Optimization-based Reactive Force Control for Robot Grasping Tasks

Rogelio de J. Portillo-Velez[1], Alejandro Rodriguez-Angeles[2] and Carlos A. Cruz-Villar[3]

Centro de Investigacin y de Estudios Avanzados del Instituto Politcnico Nacional

Av. Instituto Politécnico Nacional No. 2508 Col. San Pedro Zacatenco

C.P. 07360 Mexico, D.F. Apartado postal 14-740, 07000 Mxico, D.F.

Tel: (52) 5747 3800

{rportillo[1], aangeles[2], cacruz[3]}@cinvestav.mx

Abstract— **It is proposed an optimization-based controller that reactively adapt the position of the end effectors in cooperative robot systems or fingers, in case of robotic hands. The proposed optimization-based controller uses the force tracking error for each robot, allowing to reactively correct the applied force, thus guaranteeing a stable grasp. Force information is used to determine the modification of the desired motion of the robots in a grasping task, so that ultimately the applied force to guarantee a stable object grasp is achieved. The novelty of our approach is that the proposed controller is obtained as the solution of a dynamic optimization problem, which is solved trough the standard gradient flow approach. Moreover, the method is free of in-depth models and its convergence properties are presented. Experimental results show that the proposed controller is effective, as far as an initial contact between the robots and the object is guaranteed. Key words: Admittance, Optimization, Interaction, Safety, Manipulator.**

I. INTRODUCTION

Traditionally, robot control uses either position control or force control (or a combination of both modes). In contrast, intuitive control also considers the actual task to be performed (Pratt y Pratt, 1998; Duchaine y Gosselin, 2009); this leads to a disappearing of the former strict distinction between planning, reactive planning and reactive control. Combining reactive, stimulus-response control with cognitive, pre-planned behavior government, results in robust, flexible, autonomous, real-time robot control (Yigit et al., 2003).

A reactive algorithm means a simple algorithmic scheme where robot sensors determine immediately the actions of the actuators. However, note that the actuators themselves may interact with the sensors (e.g. by moving them or occluding them, etc.) to close a feedback loop and thus cause further goal-driven as well as corrective actions, (Teichmann y Mishra, 2000). Reactiveness is relevant for autonomous cooperative tasks such as spatial coordination and grasping. However, considering industrial applications, some drawbacks must be reported (Simonin, 2006): 1.-strong dependence to perception (quality and nature of percepts); 2.- sensors perturbations due to environmental conditions (changes); 3.- internal parameters such as

weights for actions selection may be difficult to define (can need a learning process).

The pre-planned grasp analyzes the object to be grasped and decides where the contacts should be placed before any action is carried out. The grasp selection (or grasp planning) task can be broadly defined as follows: given an object to be acquired using a grasping system, find a combination of posture and position relative to the object that results in a stable grasp that is likely to resist expected perturbations (Shapiro et al., 2010). Dexterous manipulation and grasping commonly assume an accurate model of the object to be grasped and, from such a model, an off-line geometric algorithm determines a set of grip points, where the end effectors or fingers are then placed. Over the last years, several approaches have been proposed to the problem of grasp determination, many of them based on predefined models of objects or requiring expensive computation, e.g. (Sanz et al., 1999; Roa y Suarez, 2009).

Typically, once the grip points have been determined, the geometry of the object is deemed irrelevant and the grasp is determined and maintained by only controlling the magnitudes of the forces at the grip points. This approach has provided a clear and deep understanding of stable grasp, how their existence depends on the nature of contact and the physical complexity of grasping, and so on. Nevertheless, this approach has proved to be less useful in practice, as obtaining an accurate model of the object might not be feasible, the exact location of the object might not be available, poor robot repeatability, or imprecise inverse kinematics, see (Teichmann y Mishra, 2000; Vahrenkamp et al., 2008).

Several reactive motion planning approaches exist in this context, mostly based on artificial potential fields and their algorithmic or heuristic (Khatib, 1986; Brock y Khatib, 2002; Santis et al., 2008). Another method considers the on−line generation of the Cartesian path of multiple control points on the manipulator. Alternatively, the so called admittance control has been also used for reactive planning, such that it modifies the robot trajectory in order to achieve some desired force at some direction (Santis et al., 2006). Despite of the success and simplicity of the admittance approach,

most of the proposed solutions require *a priori* knowledge of robot and/or the object dynamics, which limits their potential applications (Teichmann y Mishra, 2000; Hsiao *et al.*, 2010).

In this paper, an optimal admittance controller is proposed to ensure the desired pre-planned applied force to guarantee a stable object grasp by a cooperative robot system. 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. It is important to highlight the simple structure of the proposed admittance controller. The reference trajectory of each robot at the cooperative system is computed very fast, yielding online reactive motion planning of the robots end-effector trajectory to uncertain forces, which may arise during object interaction. This fast adaptation results in safe robot-object interaction by guaranteeing application of the desired pre-planned grasping interaction force. On the other side, it is well known that it is not advisable to use the force error time derivative, because it is a highly noisy signal. However, the proposed approach allows to manage signals with noise, thanks to the filtering properties of the time integration, which is used because of the gradient flow approach.

II. COOPERATIVE ROBOT SYSTEM

The problem faced in this papers reads as follows: *to design an optimal admittance controller to perform stable robot-object grasping by a cooperative robot system in a reactive framework.*

It is important to highlight that the compliance approach to robot force control is used, which can be viewed as unconstrained motion control. Thus, all control methods for unconstrained motion, such as PID control, sliding mode control and model based control, can be used. It is assumed fully actuated robots whose working space cover the requirements for the Cartesian task (grasping).

II-A. *Kinematic model*

Consider n_i-joint fully actuated rigid robots, non necessarily identical, where $i = 1, .., p$ identifies the p robots which conform the cooperative system. The robot joint variables are denoted by $\mathbf{q}_i \in \Re^{n_i}$. In general terms, the direct kinematics relates the joint variables, $\mathbf{q}_i$, and the $i-th$ robot end-effector Cartesian variables, $\mathbf{X}_i \in \Re^{m_i}$, all of them with respect to a general Coordinate system. It is considered that the Cartesian working space dimension m_i of each robot is at least equal to the task working space T_s, i.e. $T_s \leq m_i$ $\forall i = 1, ..., p$, such that it guarantees that all robots might execute the Cartesian task.

The direct kinematic model of the $i-th$ robot manipulator can be expressed as

$$\mathbf{X}_i = F_{DK,i}(\mathbf{q}_i) \tag{1}$$

II-B. *Contact point impedance model*

The objective of the impedance control is to establish a dynamic relation or constraint between the $i - th$ end-effector position, $\mathbf{X}_i$, and the object interaction force $\mathbf{F}_i$. This relationship can be imposed by either impedance or admittance. In the impedance relationship, the $i - th$ robot reacts to deviations from its 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, (Schutter *et al.*, 1998). When the $i-th$ robot is in closed loop with a motion controller, the desired Cartesian $i - th$ end-effector robot impedance might be modeled as follows (Seraji y Colbaugh, 1997)

$$\mathbf{M}_i\ddot{\mathbf{X}}_i + \mathbf{C}_i\dot{\mathbf{X}}_i + \mathbf{K}_i(\mathbf{X}_i - \mathbf{X}_{r,i}) = \mathbf{E}_i(t) \tag{2}$$

where $\mathbf{M}_i$, $\mathbf{C}_i$ and $\mathbf{K}_i$ are, respectively, $m_i \times m_i$ diagonal mass, damping and stiffness matrices of the desired impedance for the $i - th$ robot - object contact point. The diagonal structure of the matrices ensures that each Cartesian degree of freedom is independent from each other. The vector $\mathbf{E}_i(t) = \mathbf{F}_{r,i} - \mathbf{F}_i \in \Re^{m_i}$ is the force tracking error, and $\mathbf{F}_{r,i} \in \Re^{m_i}$ is the desired force interaction for the $i-th$ robot, which is obtained from a pre-planned grasp determination problem looking to guarantee safe grasping; $\mathbf{X}_{r,i} \in \Re^{m_i}$ is the reference end-effector position with which the desired impedance relationship, (2), is obtained. The $i-th$ reference end-effector position $\mathbf{X}_{r,i}$ will be obtained reactively based on measurement of the $i-th$ force interaction $\mathbf{F}_i$ by solving an on-line optimization problem.

From equation (2), it can be shown (Seraji y Colbaugh, 1997) that if $\mathbf{F}_{r,i}$ is constant, and if the reference position $\mathbf{X}_{r,i}$ is chosen such that $\mathbf{X}_{r,i} = \mathbf{X}_{o,i} + \mathbf{K}_{o,i}^{-1}\mathbf{F}_{r,i}$ it holds that

$$\lim_{t \to \infty} \mathbf{E}_i(t) = 0 \tag{3}$$

thus, force tracking at the $i - th$ contact point is achieved. However, in general, we are not able to know accurately *a priori* neither the position of the object, $\mathbf{X}_{o,i}$, nor the stiffness, $\mathbf{K}_{o,i}$. Then, situations which involve uncertainty, may lead to excessive forces which may cause damage to the robot or the object, or insufficient forces to guarantee a stable grasp.

III. OPTIMAL ADMITANCE CONTROLLER

As stated above, safety of the $i - th$ robot-object interaction can be violated by excessive or insufficient interaction forces. Moreover, if the object position is continuously changing, then uncertainty at the $i - th$ contact point, $\mathbf{X}_{o,i}$, and/or object stiffness, $\mathbf{K}_{o,i}$, might be considered. Thus the challenge is to *on-line* compute a proper reference trajectory $\mathbf{X}_{r,i}$ which yields the desired impedance behavior among the $i - th$ robot and the object at the contact point (2).

For this, an optimization problem is formulated. 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 y Moore, 1996).

III-A. Optimization problem

The optimization problem considers an objective function for each contact point, $\mathbf{I}_i \in \Re$, related to the contact point force error, $\mathbf{E}_i(t)$, and its time derivative, $\dot{E}_i(t)$. The optimization problem reads as follows

$$\min_{\mathbf{X}_{r,i} \in \Re^{m_i}} \qquad \mathbf{I}_i = \frac{1}{2} \left[\mathbf{E}_i + \alpha_i \dot{\mathbf{E}}_i \right]^T \left[\mathbf{E}_i + \alpha \dot{\mathbf{E}}_i \right] \qquad (4)$$

where, $\alpha_i \in \Re$, is a positive gain which weights the time derivative of the $i-th$ force error. Now, consider the gradient flow

$$\dot{\mathbf{X}}_{r,i} = -\gamma_i \frac{\partial \mathbf{I}_i}{\partial \mathbf{X}_{r,i}} \qquad (5)$$

were, $\gamma_i \in \Re^{m_i \times m_i}$, is a positive definite diagonal matrix of gains related to the convergence properties of the gradient flow.

Considering the diagonal structure of $\mathbf{M}_i$, $\mathbf{C}_i$ and $\mathbf{K}_i$ in (2), as well as vectors $\left[\mathbf{E}_i(t) + \alpha_i \dot{\mathbf{E}}_i(t) \right]^T = [(e_{i,1} + \alpha \dot{e}_{i,1}) \cdots (e_{i,m} + \alpha \dot{e}_{i,m})]$, and $\mathbf{X}_{r,i} = [X_{r,i_1} \cdots X_{r,i_m}]$, the gradient $\frac{\partial \mathbf{I}_i}{\partial \mathbf{X}_{r,i}}$ is given by

$$\frac{\partial \mathbf{I}_i}{\partial \mathbf{X}_{r,i}} = -\mathbf{K}_i \left[\mathbf{E}_i(t) + \alpha \dot{\mathbf{E}}_i(t) \right] \qquad (6)$$

Which shows that the Cartesian reference trajectory is independently generated for each end-effector Cartesian degree of freedom of the $i-th$ robot, i.e. position an orientation reference trajectories are uncoupled for each robot at the cooperative system, as well as for their own Cartesian degrees of freedom. From equations (5) and (6), the $i-th$ Cartesian reference trajectory is computed as follows

$$\mathbf{X}_{r,i} = \gamma_i \mathbf{K}_i \int_0^t \left[\mathbf{E}_i(t) + \alpha \dot{\mathbf{E}}_i(t) \right] dt \qquad (7)$$

Uncertainties at the $i-th$ contact point diagonal stiffness matrix, $\mathbf{K}_i$, are absorbed by the diagonal gain matrix, γ_i, since at the end their product can be seen as a gain which regulates the gradient flow convergence.

Notice that the proposed optimization index (4) might include barrier functions for considering performance constraints such as bounded interaction force, geometric constraints, etc., thus increasing the potential of the proposed approach. In the unconstrained case the proposed approach yields equation (7), which might be interpreted as a PI control based on force interaction error $\mathbf{E}_i$, similar to the controller proposed in (Chiaverini y Sciavicco, 1993).

III-B. Object interaction control scheme

The idea of the admittance controller is to modify the desired position of the $i-th$ robot end-effector trajectory, $\mathbf{X}_{d,i} \in \Re^{m_i}$, in order to achieve the desired robot-object interaction force $\mathbf{F}_{r,i}$. The $i-th$ desired robot end-effector trajectory, $\mathbf{X}_{d,i}$, is the ideal robot end-effector trajectory,

which should be commanded to the motion controller if no uncertainties on object position or its stiffness are considered. Thus, the implementation of the admittance controller is performed via an inner/outer control loop, see Figure 1.
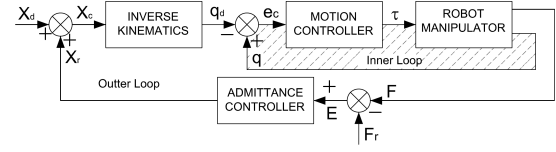

Figure 1. Implementation of the admittance controller for the i-th robot

This is, the measured force error, $\mathbf{E}_i(t)$, is used to generate a proper reference trajectory, $\mathbf{X}_{r,i}$ given by equation (7), which is added to the ideal desired position $\mathbf{X}_{d,i}$. Thus, the commanded position reference $\mathbf{X}_{c,i}$ to the motion controller of the $i-th$ robot is given by

$$\mathbf{X}_{c,i} = \mathbf{X}_{d,i} + \mathbf{X}_{r,i} \qquad (8)$$

III-C. Stability

Let us introduce the state vector $\mathbf{\Omega}_i = [\mathbf{E}_i(t) \ \dot{\mathbf{E}}(t)_i]^T \in \mathbb{R}^{2m_i}$ for each robot. Let the performance index I_{ei} in problem (4) be a candidate Lyapunov function of the state vector $\mathbf{\Omega}_i$, i.e.

$$V_i(\mathbf{\Omega}_i) = \frac{1}{2} \left[\mathbf{E}_i(t) + \alpha_i \dot{\mathbf{E}}_i(t) \right]^T \left[\mathbf{E}_i(t) + \alpha_i \dot{\mathbf{E}}_i(t) \right] \qquad (9)$$

Notice that $V_i(\mathbf{\Omega}_i) = 0$ when $\mathbf{\Omega}_i = 0$ as $\mathbf{F}_{ri} \leq \mathbf{F}_{\max i}$ and $\mathbf{F}_{ri} \geq \mathbf{F}_{\min i}$.

Differentiating equation (9) with respect to time yields

$$
\begin{aligned}
\dot{V}_i(\mathbf{\Omega}_i) &= \frac{\partial V(\mathbf{\Omega}_i)}{\partial \mathbf{\Omega}_i} \frac{\partial \mathbf{\Omega}_i}{\partial \mathbf{X}_{ri}} \frac{d\mathbf{X}_{ri}}{dt} = \\
&= \mathbf{\Omega}_i^T \overbrace{\begin{bmatrix} \mathbf{1} & \alpha_i \end{bmatrix}}^{m \times 2m} \underbrace{\begin{bmatrix} -\mathbf{K}_i \\ \mathbf{0}^{m \times m} \end{bmatrix}}_{2m \times m} \dot{\mathbf{X}}_{ri} \\
&= -\mathbf{\Omega}_i^T \left[\mathbf{K}_i \right] \dot{\mathbf{X}}_{ri}
\end{aligned} \qquad (10)
$$

Substituting equations (5) and (6) in (10) gives as result equation (11).

$$\dot{V}_i(\mathbf{\Omega}_i) = -\mathbf{\Omega}_i^T \left[\mathbf{K}_i \mathbf{\Gamma}_i \mathbf{K}_i \right] \mathbf{\Omega}_i \qquad (11)$$

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

IV. MOTION CONTROLLER

In this article a simple joint PID controller at each robot at the cooperative system is considered, this controller is given by

$$\tau_{PID,i} = K_{P,i} e_{c,i} + K_{D,i} \dot{e}_{c,i} + K_{I,i} \int e_{c,i} dt \qquad (12)$$

where $K_{P,i}, K_{D,i}, K_{I,i} \in \Re^{n_i \times n_i}$ are the proportional, derivative, and integral diagonal gain matrices, respectively. The $i-th$ joint error is denoted by $e_{c,i} \in \Re^{n_i}$ while $\dot{e}_{c,i} \in \Re^{n_i}$

represents its time derivative. The joint tracking error $e_{c,i}$ is defined as follows

$$e_{c,i} = \mathbf{q}_i - \mathbf{q}_{d,i} = \mathbf{q}_i - F_{IK}(\mathbf{X}_{c,i}) \tag{13}$$

where $\mathbf{X}_{c,i}$, represents the $i-th$ commanded robot end-effector Cartesian position, given by (8), and $F_{IK}(\mathbf{X}_{c,i})$ denotes the inverse kinematic model of the $i-th$ robot.

V. TESTBED

The proposed optimization admittance controller was tested for unidimensional robot-object interaction forces, considering an object grasping task executed by a two robots cooperative system.

V-A. *Robot manipulators*

One of the robot manipulators used to perform the experiments is a three degree of freedom planar manipulator, see Figure 2. Its 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 second robot is a closed chain five bar parallel robot, shown in Figure 2. The robot is a spatial three degree of freedom closed chain manipulator. Its joints are actuated by Maxon© motors coupled to optical encoders of 1000 ppr. The complete design of the robot is presented in (Cortes-Martinez, 2007).

Both robots are built on aluminum (alloy 6063 T-5) of 9.525 mm thickness. They are equipped with low-cost force sensors of the branch Tekskan© at the end effector.

V-B. *Force sensor*

In this paper the low cost one axis 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, (Lebosse *et al.*, 2008). The force range of measurement is $0-100$ N.

VI. RESULTS

The goal is that the robots at the cooperative system grasp and move a prismatic shaped object, which is a high density Styrofoam block ($6{\times}6{\times}5[cm]$, $mass = 0,03[Kg]$). The block is affected by gravity forces, as shown in Figure 2. The ideal desired position is such that perpendicular contact between the object and the end effectors is obtained. This guarantees that the interaction forces are aligned to the force sensor axis. Two cases are tested, external force perturbation on a grasped object, and transporting a grasped object by the cooperative system.

A grasping analysis was carried out to select the best grasping positions on the object, while considering its inertial properties, (Murray y Sastry, 1994). Therefore, the selected grasping points are located at the centroid of the opposite squared faces of the block, and assuming a static friction coefficient $\mu = 0,5$ (plastic-styrofoam), the desired force which guarantees stable grasp is $F_{r,i} = 0,265[N]$. However, due to uncertainty on the friction coefficient and the unknown stiffness coefficient $K_{o,i}$ we set $F_{r,i} = 1[N]$.
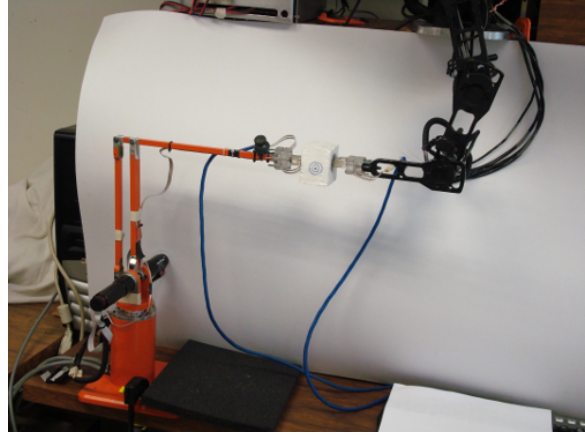

Figure 2. Cooperative grasping task.

VI-A. *Experiment Setup*

To perform cooperative transport, both manipulator workspaces must intersect in the area where the object is transported. This fact imposes some restrictions to the experimental set-up. First, a reference frame must be selected to provide an absolute value of the object position, as shown in Figure 2. On the other hand, the parallel manipulator is spatial and the serial manipulator is planar. Then, we are limited to perform cooperative tasks in the 2D serial robot workspace. This is accomplished by fixing the first degree of freedom of the parallel manipulator that is in charge of waist rotation. The final configuration for the experiments is shown in Figure 2.

The experiments were performed as follows. First the manipulators are commanded to a *home* position with its end-effectors *near* the object, i.e. the object position is *not exactly* known. Once the manipulators are at home, they are commanded to *pinch or squeeze* the object by two contact points applying the desired force, previously selected via the grasp analysis. The pinch command is performed by setting the end effector trajectories such that the difference between the end effectors is smaller than the width of the block, $W = 0,05[m]$. The gains of the admittance controller were set to $\gamma_1 = 0,00022$ and $\alpha_1 = 0,1$, for the parallel robot and $\gamma_2 = 0,001$ and $\alpha_2 = 0,1$ for the serial robot.

VI-B. *Test of stable grasp*

At the first case a fixed object position is commanded, and after the setting forces have reached the steady state, the object is perturbed by an unknown external force. The goal is that the controller compensates the external force ensuring stable object grasp. The problem arises in the *pinch* command. Due to the *uncertainty* on the object position, unexpected forces may appear, which are not desirable for the grasp because they can cause unstable behavior or contact breakage/slippage.

The desired $\mathbf{X}_{d,i}$, commanded $\mathbf{X}_{c,i}$ and robot cartesian $\mathbf{X}_i$ trajectories are shown in Figure 3. The dashed line represents the desired trajectory $\mathbf{X}_d$, which is designed
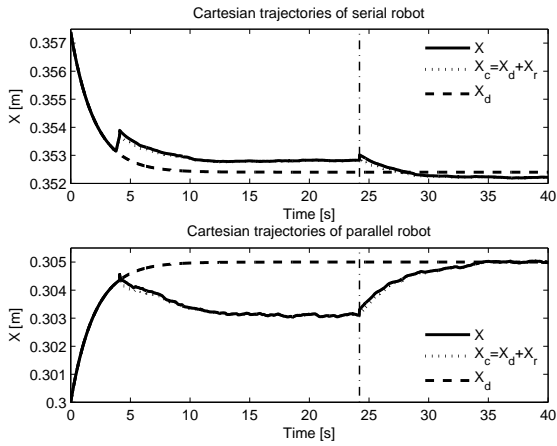
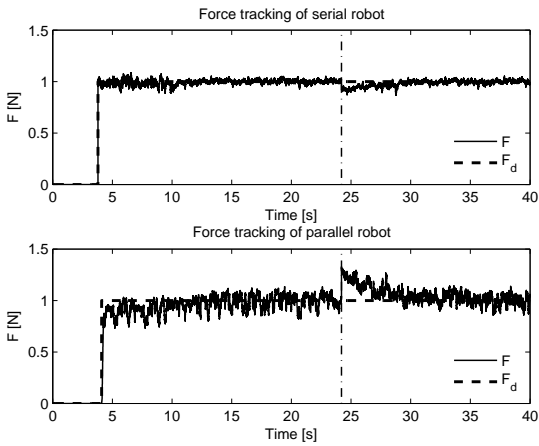Figure 3. Cartesian trajectories
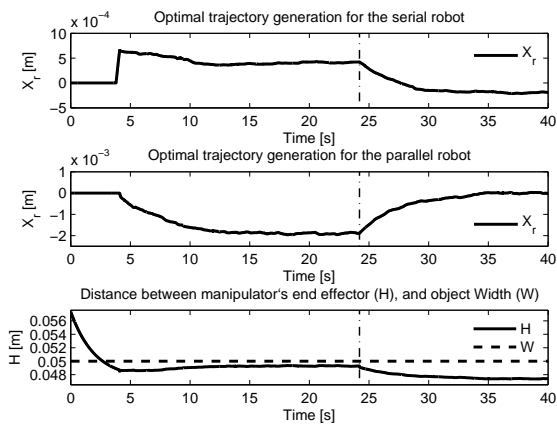

Figure 4. Force regulation

Figure 5. Optimal trajectories

to perform the pinch command and to grasp the object. Thus, the optimal admittance controller generates proper trajectories in order to achieve the desired force $\mathbf{F}_{r,i} = 1[N]$,

which are shown in Figure 4. Then, around time $t = 24[s]$, an external force is applied on the object, this effect is depicted in Figures 3 and 4.

Figure 5 shows the optimal reference trajectories $\mathbf{X}_r$, generated to keep the stable grasp, despite the uncertainty in object position, friction coefficient, stiffness and external perturbations. The bottom plot of Figure 5 shows that the generated trajectories makes the robot to grasp the object by squeezing it, thus the distance between the end effectors, H is such that $H < W$.

VI-C. *Object position by grasping*

For the second experiment the robots are commanded to follow a desired trajectory in cartesian space while stable grasping is guaranteed.

The first step is to grasp the object stably, while the manipulators are commanded to follow a synchronized sinusoidal trajectory along the x axis of the global coordinate frame, located at the base of the parallel manipulator. The cartesian trajectories are shown in Figure 6.
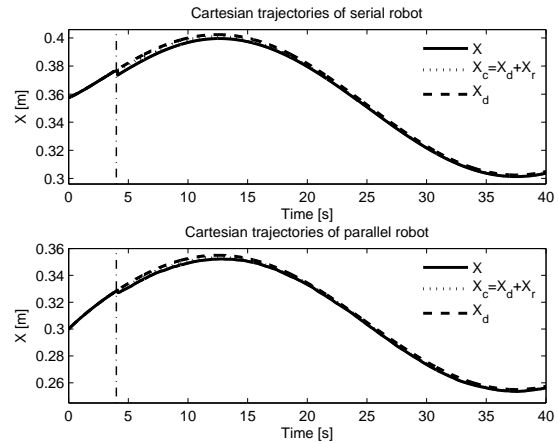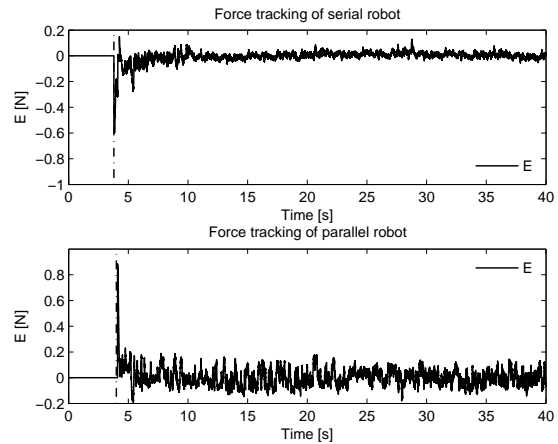

Figure 6. Cartesian trajectories
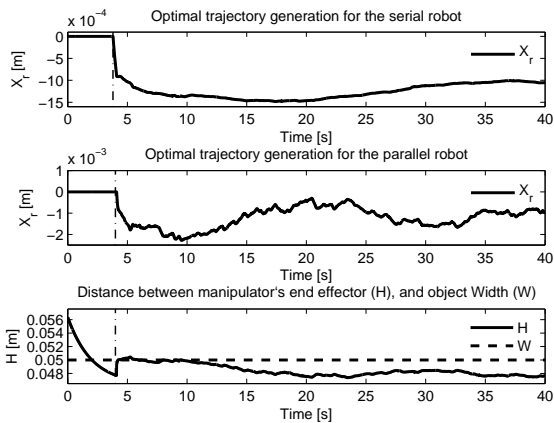

Figure 7. Force tracking errors

Figure 8. Optimal trajectories

Before the object contact time $t \approx 4[s]$, the robots follow their trajectories accurately, however after $t \approx 4[s]$, the admittance controller modifies the commanded trajectories by generating reference trajectories $\mathbf{X}_r$, which yields the force set point, the force tracking errors are shown in Figure 7. Again, the bottom plot of Figure 8 shows that the generated trajectories makes the robot to grasp the object by squeezing it, thus the distance between the end effectors, H is such that $H < W$.

VII. CONCLUSIONS AND FUTURE WORK

In this paper an optimal reactive admittance approach for safe robot-object interactions in cooperative robot grasping task is proposed. The optimal admittance controller is free of robot dynamic model, however it has been shown by experimental results that our approach is effective, yielding stable object grasp. 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 important to highlight that the success of the implementation of the admittance controller is dependent on the performance of the motion controller. As future applications, this approach might be extended to consider on-line repositioning of the contact points to increase flexibility and robustness of cooperative robot systems.

VIII. ACKNOWLEDGMENTS

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