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Fuzzy unidirectional force control of constrained robotic manipulators

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Abstract

The end effector of a robotic arm is required to keep a contact on the contour of the constraint surface in tasks such as deburring and grinding. Being different from contacts resulted from general mechanical pairs, such a contact is unidirectional, or equivalently, the contact force can only act along the outward normal of the constraint surface at the contact point. How to achieve this specification was not addressed explicitly in many position/force control schemes developed so far, instead it was assumed in the development of controllers. In this paper, the unidirectionality of the contact force is explicitly included in modeling and control of constrained robot system. A fuzzy tuning mechanism is developed to generate the impedance model resulted from the continuous contact made by the end effector of the robotic manipulator on the constraint surface while it is in motion. A controller is then developed based on the fuzzy rule bases and the nonlinear feedback technique. The simulation is carried out to verify the effectiveness of the approach. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuzzy relations; Force control; Impedance control

1. Introduction

To keep the end effector of the robotic arm in constant contact with the constraint surface is a basic requirement for many tasks such as deburring and grinding by robots. It is also a pre-requisite for many well-developed controllers for constrained robots such as *hybrid position/force control* [5, 7, 15] and *constrained robot control* [6, 11, 12]. Though *impedance control* [4, 14] takes care of both constrained and unconstrained motion by specifying the performance of the controlled system as a desired generalized dynamic impedance, it does not address explicitly how to keep the end effector of the robotic manipulator in contact with the constraint surface.

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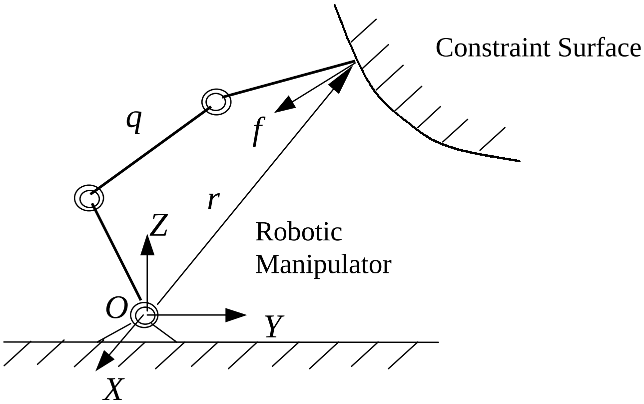

Fig. 1. Constrained robot.

As pointed out in [2], the force control schemes developed on the assumption that manipulator end effector always keeps contact with the environment cannot handle the impact caused by the loss of contact. It is also difficult to model the transition from non-contact into contact and vice versa. Even it is modeled with some assumptions, it may be too complicated to be used in controller design, or results in very complicated controllers [1, 13] . On the other hand, to make one's finger to keep contact on a constraint surface is trivial as he only needs to press his finger roughly along the normal "penetrating" the constraint surface at the contact point, thus he only feels the unidirectional contact force acting along the outward normal direction. If he feels that the force is too big, he just needs to change the gestures of his hand to make him feel better. Based on this observation and motived by the fuzzy rule construction method in [10], a fuzzy unidirectional force control approach for a constrained robot is developed in this paper. An impedance model is tuned by a set of fuzzy rules corresponding to the situation that end effector of the robotic manipulator keep contact on the constraint surface while it move along it. A controller is then developed by combining this rule base and the nonlinear feedback technique. The simulation is carried out to verify the effectiveness of the approach.

The rest of paper is organized as follows. In Section 2, the dynamic model of the constrained robot is given. In Section 3, the impedance model of the robot and environment is described and the fuzzy unidirectional force control scheme is developed. In Section 4, simulation studies are carried out to show the effectiveness of the proposed controller. In Section 5, the conclusion about the work presented in the paper is described.

2. Dynamic model

A general constrained robotic system is schematically shown in Fig. 1. The dynamic model of a constrained manipulator in joint space are described by

$$M(q)\ddot{q} + C(q,\ \dot{q})\dot{q} + G(q) = \tau + J^{\mathrm{T}}(q)f, \tag{1}$$

where q are the joint displacements, $\dot{q}$ are the joint velocities, $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the coriolis and centrifugal force matrix, $G(q)$ is the gravitational force, τ are the joint torques, $J(q)$ is the Jacobian matrix and f is the contact force.

Through the following kinematic relations between the Cartesian position r and velocity $\dot{r}$ of the end effector and joint position q and velocity $\dot{q}$

$$r = \phi(q), \tag{2}$$

$$\dot{r} = J(q)\dot{q}, \tag{3}$$

the dynamic model (1) is expressed in workspace as

$$M_r(q)\ddot{r} + C_r(q,\dot{q})\dot{r} + G_r(q) = J^{-\mathrm{T}}(q)\tau + f, \tag{4}$$

where

$$M_r(q) = J^{-\mathrm{T}}(q)M(q)J^{-1}(q),$$

$$C_r(q,\dot{q}) = J^{-\mathrm{T}}(q)(M(q)\dot{J}^{-1}(q) + C(q,\dot{q})J^{-1}(q)),$$

$$G_r(q) = J^{-\mathrm{T}}(q)G(q).$$

For clarity, the arguments of the terms will be dropped if there is no ambiguity in the context of the discussion in the following.

It is easy to prove that the dynamic model (4) has the following properties

Property 1. The inertial matrix M_r is symmetric positive definite matrix, provided that J is of full rank.

Property 2. The matrix $\dot{M}_r - 2C_r$ is skew symmetric given that the matrix $\dot{M} - 2C$ is skew symmetric.

3. Fuzzy unidirectional force control

The objective of the controller is to achieve the position/force control for the constrained robot system (4), so that the end effector of the robotic manipulator keeps contact on the constraint surface, and the stabilities of the closed-loop system are guaranteed.

Our discussion begins with commonly-used impedance control scheme in which the closed-loop dynamics is specified by the following impedance [2]:

$$f_{\mathrm{d}} - f = M_m(\ddot{r}_{\mathrm{d}} - \ddot{r}) + D_m(\dot{r}_{\mathrm{d}} - \dot{r}) + K_m(r_{\mathrm{d}} - r), \tag{5}$$

where $M_m \in R^{l\times l}$, $D_m \in R^{l\times l}$ and $K_m \in R^{l\times l}$ are inertia matrix, damping matrix and the stiffness matrix, respectively, f_{d} is the desired force and f is the actual force.

If M_m, D_m and K_m are taken as diagonal matrices: $M_m = m_m I^{l\times l}$, $D_m = d_m I^{l\times l}$, $K_m = k_m I^{l\times l}$ with m_m, d_m and k_m being constant scalars and l being the dimension of workspace, the resulted impedance is then rewritten as

$$e_f = m_m \ddot{e}_r + d_m \dot{e}_r + k_m e_r, \tag{6}$$

where $e_f = f_{\mathrm{d}} - f$, $\ddot{e}_r = \ddot{r}_{\mathrm{d}} - \ddot{r}$, $\dot{e}_r = \dot{r}_{\mathrm{d}} - \dot{r}$, $e_r = r_{\mathrm{d}} - r$.

Considering the following controller:

$$\tau = J^{\mathrm{T}}[M_r(\ddot{r}_{\mathrm{d}} + m_m^{-1}(d_m\dot{e}_r + k_m e_r + f - f_{\mathrm{d}})) + C_r\dot{r} + G_r - f] \tag{7}$$

and substituting it into the dynamic model (4) and considering the properties of the model, it is easy to verify that the desired impedance (6) is achieved.

Obviously, the resulted impedance does not require that f be unidirectional, as the force in a normal mass–spring–damper system can act in either pushing or pulling direction. In practice, f should be acted along the normal pointing out of the constraint surface at the contact point, or mathematically

$$f = f_m n, \tag{8}$$

where n is the normal vector at the contact point on the constraint surface and $f_m = \|f\|$ is the magnitude of the constraint force.

Considering Eq. (8), the impedance model (5) is rewritten as

$$f_{\mathrm{d}m}n - f_m n = m_m\ddot{e}_r + d_m\dot{e}_r + k_m e_r, \tag{9}$$

$$0 < f_m < f_{\max}, \tag{10}$$

where $f_{\mathrm{d}m} = \|f_{\mathrm{d}}\|$ is the desired magnitude of the contact force and $f_{\max}$ is an additional constant representing the maximum contact force allowed.

Projecting Eq. (9) along n by multiplying its both sides with n^{T} and rearranging Eq. (10), we have

$$e_{fm} = m_m n^{\mathrm{T}}\ddot{e}_r + d_m n^{\mathrm{T}}\dot{e}_r + k_m n^{\mathrm{T}} e_r, \tag{11}$$

$$e_{f\min} < e_{fm} < e_{f\max}, \tag{12}$$

where $e_{fm} = f_{\mathrm{d}m} - f_m$, $e_{f\min} = f_{\mathrm{d}} - f_{\max}$ and $e_{f\max} = f_{\mathrm{d}}$.

Note that Eq. (11) describes the behaviors of contact force along the normal n and its relations with state tracking errors of the system. Eq. (12) specifies the condition to keep the end effector of the robot in contact with constraint surface.

By viewing m_m, d_m and k_m as the weights determining the contributions of $\ddot{e}_r$, $\dot{e}_r$ and e_r to the overall force difference, respectively, it is obvious that they can be tuned for the realization of unidirectional force control. The trends of the changes in acceleration/velocity/position errors and force errors can be used to determine how this adjustment should be made. By observing Eq. (11), the following fuzzy rules are derived to tune d_m and k_m.

Fuzzy Rules Set 1.

- IF $n^{\mathrm{T}}\dot{e}_r$ is *positive* and $n^{\mathrm{T}}e_r$ is *positive* and $e_{fm} - e_{f\max}$ is *positive* THEN d_m is *small* and k_m is *small*,
- IF $n^{\mathrm{T}}\dot{e}_r$ is *positive* and $n^{\mathrm{T}}e_r$ is *positive* and $e_{fm} - e_{f\min}$ is *negative* THEN d_m is *big* and k_m is *big*,
- IF $n^{\mathrm{T}}\dot{e}_r$ is *positive* and $n^{\mathrm{T}}e_r$ is *negative* and $e_{fm} - e_{f\max}$ is *positive* THEN d_m is *small* and k_m is *big*,

- IF $n^T\dot{e}_r$ is *positive* and n^Te_r is *negative* and $e_{fm} - e_{f\,\min}$ is *negative* THEN d_m is *big* and k_m is *small*,
- IF $n^T\dot{e}_r$ is *negative* and n^Te_r is *positive* and $e_{fm} - e_{f\,\max}$ is *positive* THEN d_m is *big* and k_m is *small*,
- IF $n^T\dot{e}_r$ is *negative* and n^Te_r is *positive* and $e_{fm} - e_{f\,\min}$ is *negative* THEN d_m is *small* and k_m is *big*,
- IF $n^T\dot{e}_r$ is *negative* and n^Te_r is *negative* and $e_{fm} - e_{f\,\max}$ is *positive* THEN d_m is *big* and k_m is *big*,
- IF $n^T\dot{e}_r$ is *negative* and n^Te_r is *negative* and $e_{fm} - e_{f\,\min}$ is *negative* THEN d_m is *small* and k_m is *small*,
- IF $e_{fm} - e_{f\,\min}$ is *positive* and $e_{fm} - e_{f\,\max}$ is *negative* THEN d_m is *medium* and k_m is *medium*,

where *positive*, *negative*, *big*, *small* and *constant* are linguistic terms. Following the same methods in [10], the membership functions of their corresponding fuzzy sets are selected as

$$\mu_{\text{positive}}(x) = \frac{1}{1 + e^{-k_p x}}, \tag{13}$$

$$\mu_{\text{negative}}(x) = \frac{1}{1 + e^{k_n x}}, \tag{14}$$

$$\mu_{\text{big}}(y) = e^{-k_b(y-d_b)^2}, \tag{15}$$

$$\mu_{\text{small}}(y) = e^{-k_s(y-d_s)^2}, \tag{16}$$

$$\mu_{\text{medium}}(y) = e^{-k_{\text{med}}(y-d_{\text{med}})^2}, \tag{17}$$

where x takes as $\dot{e}_r, e_r$ or e_f, y takes d_m or $k_m, k_p, k_n, k_b, k_s, k_{\text{med}}, d_b, d_s$ and d_{med} are positive constants determining the shape of the membership functions.

Note that m_m is not tuned due to the difficulty to obtain the acceleration feedback in practice, but the above fuzzy rules are still valid even the acceleration errors are included. m_m can also be set a small value to reduce the contribution to the overall control effort due to the acceleration errors.

How to choose parameters $k_p, k_n, k_s, k_{\text{med}}, k_b, d_s, d_{\text{med}}$ and d_b relies on the knowledge about the constrained robot system and the experience of controlling robotic manipulators. For example, the membership functions may introduce switching behaviors into the controlled system and cause chattering if k_p and k_n are too big. On the other hand, if they are too small the fuzzy adaptation might become less responsive to the change of the states of the system.

Considering the fact that the effects of n^Te_r and $n^T\dot{e}_r$ on the contact force are different, a new variable s is defined as the weighted combination of $n^T\dot{e}_r$ and n^Te_r

$$s = n^T\dot{e}_r + \lambda n^T e_r, \tag{18}$$

where $\lambda > 0$ is a constant. To assign higher weights to n^Te_r, we should choose $\lambda > 1$.

With s being defined and letting $k_m = \lambda d_m$, the impedance model (11) is modified to be

$$e_{fm} = m_m n^T\ddot{e}_r + d_m s. \tag{19}$$

With the same assumption that the effect of acceleration to the force error is minimal and choosing m_m to be a small value, we can now produce another set of fuzzy rules to tune d_m as follows.

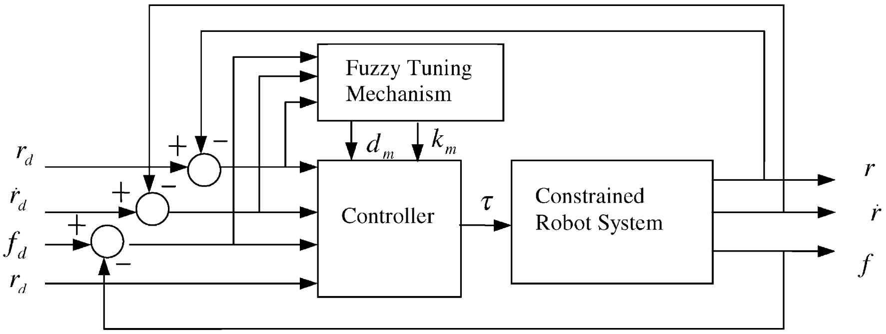

Fig. 2. Fuzzy unidirectional force controller.

Fuzzy Rules Set 2.

- IF s is *positive* and $e_{fm} - e_{f\,\max}$ is *positive* THEN d_m is *small*,
- IF s is *positive* and $e_{fm} - e_{f\,\min}$ is *negative* THEN d_m is *big*,
- IF s is *negative* and $e_{fm} - e_{f\,\max}$ is *positive* THEN d_m is *big*,
- IF s is *negative* and $e_{fm} - e_{f\,\min}$ is *negative* THEN d_m is *small*,
- IF $e_{fm} - e_{f\,\min}$ is *positive* and $e_{fm} - e_{f\,\max}$ is *negative* THEN d_m is *medium*,

where the linguistic variable and their membership function are the same as those in Fuzzy Rules Set 1.

Fuzzy Rules Set 2 has much less rules than that of Fuzzy Rules 1 and is used to derive d_m. By using singleton fuzzifier, product inference engine and the center average defuzzifier, the crisp d_m is derived such that

$$d_m = w_1 d_s + w_2 d_b + w_3 d_{\text{med}}, \tag{20}$$

where

$$w_1 = w^{-1}[\mu_{\text{positive}}(s)\mu_{\text{positive}}(e_{fm} - e_{f\,\max}) + \mu_{\text{negative}}(s)\mu_{\text{negative}}(e_{fm} - e_{f\,\min})],$$

$$w_2 = w^{-1}[\mu_{\text{positive}}(s)\mu_{\text{negative}}(e_{fm} - e_{f\,\min}) + \mu_{\text{negative}}(s)\mu_{\text{positive}}(e_{fm} - e_{f\,\max})],$$

$$w_3 = w^{-1}[\mu_{\text{positive}}(e_{fm} - e_{f\,\min})\mu_{\text{negative}}(e_{fm} - e_{f\,\max})],$$

$$w = [\mu_{\text{positive}}(s) + \mu_{\text{negative}}(s)][\mu_{\text{positive}}(e_{fm} - e_{f\,\max}) + \mu_{\text{negative}}(e_{fm} - e_{f\,\min})] + \mu_{\text{positive}}(e_{fm} - e_{f\,\min})\mu_{\text{negative}}(e_{fm} - e_{f\,\max}).$$

The controller is thus formed by combining Eqs. (7) and (20) and is schematically sketched in Fig. 2.

Remarks.

(1) The stability of e_r and e_{fm} is also guaranteed by the controller. This is due to the fact that the right-hand side of Eq. (6) remains Hurwitz for d_m and k_m obtained through the fuzzy laws.

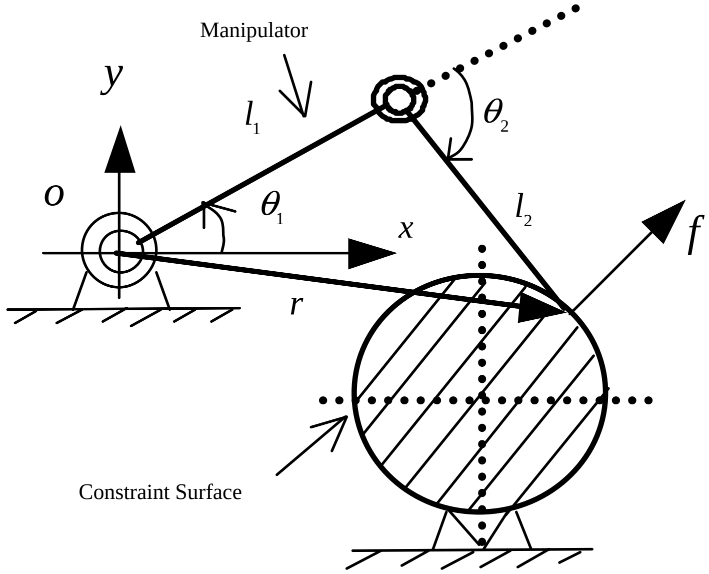

Fig. 3. Simulation example.

(2) Fuzzy tuning of impedance model needs the knowledge of normal vector n which can be estimated from information of the measured force [16].
(3) Controller (7) requires the exact knowledge of dynamic model of the robot. To deal with uncertainties in dynamics, additional control efforts can be derived through adaptive control or robust control schemes [8, 9]. Using fuzzy techniques to compensate such uncertainties is to be developed.

4. Simulation

The system used for simulation is schematically shown in Fig. 3. The end effector of the two-link manipulator moves along a circular constraint surface described by

$$(x_d - 0.8)^2 + (y + 0.4)^2 = 0.09$$

in the world coordinates XOY.

The length, inertia and the mass of each link of the manipulator is $l_i = 0.6$ m, $I_i = 0.3$ kgm^2 and $m_i = 0.1$ kg, respectively $(i = 1, 2)$. The mass center of each link is assumed to be in the middle of the link. The joint displacements of the robot is $q = [\theta_1 \;\; \theta_2]^T$ and the actual position of the end effector is $r = [x \;\; y]^T$. The kinematic and dynamic equations for the robot system can be derived accordingly as done in [3].

Considering the fact that the loss of the contact is normally caused by the external disturbances, a disturbance $\tilde{f}$ with magnitude $\|\tilde{f}\| = 2$ is added to the system at $t = 2$ s for the verification of the effectiveness of the proposed approach. The disturbance last 0.06 s and during this period, the system

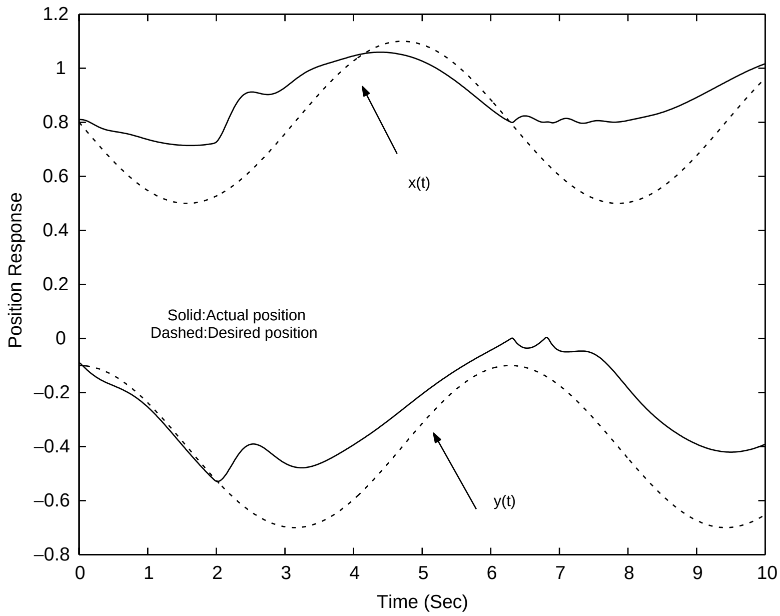

Fig. 4. Position response without fuzzy adaption.

dynamics becomes

$$M_r(q)\ddot{r} + C_r(q, \dot{q})\dot{r} + G_r(q) = J^{-\mathrm{T}}(q)\tau + f + \tilde{f}.$$

The planned trajectory of the end effector of the manipulator is specified as

$$x_{\mathrm{d}}(t) = 0.8 - 0.3 \sin t, \tag{21}$$

$$y_{\mathrm{d}}(t) = -0.4 + 0.3 \cos t \tag{22}$$

and the desired force along the normal of the constraint surface is set to be $f_{\mathrm{d}m} = 10$N. The maximum contact force is limited to $f_{\max} = 12$ N and the minimum contact force is set to $f_{\min} = 1$ N.

The traditional impedance control without fuzzy adaptation is simulated first where the desired impedance parameters are fixed as $m_m = 1.2$, $d_m = 15$ and $k_m = 60$. The responses of position and force under the controller are plotted in Figs. 4 and 5, respectively. The control torques for the manipulators are given in Fig. 6.

For the fuzzy impedance controller, the control parameters are chosen as $m_m = 1.2$, $d_s = 5$, $d_{\mathrm{med}} = 15$, $d_b = 25$, $\lambda = 5$ and $k_p = k_n = 1$. The responses of position and force under the controller are plotted in Figs. 7 and 8, respectively. The control torques for the manipulators and the impedance parameter are shown in Figs. 9 and 10, respectively.

From the simulation results, it can be seen that under the proposed controller, the performances of position response and force response are better than those of traditional impedance controller. The loss of contact of the end effector to the constraint surface happens for the traditional impedance controller (negative force along the normal), whereas the contact is maintained under the proposed

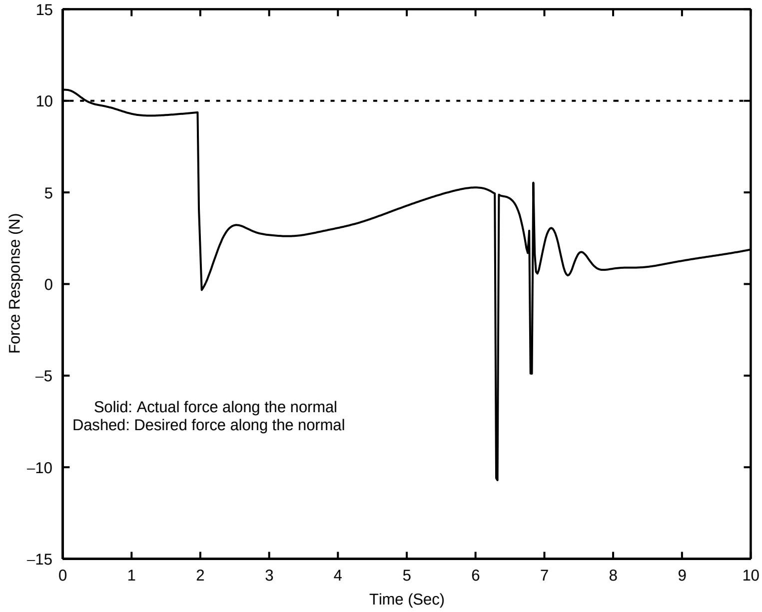

Fig. 5. Force response without fuzzy adaptation.

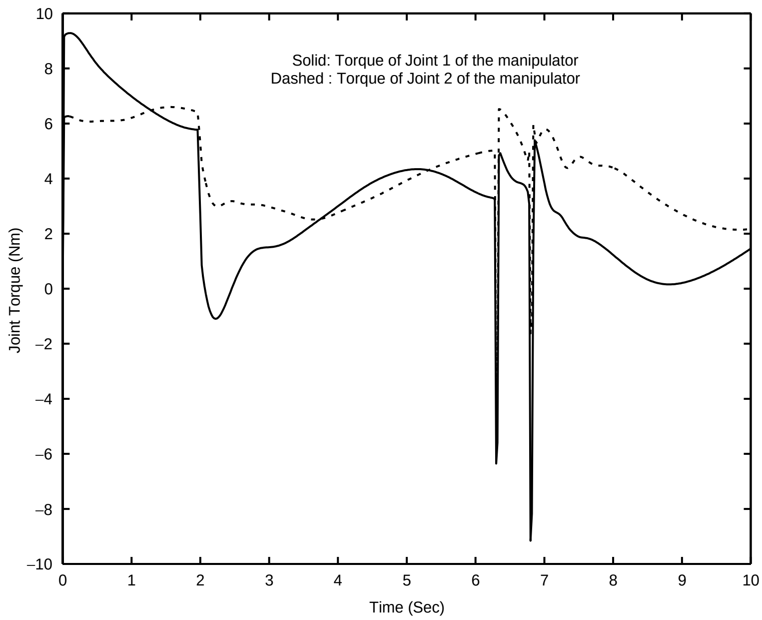

Fig. 6. Torques of the manipulator without fuzzy adaptation.

fuzzy impedance controller as the force is always positive along the normal. The control torques are also in the reasonable ranges.

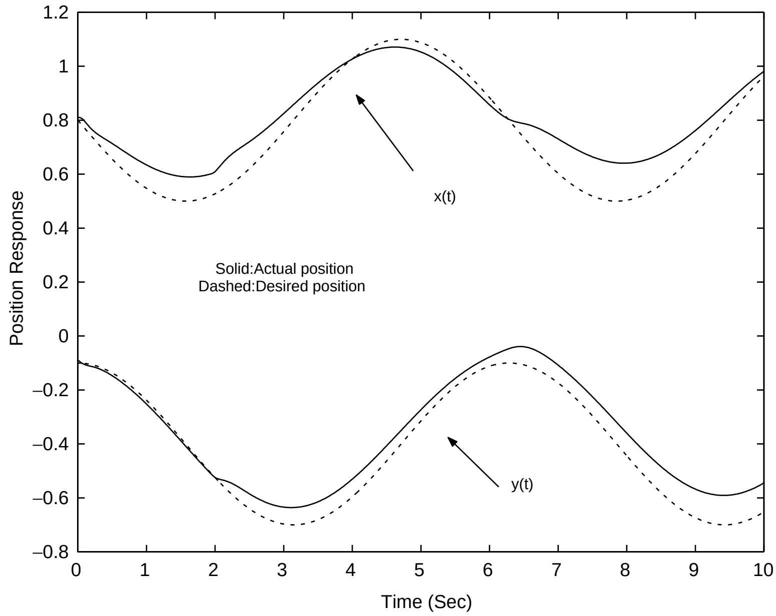

Fig. 7. Position response with fuzzy adaption.

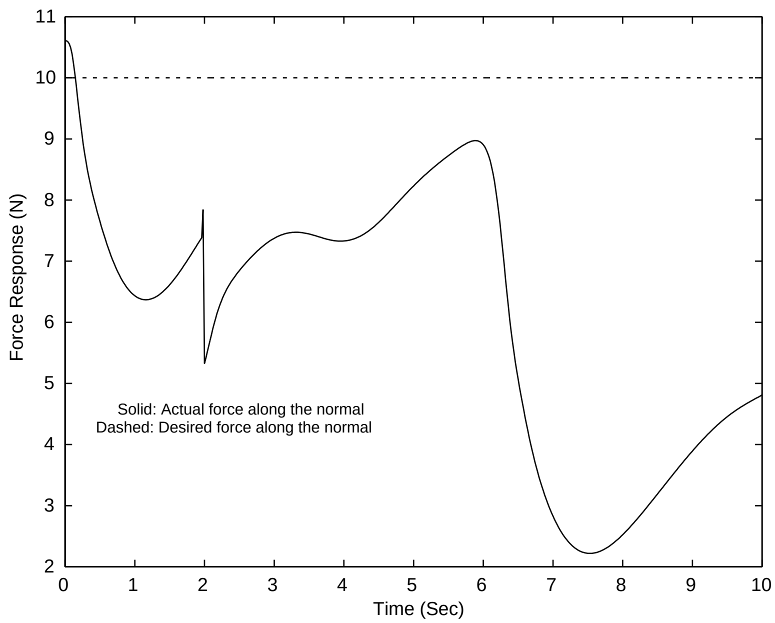

Fig. 8. Force response with fuzzy adaptation.

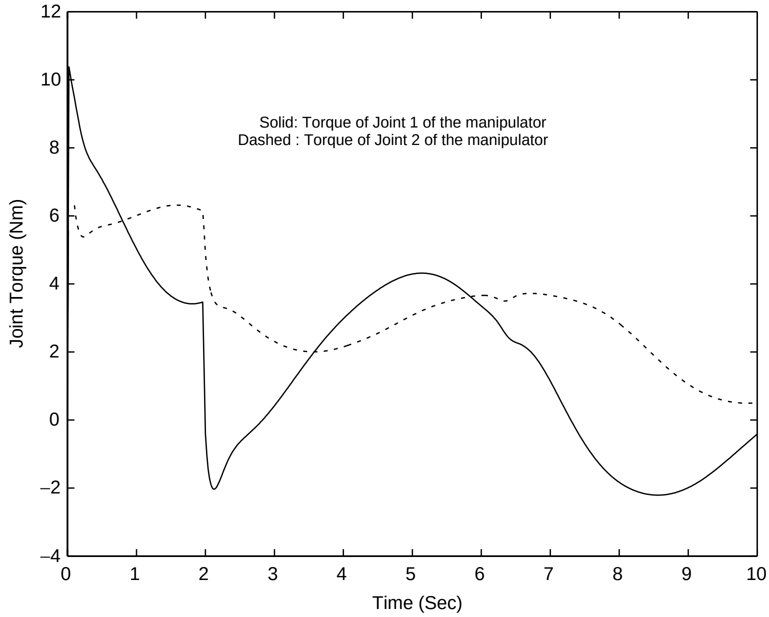

Fig. 9. Torques of the manipulator with fuzzy adaptation.

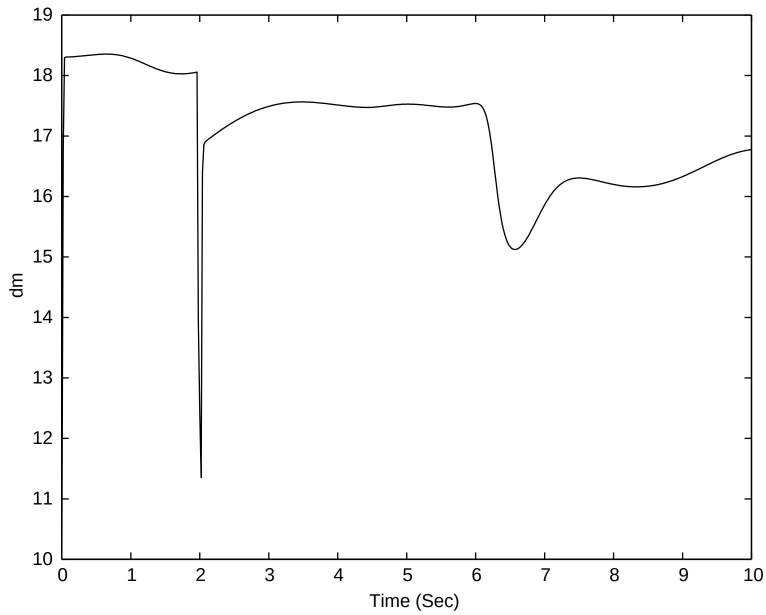

Fig. 10. Impedance parameter dm.

5. Conclusion

In this paper, a fuzzy unidirectional force control for a constrained robot is presented. The controller aims at achieving a desired impedance with bounded unidirectional contact force while the robot is in motion. For this purpose, a fuzzy tuning mechanism was developed to tune the control parameters of the controller. Theoretical analysis and simulation results were provided to show the effectiveness of the proposed controller.

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