot and/or the environment dynamics, thus limiting further applications. Moreover, some factors as geometric uncertainty may lead to excessive forces, which possibly overcome safety by causing damage to the robot structure or the environment. Thus, adaptation schemes are chosen as an alternative solution to deal with uncertainty and to guarantee safe robot-environment interaction. Nevertheless, when adaptation approaches are considered most of the times direct force measurement is needed. These schemes are referred as direct or explicit methods (Colbaugh and Glass, 1997; Seraji and Colbaugh, 1997). Other methods used estimates of the parameters of the robot and/or the environment. Such methods are denominated indirect or implicit methods (Seraji, 1998; Jung et. al., 2001). The methods described above have been proved to be effective, nonetheless they require a considerable amount of computations.

In this paper, an optimal admittance controller is proposed to ensure safe robot-environment interaction. The novelty of the proposed algorithm is that the admittance controller is obtained as the solution of a dynamic optimization problem which is solved *via* the standard gradient flow. The optimization problem considers the force error tracking and its time derivative in order to minimize the maximum interaction force, which has been recently proposed as a safety measure (VanDamme et. al., 2010). It is important to highlight the simple structure of the proposed admittance controller, which is free of the dynamical model of the robot. A reference trajectory is computed very fast, giving as result fast adaptation of the robot end-effector trajectory to unexpected forces, which may arise during the robot environment-interaction. This reference trajectory generation results in safer interaction by avoiding excessive interaction forces. On the other side, it is well known that it is not advisable to use the force error time derivative, which is a highly noisy signal. However, the proposed approach allows to manage signals with noise, thanks to the filtering properties of the time integration as a consequence of the gradient flow approach, used in this work.

II. Mathematical models

The required mathematical models for the problem statement are presented below.

II-A. Kinematic Model

Consider a n-joint fully actuated rigid serial robot. Its joint variables are denoted by $\mathbf{q} \in \mathbb{R}^n$. In general terms, the direct kinematics relates the joint variables, $\mathbf{q}$, and the robot end-effector cartesian variables, $\mathbf{X} \in \mathbb{R}^m$. Thus, the direct kinematic model of the robot manipulator can be expressed as

$$\mathbf{X} = h(\mathbf{q}) \tag{1}$$

To fully relate the joint and cartesian spaces of the robot manipulator, it is required to establish a relation among robot joint velocities, $\dot{\mathbf{q}} \in \mathbb{R}^n$, and end-effector cartesian velocities, $\dot{\mathbf{X}} \in \mathbb{R}^m$. For this, we compute the robot Jacobian as follows

$$J(\mathbf{q}) = \frac{\partial h(\mathbf{q})}{\partial \mathbf{q}} \in \mathbb{R}^{m\times n} \tag{2}$$

Notice that redundant manipulators are considered when $n > m$.

II-B. Dynamic Model

Applying the Euler-Lagrange formalism, the joint space dynamic model of the robot manipulator is given by

$$M(\mathbf{q})\ddot{\mathbf{q}} + H(\mathbf{q}, \dot{\mathbf{q}}) = \tau + J^T(\mathbf{q})\mathbf{F} \tag{3}$$

where $M(\mathbf{q}) \in \mathbb{R}^{n\times n}$ is the symmetric, positive-definite inertia matrix, $H(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^n$, contains the nonlinear forces as Coriolis forces, gravity forces and the friction forces. The vector of input torques for the robot manipulator is $\tau \in \mathbb{R}^n$, and the vector $\mathbf{F} \in \mathbb{R}^m$ represents the robot-environment interaction forces.

II-C. Environment Force Model

Typically, the environment force model is represented as a simple linear spring. Hence the environment force is

$$\mathbf{F} = \mathbf{K}_e(\mathbf{X} - \mathbf{X}_e) \quad \text{if} \quad \mathbf{X} \geq \mathbf{X}_e \tag{4}$$

where $\mathbf{K}_e \in \mathbb{R}^{m\times m}$ is the equivalent stiffness of the environment and the force sensor mounted at the robot end effector. The vector $\mathbf{X}_e \in \mathbb{R}^m$, represents the position of the undeformed environment.

II-D. Impedance Model

The objective of the impedance control is to establish a dynamic relation or constraint between the end-effector position, $\mathbf{X}$, and the environment force $\mathbf{F}$. This relationship can be imposed by either impedance or admittance. In the impedance relationship, the robot reacts to deviations from the commanded end-effector trajectory by generating forces. Typically no force sensing is required for this. In the admittance relationship, the measured end-effector force is used to modify the robot end-effector trajectory in order to achieve a desired force. In this paper the admittance approach is considered, (De Schutter, 1997). When the robot is in closed loop with a suitable motion controller, the cartesian end-effector robot impedance (Seraji and Colbaugh, 1997), can be written as follows:

$$\mathbf{D}\ddot{\mathbf{X}} + \mathbf{B}\dot{\mathbf{X}} + \mathbf{K}(\mathbf{X} - \mathbf{X_r}) = \mathbf{E}(t) \tag{5}$$

where $\mathbf{D}$, $\mathbf{B}$ y $\mathbf{K}$ are, respectively, $m \times m$ diagonal mass, damping and stiffness matrices of the cartesian impedance of the robot. The diagonal structure of the matrices ensures that each cartesian D.O.F. is independent from each other. The vector $\mathbf{E}(t) = \mathbf{F_r} - \mathbf{F} \in \mathbb{R}^m$ stands for the force tracking error and the vector $\mathbf{F_r} \in \mathbb{R}^m$ represents the desired force, which is set to guarantee safe robot environment interaction. The vector $\mathbf{X_r} \in \mathbb{R}^m$ is the reference end-effector position, which will be sent as a command to the motion controller of the robot.

From equation (5), it can be shown that if $\mathbf{F_r}$ is constant, and if the reference position $\mathbf{X_r}$ is chosen such that $\mathbf{X_r} = \mathbf{X}_e + \mathbf{K}_e^{-1}\mathbf{F_r}$ it holds that

$$\text{lím}_{t\to\infty} \mathbf{E}(t) = 0 \tag{6}$$

thus, force tracking is achieved. However, in general, we are not able to accurately know *a priori* neither the position of the environment, $\mathbf{X}_e$, nor the equivalent stiffness, $\mathbf{K}_e$. Thus, situations which involve uncertainty, may lead to excessive forces which may cause damage the robot or the environment.

III. Problem statement

As stated above, safety of the robot-environment interaction can be violated by excessive forces. More over, if the environment is changing continuously, different or time varying values of the environment position, $\mathbf{X}_e$, and/or the environment stiffness, $\mathbf{K}_e$, can be considered. Thus the challenge is to *on-line* compute a proper reference trajectory $\mathbf{X_r}$ of the robot impedance behavior represented by equation (5). For this, an optimization problem is formulated in the next section.

Consider the impedance model of the robot (5), the problem is to design an optimal admittance controller, via trajectory shaping of $\mathbf{X_r}$ in equation (5), in order to perform safe robot-environment interaction by avoiding excessive interaction forces.

It is important to highlight that the admittance approach to robot force control is used, which can be viewed as unconstrained motion control. Thus, all control methods for unconstrained motion, such as model based control, sliding mode control and PID control, can be used.

III-A. Optimization Problem

The optimization problem considers a performance index $I \in \mathbb{R}$, related to the force error $\mathbf{E}(t)$, and its time derivative,

$\dot{\mathbf{E}}(t)$. Mathematically, this is a constrained optimization problem and it is written as follows

$$\begin{array}{ccc} \min\limits_{\mathbf{X_r}\in\mathbb{R}^m} & I = & \frac{1}{2}\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right]^T\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right] \\ \text{subject to:} & & \mathbf{D}\ddot{\mathbf{X}}+\mathbf{B}\dot{\mathbf{X}}+\mathbf{K}(\mathbf{X}-\mathbf{X_r})=\mathbf{E}(t) \end{array} \quad (7)$$

where, $\boldsymbol{\alpha} \in \mathbb{R}^{m\times m}$, is a diagonal matrix of gains which weights the time derivative of the force error. Notice that the performance index I in equation (7) is convex since $\nabla^2_{\mathbf{E(t)}} I \geq 0$. Moreover, straightforward computations show that the performance index I has a unique minimum at $\mathbf{E}(t) = \dot{\mathbf{E}}(t) = 0$, therefore the performance index I a strictly convex function.

III-B. Solution: optimal admittance controller

To deal with *on-line* solutions to optimization problems, there are few admissible approaches. In this paper, a dynamic optimization problem is on-line solved by using the *gradient flow* approach, see (Helmke, U., and J.B. Moore, 1996). The gradient flow approach suggests that the solution $\mathbf{X}^*_\mathbf{r}$ to the problem (7) is the solution to the following differential equation

$$\dot{\mathbf{X}}_\mathbf{r} = -\boldsymbol{\Gamma}\frac{\partial I}{\partial \mathbf{X_r}} \quad (8)$$

were, $\boldsymbol{\Gamma} \in \mathbb{R}^{m\times m}$, is a diagonal matrix of gains related to the convergence properties of the gradient flow.

Considering the diagonal structure of $\mathbf{D}$, $\mathbf{B}$ and $\mathbf{K}$ as equality constraint in problem (7), the vectors $\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right]^T = [(e_1+\alpha_1\dot{e_1}) \cdots (e_m+\alpha_m\dot{e_m})]$, and $\mathbf{X_r} = [X_{r_1} \cdots X_{r_m}]$ computation of, $\frac{\partial I}{\partial \mathbf{X_r}}$, in (8) yields

$$\frac{\partial I}{\partial \mathbf{X_r}} = \mathbf{K}\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right] \quad (9)$$

This shows that the reference trajectory is independently generated for each end-effector cartesian degree of freedom, i.e. position an orientation reference trajectories are decoupled. From equations (8) and (9), the reference trajectory is computed as follows

$$\mathbf{X_r} = -\boldsymbol{\Gamma}\mathbf{K}\int_0^t \left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right]dt \quad (10)$$

It is important to remark that the trajectory generation depends only on diagonal stiffness matrix, $\mathbf{K}$. Moreover, considering the constant diagonal stiffness matrix $\mathbf{K}$ is constant, then it can be compensated by the diagonal matrix of gains of the gradient flow approach, $\boldsymbol{\Gamma}$.

III-C. Stability

The stability of the proposed approach is addressed via Lyapunov arguments as follows. Consider the state vector $\boldsymbol{\xi} = [\mathbf{E}(t)\ \dot{\mathbf{E}}(t)]^T \in \mathbb{R}^{2m}$. Let the performance index given in equation (7) be a candidate Lyapunov function of the state vector, i.e.

$$V(\boldsymbol{\xi}) = \frac{1}{2}\left[\mathbf{E}(t)+\alpha\dot{\mathbf{E}}(t)\right]^T\left[\mathbf{E}(t)+\alpha\dot{\mathbf{E}}(t)\right] \quad (11)$$

The time derivative of equation (11) yields

$$\begin{aligned} \dot{V}(\boldsymbol{\xi}) &= \frac{\partial V(\boldsymbol{\xi})}{\partial \boldsymbol{\xi}}\frac{\partial \boldsymbol{\xi}}{\partial \mathbf{X_r}}\frac{d\mathbf{X_r}}{dt} \\ &= \left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right]^T \overbrace{[\mathbf{1}\quad \boldsymbol{\alpha}]}^{m\times 2m} \underbrace{\begin{bmatrix} -\mathbf{K} \\ 0^{m\times m}\end{bmatrix}}_{2m\times m}\dot{\mathbf{X}}_\mathbf{r} \end{aligned} \quad (12)$$

Substituting equations (8) and (9) in (12) results in equation (13).

$$\dot{V}(\boldsymbol{\xi}) = -\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right]^T\mathbf{K}\boldsymbol{\Gamma}\mathbf{K}\left[\mathbf{E}(t)+\boldsymbol{\alpha}\dot{\mathbf{E}}(t)\right] < 0 \quad (13)$$

Thus, due to the positive definiteness properties of the matrices $\boldsymbol{\Gamma}$ and $\mathbf{K}$ it is fulfilled that $\dot{V}(\boldsymbol{\xi}) \leq 0$. To conclude asymptotic stability of $\boldsymbol{\xi}$, it is necessary that $\dot{V}(\mathbf{0}) = 0$, which is evident from the definition for $\boldsymbol{\xi}$.

IV. Impedance control

The challenge is now to achieve the impedance behavior (5) on the robot manipulator, given its dynamical model, see equation (3). It is well known that a simple PD plus gravity compensation controller yields a stiffness behavior, (Chiaverini et. al., 1999). Nonetheless, an approach to achieve a desired impedance behavior using the standard decentralized PID motions controllers of industrial manipulators has been proposed in (Ferretti et. al., 2004). Thus, we propose to use a simple PID controller as a motion controller for the robot. The selected PID motion controller is cartesian type, in order to tackle two problems: to avoid solving the inverse kinematic of the manipulator and to consider the case of redundant manipulators.

IV-A. PID Cartesian Controller

The cartesian PID controller for the robot manipulator, F_{PID}, is based on cartesian space variables. Then, by considering the direct kinematic model of the robot, given in equation (1), it follows that the PID cartesian controller is expressed by

$$F_{PID} = K_p e_c + K_d \dot{e}_c + K_i \int e_c dt \quad \in \mathbb{R}^m \quad (14)$$

where $K_p, K_d, K_i \in \mathbb{R}^{m\times m}$ are the proportional, derivative, and integral diagonal gain matrices, respectively. The cartesian error is denoted by $e_c \in \mathbb{R}^m$ while $\dot{e}_c \in \mathbb{R}^m$ represents its time derivative. They are defined as follows

$$\begin{aligned} e_c &= \mathbf{X}_c - \mathbf{X} = \mathbf{X}_c - F_{DK}(\mathbf{q}) \quad \in \mathbb{R}^m \\ \dot{e}_c &= \dot{\mathbf{X}}_c - \dot{\mathbf{X}} = \dot{\mathbf{X}}_c - J(\mathbf{q})\dot{\mathbf{q}} \quad \in \mathbb{R}^m \end{aligned} \quad (15)$$

where the vector $\mathbf{X}_c \in \mathbb{R}^m$, represents the *commanded* robot end-effector cartesian position, and $\dot{\mathbf{X}}_c$ denotes its time derivative.

IV-B. Joint Controllers

Given the dynamical model (3), it is required to establish a relation among the joint torques $\tau = \tau_{PID} \in \mathbb{R}^n$ and the cartesian controller (14). For this purpose, the transposed of the robot Jacobian, $J^T(\mathbf{q})$, is considered. Thus, the relation between joint input torques and cartesian controller can be expressed by

$$\tau_{PID} \quad = \quad J(\mathbf{q})^T F_{PID} \tag{16}$$

V. Implementation of the admittance controller

The idea of the admittance controller is to modify the desired position of the *desired* robot end-effector trajectory, $\mathbf{X}_d \in \mathbb{R}^m$, in order to achieve safe robot-environment force interaction $\mathbf{F_r}$. The desired robot end-effector trajectory, $\mathbf{X}_d$, is the ideal robot end-effector trajectory, which should be commanded to the motion controller if no uncertainties are considered. This is, the measured force error, $\mathbf{E}(t)$, is used to generate a proper reference trajectory, $\mathbf{X_r}$ given by equation (10), which is added to the desired position $\mathbf{X}_d$. Thus, the position tracking commanded to the motion controller (16) is given by

$$\mathbf{X}_c \quad = \quad \mathbf{X}_d + \mathbf{X_r} \tag{17}$$

Therefore, the implementation of the admittance controller is performed via an inner/outer control loop, see figure 1.

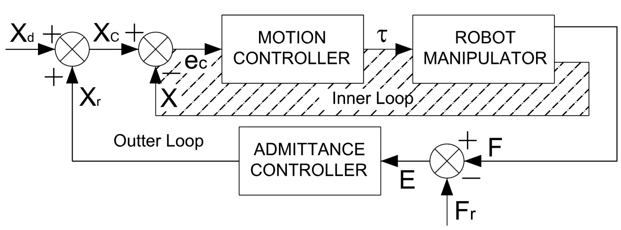

Figure 1. Implementation of the admittance controller

VI. Testbed

In the following the experimental testbed is described, then experimental results are shown. The proposed admittance controller was tested for an unidimensional force-environment interaction task, considering a standard right hand universal coordinate system.

VI-A. Robot Manipulator

The robot manipulator used to perform the experiments is a 3 D.O.F. planar manipulator, see figure 2. It is built on aluminum (alloy 6063 T-5) of 9.525 mm thickness. The joints are driven by three DC brushless servomotors of the brand Micromo© Electronics Inc. The complete design of the robot manipulator is presented in (Muro-Maldonado, 2006). The robot manipulator direct kinematics, (1), is given by

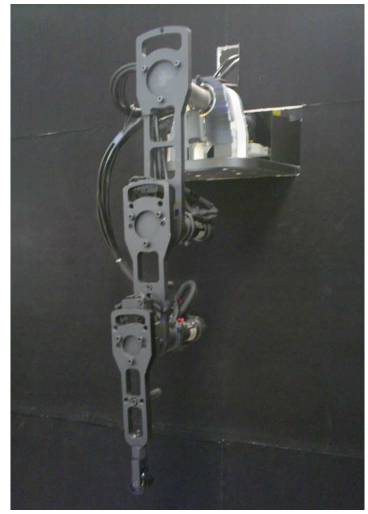

Figure 2. 3 D.O.F. Robot Manipulator

$$\begin{aligned} x &= l_1 \sin(q_1) + l_2 \sin(q_1 + q_2) \\ &\quad + l_3 \sin(q_1 + q_2 + q_3) \\ y &= -l_1 \cos(q_1) - l_2 \cos(q_1 + q_2) \\ &\quad - l_3 \cos(q_1 + q_2 + q_3) \\ \theta &= q_1 + q_2 + q_3 \end{aligned} \tag{18}$$

Where q_i, represent the angular position of the i-th robot joint, for $i = 1, 2, 3$.

VI-B. Force Sensor

Most of commercial force sensors are expensive and has large dimensions, which limits its applications. On the other hand, low cost force sensors have received attention from robotics community because they are tiny and their applications are wider as explained in (Lebosse et. al., 2011). In this paper the low cost force sensor from Tekskan© Flexiforce© is considered. The Flexiforce© A201 force sensor is made of two layers of polyester film. On each layer, a conductive material (silver) is applied. Between the two layers a layer of pressure-sensitive ink is applied. The active sensing area is defined by the silver circle on top of the pressure-sensitive ink. The force sensors are terminated with male square pins, allowing them to be easily incorporated into a circuit. The force range of measurement is $0 - 100$ N, however it can be adjusted by circuitry. The signal conditioning circuit for the force sensor consists of an operational amplifier and analog filter, as recommended by the manufacturer. The circuit and the force sensor are presented in figure 3.

VI-C. Force Sensor Mounting

In order to ensure that the force is always applied on the force sensing area, a mechanical cover was designed and build. A finger-type silicon cover was placed at the end-effector due to safety reasons. The sensor was then mounted on the end-effector of the 3 D.O.F. robot manipulator, as shown in figure 4.

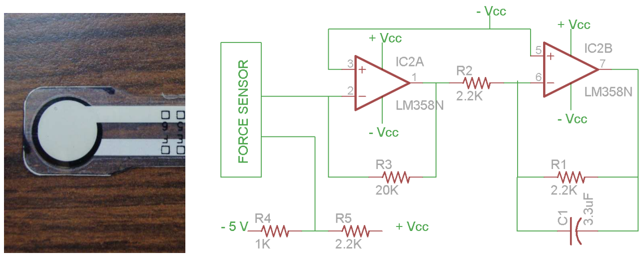

Figure 3. Flexiforce© Force Sensor (right), Conditioning Circuit (left)

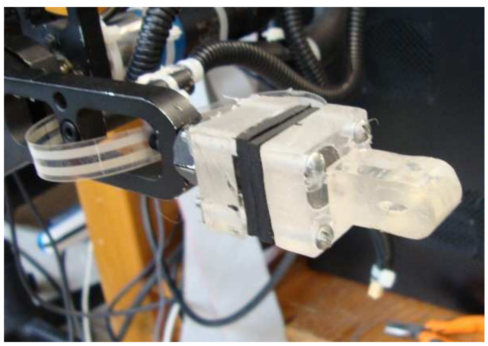

Figure 4. Force Sensor Mounting

VII. RESULTS

The motion controller, presented in section IV-A, together with the admittance controller, presented in section III, were tested in simulations and experimentally.

VII-A. Simulations

For the sake of simulations, the dynamical parameters of the real robot manipulator, see figure 2 were approximated via CAD tools, see (Muro-Maldonado, 2006). The gains for the optimal admittance controller and the PID controller were selected by simulations and they were set as $K_p = diag\{1200\} \in \mathbb{R}^{2\times 2}$, $K_d = diag\{170\} \in \mathbb{R}^{2\times 2}$, $K_i = diag\{70\} \in \mathbb{R}^{2\times 2}$, $\mathbf{\Gamma}_x = 0{,}00001$ and $\alpha_x = 0{,}1$.

A wall was modeled by the force environment model, see equation (4). The commanded task to the robot manipulator task is set to interact with the wall, located at $x_e = 0{,}20 \quad [m]$, with a desired normal force $\mathbf{F_r} = 5\ N$ in the X axis, while moving the robot end-effector along the Y axis. The task was performed with a fixed end-effector horizontal orientation. This is described by

$$\begin{aligned} x_d &= 0{,}2 \quad [m] \\ y_d &= 0{,}025\sin(0{,}2\pi t) - 0,25 \quad [m] \\ \theta_d &= \pi/2 \quad [rad] \end{aligned} \tag{19}$$

The initial value of the environment stiffness $\mathbf{K}_e$ was set to 50000 $[N/m]$. Though, with the aim of verify the robustness of our approach, in $t = 15 \quad [s]$ as an abrupt change of the environment stiffness was performed to set $\mathbf{K}_e = 100000 \ [N/m]$. The gains of the PID controller were set to $K_p = diag\{2500 \ \ 2500 \ \ 1000\}$, $K_d = diag\{50 \ \ 50 \ \ 5\}$ and $K_i = diag\{200 \ \ 200 \ \ 200\}$.

Figure 5 depicts the trajectory tracking errors.

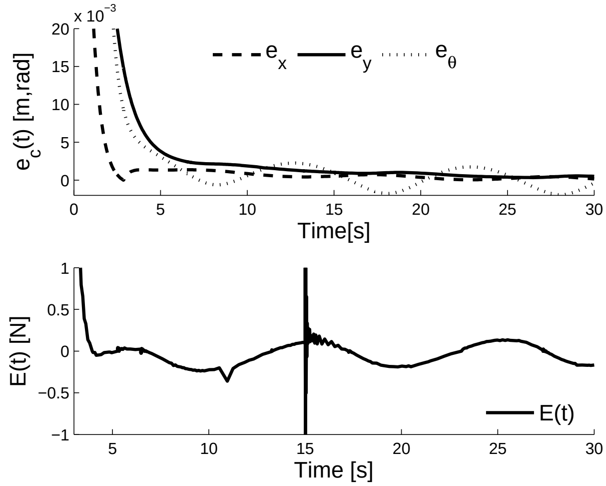

Figure 5. Cartesian Errors (Above) and Force Errors (Below) -PID-

Figure 6 depicts the trajectory generated by the admittance controller. Notice that despite the change of the environmental equivalent stiffness, $\mathbf{K}_e$, in $t = 15 \quad [s]$ the reference force $\mathbf{F_r}$ is still achieved at the end effector. In $t = 15 \quad [s]$ this change is compensated very fast by the on-line modification of the end effector trajectory, x_d in (19), by an amount given by the admittance controller by generating the reference trajectory $x_{\mathbf{r}}$ properly. This fast trajectory modification, allows to avoid excessive robot environment forces, thus guaranteeing safe robot-environment interaction.

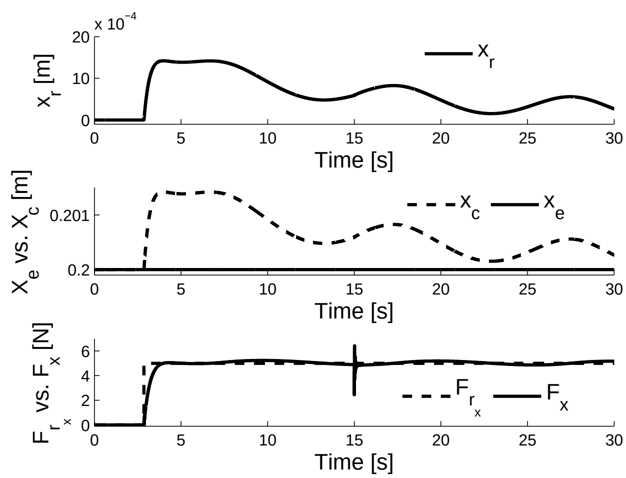

Figure 6. Reference trajectory

VII-B. Experiments

The robot manipulator task is set to interact with a real wall located *approximately* at $x_e = 0{,}15 \quad [m]$, with a desired normal force $\mathbf{F_r} = 5\ N$ along the X axis, while keeping fixed the robot end-effector position at the Y axis. The task was performed with a fixed robot end-effector horizontal orientation. The desired position in the X direction was set to $x_d = 0{,}2$. Notice that the desired position is farther than the real position of the environment. Thus, if the admittance controller is not considered, excessive forces may arise and damage the robot and/or the environment. To test the robustness of our approach it was desired to move the wall, i.e. when the robot-environment interaction is performed, suddenly the wall begins to move (around $t = 2{,}5\ [s]$). Thus, the admittance controller must generate trajectories $x_{\mathbf{r}}$, in order to keep contact with the wall and to achieve force trajectory tracking. Figure 7 depicts the force trajectory for the admittance controller with the PID Controller as the motion controller. Notice that despite the movement of the wall, the admittance controller generates a proper reference trajectory $x_{\mathbf{r}}$, such that the robot end effector keeps in contact with the environment. Moreover, the desired safe robot-environment interaction force is tracked accurately.

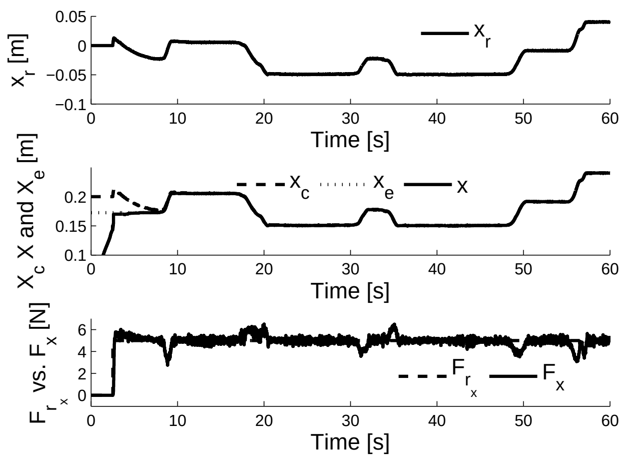

Figure 7. Reference trajectory

VIII. CONCLUSIONS AND FUTURE WORK

In this paper an optimal approach for safe robot-environment interactions hand been introduced. The optimal admittance controller is free of robot dynamic model, however it has been shown by simulations and experimental results that our approach is effective.

The admittance controllers allows to avoid excessive robot-environment interaction forces, even when no explicit bounds exist on the interaction force. This is achieved due to the fast *on-line* generation of the reference trajectory, which modifies the commanded trajectory to the motion controller. It is interesting to highlight that the success of the implementation of the admittance controller is dependent on the performance of the motion controller. As future work we consider the optimization approach with *explicit* bounds on interaction forces and future applications to manipulation and grasping tasks.

IX. ACKNOWLEDGMENTS

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