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Adaptive Impedance Control for Unknown Time-Varying Environment Position and Stiffness

Norsinnira Zainul Azlan and Hiroshi Yamaura

***Abstract*—**This study is concerned with a new adaptive impedance control strategy to compensate for unknown time-varying environment stiffness and position. The uncertainties are expressed by Function Approximation Technique (FAT), which allows the update laws to be derived easily using Lyapunov stability theory. Computer simulation results are presented to validate the effectiveness of the proposed strategy.

***Keywords*—**Adaptive Impedance Control, Function Approximation Technique (FAT), unknown time-varying environment position and stiffness.

I. Introduction

FORCE control is crucial in regulating the amount of force applied by a robot on the environments or objects. In some applications, such as massaging, polishing, wiping, folding, writing, carving and medical surgery, it is desirable for the robot to exert the desired of force on the environment, while tracking a required position trajectory in the orthogonal direction. Impedance control is one of the control strategies in accomplishing this task. The advantage of impedance control is that it provides a smooth transition between noncontact and noncontact spaces. However, the disadvantage of this method is that it requires the exact knowledge of the environment position and stiffness beforehand [1]. Nevertheless, this information may not be available a priori in practical [2].

Seraji and Colbaugh [1] presented a direct and an indirect adaptive impedance control to deal with unknown environment position and stiffness. The method has also been applied in [3] for controlling pneumatic legs. However the technique is limited for constant environment position and stiffness only. Jung et al. [2] derived a simple adaptive control to cater for time varying uncertainties in the environment position and stiffness, but the desired stiffness gain imposed in the target impedance is set as a constant during free space and switched to zero during contact space. The discontinuity in the control parameter, as has been reported by many researchers may induce instability in the case of unexpected contact with a stiff environment [3]. Lee and Buss [4], presented a novel force tracking impedance control strategy with an adaptation in the controller gain to cater for uneven and triangular shaped environmental geometries, and abruptly changing environment stiffness. Nonetheless, the method does not ensure the convergence of the force error to zero for a nonzero reference force and the presented stability proof is limited to constant desired force only.

This paper presents a new adaptive impedance control to compensate for unknown time-varying environment stiffness and position (or non-flat environment shape) using Function Approximation Technique (FAT). The uncertainties are expressed by FAT [5], making it easy for the update laws to be derived using Lyapunov stability theory. The simulation results under two environment conditions are presented to demonstrate the effectiveness of the proposed method.

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II. FAT Based Adaptive Impedance Control for Unknown Environment Stiffness and Position

A. FAT based Adaptive Target Impedance

This study proposes two phases control law for the force controllable direction, which are the contact phase and noncontact phase. During contact space, the robotic finger is already in contact with the environment. The precise knowledge of the environment position and stiffness are required so that the reference trajectory to achieve the desired force can be realized [1]. However, this information may not be available a priori in practice. Therefore, this study proposes an FAT-based target impedance for *n* degree of freedom (DOF) robot, described by

$$B_d\left(\dot{X}-\dot{X}_e^{'}\right)+K_d\left(X-X_e^{'}\right)+\Omega_1+\Omega_2+\Omega_3 \\ +\Omega_4+\Omega_5+\Omega_6+\Omega_7=-K_f E_f \qquad (1)$$

where $X\in\Re^{n\times1}$ is the vector of the robot's end position, $\dot{X}\in\Re^{n\times1}$ is the time derivative of $X\in\Re^{n\times1}$. $B_d\in\Re^{n\times n}$, $K_d\in\Re^{n\times n}$ and $K_f\in\Re^{n\times n}$ are the diagonal symmetric positive definite desired damping, stiffness and force error factor matrices respectively, which can be specified by the designer. E_f is the force error described by

$$E_f=F_e-F_d \qquad (2)$$

where $F_e \in \Re^{n\times1}$ is the vector of the force exerted by the robot on the environment, and $F_d \in \Re^{n\times1}$ is the vector of desired force. $X_e^{'} \in \Re^{n\times1}$ is the initial environment position estimation since the accurate environment position is unknown in advance. $X_e^{'} \in \Re^{n\times1}$ is governed by

$$X_e^{'} = X_e + \delta_{Xe} \tag{3}$$

where $X_e \in \Re^{n\times1}$ is vector of the true value of the time varying environment position and $\delta_{Xe} \in \Re^{n\times1}$ is the vector of inaccuracy in the initial environment position estimate. $\dot{X}_e \in \Re^{n\times1}$ is the time derivative of $X_e \in \Re^{n\times1}$, $\Omega_1,\Omega_2,\Omega_3,\Omega_4,\Omega_5,\Omega_6$ and Ω_7 are FAT-based compensators represented by

$$\Omega_1 = \frac{-B_d\hat{W}_{KXdot}Z_{KXdot}}{K_e^{'}}, \Omega_2 = \frac{-K_d\hat{W}_{KX}Z_{KX}}{K_e^{'}},$$
$$\Omega_3 = \frac{B_d\hat{W}_{KDdot}Z_{KDdot}}{K_e^{'}}, \Omega_4 = \frac{K_d\hat{W}_{KD}Z_{KD}}{K_e^{'}}, \Omega_5 = \frac{-B_d\dot{F}_d - K_dF_d}{K_e^{'}}$$
$$\Omega_6 = -\frac{K_f\hat{W}_KZ_KE_f}{K_e^{'}}, \Omega_7 = \frac{B_d\hat{W}_{KXX}Z_{KXX}}{K_e^{'}} \tag{4}$$

where $\hat{W}_{KXdot},\hat{W}_{KX},\hat{W}_{KD},\hat{W}_{KDdot},\hat{W}_{KXX}$ and $\hat{W}_K$ are the matrices of the estimation of the weighting function, $Z_{KXdot},Z_{KX},Z_{KDdot},Z_{KD},Z_K$ and Z_{KXX} are the matrices of the basis function, $\dot{F}_d \in \Re^{n\times1}$ is the time derivative of F_d. $K_e^{'} \in \Re^{n\times1}$ is the vector of the initial estimate of the environment stiffness which is introduced since the true environment stiffness is unknown and is represented by

$$K_e^{'} = K_e + \delta_{Ke} \tag{5}$$

where $K_e \in \Re^{n\times n}$ is the diagonal symmetric positive definite matrix of the true environment stiffness and $\delta_{Ke} \in \Re^{n\times n}$ is the diagonal symmetric positive definite matrix of inaccuracy in the environment stiffness estimate. Both of these values are unknown and time-varying.

Considering that force is applied in one directions only for simplicity. Letting $b_d,k_d,k_f,x,f_d,f_e,e_f$ be the elements of $B_d,K_d,K_f,X,F_d,F_e,E_f$ respectively and $\hat{W}_{kxdot},\hat{W}_{kx}$, $\hat{W}_{kd},\hat{W}_{kddot},\hat{W}_{kxx},\hat{W}_k,Z_{kxdot},Z_{kx},Z_{kddot},Z_{kd},Z_k,Z_{kxx}$ be the vectors in $\hat{W}_{KXdot},\hat{W}_{KX},\hat{W}_{KD},\hat{W}_{KDdot},\hat{W}_{KXX},\hat{W}_K$, $Z_{KXdot},Z_{KX},Z_{KDdot},Z_{KD},Z_K,Z_{KXX}$ respectively, (1)-(5) can be rewritten as

$$\begin{aligned} &b_d\left(\dot{x}_e^{'} - \dot{x}\right) + k_d\left(x_e^{'} - x\right) + \Omega_1 + \Omega_2 + \Omega_3 \\ &+ \Omega_4 + \Omega_5 + \Omega_6 + \Omega_7 = -k_fe_f \end{aligned} \tag{6}$$

where

$$x_e^{'} = x_e + \delta_{xe}, \qquad k_e^{'} = k_e + \delta_{ke}$$
$$\Omega_1 = \frac{-b_d\hat{W}_{kxdot}Z_{kxdot}}{k_e^{'}}, \Omega_2 = \frac{-k_d\hat{W}_{kx}Z_{kx}}{k_e^{'}}$$
$$\Omega_3 = \frac{b_d\hat{W}_{kddot}Z_{kddot}}{k_e^{'}}, \Omega_4 = \frac{k_d\hat{W}_{kd}Z_{kd}}{k_e^{'}}, \Omega_5 = \frac{-b_d\dot{F}_d - k_dF_d}{k_e^{'}},$$
$$\Omega_6 = -\frac{k_f\hat{W}_kZ_ke_f}{k_e^{'}}, \Omega_7 = \frac{b_d\hat{W}_{kxx}Z_{kxx}}{k_e^{'}} \tag{7}$$

The environment model with the true time-varying environment stiffness and position [1] and its derivative can be described by

$$f_e = k_e\left(x - x_e\right). \tag{8}$$
$$\dot{f}_e = k_e\left(\dot{x} - \dot{x}_e\right) + \dot{k}_e\left(x - x_e\right) \tag{9}$$

The update law for $\hat{W}_{(.)}$ in (7) can be obtained by defining the inaccurate force exerted on the environment, f_{e_e} containing the initial environment stiffness and position as

$$f_{e_e} = f_e + \delta_{ke}\left(x - \left(x_e + \delta_{xe}\right)\right) - k_e\delta_{xe}. \tag{10}$$

and its derivative can be determined as

$$\begin{aligned} \dot{f}_{e_e} &= \dot{f}_e + \delta_{ke}\left(\dot{x} - \left(\dot{x}_e + \dot{\delta}_{xe}\right)\right) \\ &+ \dot{\delta}_{ke}\left(x - \left(x_e + \delta_{xe}\right)\right) - k_e\dot{\delta}_{xe} - \dot{k}_e\delta_{xe} \end{aligned}, \tag{11}$$

x and $\dot{x}$ can also be expressed using f_{e_e} and $\dot{f}_{e_e}$ as

$$x = \frac{f_{e_e}}{\left(k_e + \delta_{ke}\right)} + \left(x_e + \delta_{xe}\right), \tag{12}$$

$$\dot{x} = \frac{\dot{f}_{e_e}}{\left(k_e + \delta_{ke}\right)} + \left(\dot{x}_e + \dot{\delta}_{xe}\right). \tag{13}$$

Defining functions of the environment parameters in terms of Function Approximation Technique (FAT) as

$$\begin{aligned}
&\delta_{ke}\left(x-\left(x_e+\delta_{xe}\right)\right)=W_{kx}Z_{kx}+\varepsilon_{kx},, \\
&\delta_{ke}\left(\dot{x}-\left(\dot{x}_e+\dot{\delta}_{xe}\right)\right)=W_{kxdot}Z_{kxdot}+\varepsilon_{kxdot}, \\
&k_e\delta_{xe}=W_{kd}Z_{kd}+\varepsilon_{kd}, \quad k_e\dot{\delta}_{xe}=W_{kddot}Z_{kddot}+\varepsilon_{kddot}, \\
&\delta_{ke}=W_kZ_k+\varepsilon_k, \qquad \dot{k}_e\left(x-x_e\right)=W_{kxx}Z_{kxx}+\varepsilon_{kd}
\end{aligned} \tag{14}$$

their respective estimations in (7) can be expressed as

$$\begin{aligned}
&\hat{\delta}_{ke}\left(x-\left(x_e+\hat{\delta}_{xe}\right)\right)=\hat{W}_{kx}Z_{kx}, \quad k_e\hat{\delta}_{xe}=\hat{W}_{kd}Z_{kd}, \\
&\hat{\delta}_{ke}\left(\dot{x}-\left(\dot{x}_e+\hat{\dot{\delta}}_{xe}\right)\right)=\hat{W}_{kxdot}Z_{kxdot}, \quad \delta_{ke}=\hat{W}_kZ_k, \\
&k_e\hat{\dot{\delta}}_{xe}=\hat{W}_{kddot}Z_{kddot}, \qquad \hat{\dot{k}}_e\left(x-\hat{x}_e\right)=\hat{W}_{kxx}Z_{kxx}
\end{aligned} \tag{15}$$

where $W_{(.)}\in\Re^{1\times\beta_{(.)}}$ is the vector of the true value of the weighting function, $Z_{(.)}\in\Re^{\beta_{(.)}\times 1}$ is vector of the basis function, $\hat{W}_{(.)}\in\Re^{1\times\beta_{(.)}}$ is the vector of the estimated weighting function, $\beta_{(.)}$ is the number of basis function implemented and $\varepsilon_{(.)}$ are the approximation errors. It is assumed that sufficient number of basis function is utilized, thus, $\varepsilon_{(.)}$ can be assumed to be zero. From (14) and (15), it can be seen that since FAT can be used to describe time varying function, this technique can be utilized to estimate the uncertainties that are functions of x and $\dot{x}$, which can not be done by adopting the traditional adaptive scheme directly.

Substituting (14), $x,\dot{x}$ from (10) and (11), into (6) and multiplying with $k_e+\delta_{ke}$, the modified target impedance becomes

$$\begin{aligned}
&b_d\dot{e}_f+\left(k_d+k_fk_e\right)e_f+b_d\tilde{W}_{kxdot}Z_{kxdot} \\
&\quad +k_d\tilde{W}_{kx}Z_{kx}-b_d\tilde{W}_{kddot}Z_{kddot}-k_d\tilde{W}_{kd}Z_{kd} \\
&\quad -b_d\tilde{W}_{kxx}Z_{kxx}+k_f\tilde{W}_kZ_ke_f=0
\end{aligned} \tag{16}$$

where $\tilde{W}_{(.)}$ is the estimation error, $\tilde{W}_{(.)}=W_{(.)}-\hat{W}_{(.)}$.

The Lyapunov-like function candidate can be defined as

$$\begin{aligned}
V=&\frac{1}{2}e_f^Tb_de_f+\frac{1}{2}\tilde{W}_{kxdot}^TQ_{kxdot}\tilde{W}_{kxdot} \\
&+\frac{1}{2}\tilde{W}_{kx}^TQ_{kx}\tilde{W}_{kx}+\frac{1}{2}\tilde{W}_{kddot}^TQ_{kddot}\tilde{W}_{kddot} \\
&+\frac{1}{2}\tilde{W}_{kd}^TQ_{kd}\tilde{W}+\frac{1}{2}\tilde{W}_k^TQ_k\tilde{W}_k+\frac{1}{2}\tilde{W}_{kxx}^TQ_{kxx}\tilde{W}_{kxx}
\end{aligned} \tag{17}$$

Taking its derivative gives

$$\begin{aligned}
\dot{V}=&e_f^Tb_d\dot{e}_f-\tilde{W}_{kxdot}^TQ_{kxdot}\dot{\hat{W}}_{kxdot}-\tilde{W}_{kx}^TQ_{kx}\dot{\hat{W}}_{kx} \\
&-\tilde{W}_{kdot}^TQ_{kddot}\dot{\hat{W}}_{kddot}-\tilde{W}_{kd}^TQ_{kd}\dot{\hat{W}}_{kd} \\
&-\tilde{W}_k^TQ_k\dot{\hat{W}}_k-\tilde{W}_{kxx}^TQ_{kxx}\dot{\hat{W}}_{kxx}
\end{aligned} \tag{18}$$

Substituting $b_d\dot{e}_f$ from (16) into (18), $\dot{V}$ becomes

$$\begin{aligned}
\dot{V}=&-e_f^T\left(k_d+k_e\right)e_f+\tilde{W}_k\left[-k_fZ_ke_f^2-Q_k\dot{\hat{W}}_k\right] \\
&+\tilde{W}_{kxdot}\left[-b_dZ_{kxdot}e_f-Q_{kxdot}\dot{\hat{W}}_{kxdot}\right] \\
&+\tilde{W}_{kx}\left[-k_dZ_{kx}e_f-Q_{kx}\dot{\hat{W}}_{kx}\right] \\
&+\tilde{W}_{kddot}\left[b_dZ_{kddot}e_f-Q_{kddot}\dot{\hat{W}}_{kddot}\right] \\
&+\tilde{W}_{kd}\left[k_dZ_{kd}e_f-Q_{kd}\dot{\hat{W}}_{kd}\right]
\end{aligned} \tag{19}$$

The update laws for the weighting function in (7) can be chosen to make the second to sixth terms on the right hand side of (19) equal to zero. Therefore, the update laws are set as

$$\begin{aligned}
&\dot{\hat{W}}_{kx}=-Q_{kxdot}^{-1}b_dZ_{kxdot}e_f, \qquad \dot{\hat{W}}_{kx}=-Q_{kx}^{-1}k_dZ_{kx}e_f, \\
&\dot{\hat{W}}_{kddot}=Q_{kddot}^{-1}b_dZ_{kddot}e_f, \qquad \dot{\hat{W}}_{kd}=Q_{kd}^{-1}k_dZ_{kd}e_f, \\
&\dot{\hat{W}}_k=-Q_k^{-1}k_fZ_ke_f^2, \qquad \dot{\hat{W}}_{kxx}=Q_{kxx}^{-1}b_dZ_{kxx}e_f,
\end{aligned} \tag{20}$$

Substituting (20) in to the derivative term in (19) results in

$$\dot{V}=-e_f^T\left(k_d+k_e\right)e_f \tag{21}$$

Since (17) is positive definite and (21) is negative semi-definite, $e_f,\tilde{W}_{kxdot},\tilde{W}_{kx},\tilde{W}_{kddot},\tilde{W}_{kd},\tilde{W}_k,\tilde{W}_{kxx}$ are bounded. Differentiating (21), gives

$$\ddot{V}=-2e_f^T\left(k_d+k_e\right)\dot{e}_f \tag{22}$$

From (16) and (22), it can be observed that $\ddot{V}$ is also bounded. Therefore, from Barbalat theory,

$$\lim_{t\to\infty}\dot{V} = 0 \quad \text{and} \quad \lim_{t\to\infty} e_f = 0 \tag{23}$$

Therefore, provided that the target impedance is achieved, with the adaptive target impedance (6) and the updating law (20), the actual force exerted on the environment converges to the desired value, $f_e \to f_d$ as $t \to \infty$ although the true time-varying environment position and stiffness are not known accurately in advance.

In the non-contact or free space, the robotic finger is not in contact yet and is moving towards the environment. The target impedance for the force controllable direction during this phase is governed by,

$$M_d\left(\ddot{X} - \ddot{X}_d\right) + B_d\left(\dot{X} - \dot{X}_d\right) + K_d\left(X - X_d\right) = -K_f E_f \tag{24}$$

where $X_d \in \Re^{n\times 1}$ is the vector of the reference position of the robot's end-effector, which can be set by the designer since the information of the environment position and stiffness are not necessary in this phase, $\dot{X}_d \in \Re^{n\times 1}$ is the vector of the reference velocity and $\ddot{X}_d \in \Re^{n\times 1}$ is the vector of the reference acceleration, $\ddot{X} \in \Re^{n\times 1}$ is the vector of the acceleration of the robot's end point $M_d \in \Re^{n\times n}$ is the diagonal symmetric positive definite desired inertia, which can be specified by the designer. The same target impedance in (24) is implemented for position controllable direction in both free and contact phases.

A. Impedance Control Law for Uncertain Finger Dynamics

The impedance control law as in [6] is applied to drive the system to reach the target impedance. The control input to can be written as

$$F = F_s + F_f + F_e \tag{25}$$

where

$$F_s = -\left(K_1\left\|\ddot{X}_r\right\| + K_2\left\|\dot{X}\right\|\left\|\dot{X}_r\right\| + K_3\right)\left(\frac{Z}{Z+\delta_z}\right) \tag{26}$$

$$F_f = -KZ\,, \quad Z = \dot{X} - \dot{X}_r \tag{27}$$

The control parameters $K \in \Re^{n\times n}, K_1 \in \Re^{n\times n}$, $K_2 \in \Re^{n\times n}$, and $K_3 \in \Re^{n\times n}$ are definite positive diagonal matrices. The elements of K_1, K_2 and $, K_3$ are chosen large enough such that [6]

$$k_{1,i} \geq kM, k_{2,i} \geq kC, k_{3,i} \geq kG, \quad \text{for } i = 1,2,...,n \tag{28}$$

where

$$kM \geq \left\|M(X)\right\|, kC\left\|\dot{X}\right\| \geq \left\|C(X,\dot{X})\right\|, \quad kG \geq \left\|G(X)\right\|, \tag{29}$$

$M(X)$, $C(X,\dot{X})$ and $G(X)$ are the positive definite inertia matrix, Coriolis and Centrifugal force and gravitational force of the robot respectively. In this study, the augmented impedance error, Z is defined based on the target impedance in (1) and (24), where

$$Z = \begin{cases} Z_f & \text{(position controllable direction and force controllable direction in free space)} \\ Z_c & \text{(force controllable direction in contact space)} \end{cases} \tag{30}$$

From (1), the augmented impedance error for the force controllable direction during contact mode can be obtained as,

$$Z_c = \dot{E}' + B_d^{-1}\left(K_d E' + \Omega_1 + \Omega_2\right) + B_d^{-1}\left(\Omega_3 + \Omega_4 + \Omega_5 + \Omega_6 + \Omega_7 + K_f E_f\right) \tag{31}$$

where $E' = X - X_e'$ and $\dot{E}' \in \Re^{n\times 1}$ is its time derivative.

For position controllable direction in both phases and force controllable direction during non-contact mode, from (24), Z_f in this phase can be defined as [6]

$$Z_f = \dot{E} + \lambda E + E_{fl}, \tag{32}$$

where $E = X - X_d$, $\dot{E}_{fl} + \gamma E_{fl} = M_d^{-1}E_f$, λ and γ are positive definite matrices chosen such that

$$\lambda + \gamma = M_d^{-1}B_d \qquad \dot{\lambda} + \lambda\gamma = M_d^{-1}K_d. \tag{33}$$

The stability proof for the control law in (25) can be referred in [6].

III. Simulation Results

Simulation tests have been performed on a 2 DOF robotic finger [7]. It is assumed that the contact occurs at the end of the distal phalanx for simulation simplicity. The robotic finger is desired to approach the object and become in contact with it after 0.0833 seconds. The uncertainties in (15) have been approximated by the first 11 terms of Fourier Series and the period of the Fourier series has been set as 1.4 seconds. It is assumed that the contact point and time can be obtained from the experiment.

The controller has been tested under two cases of unknown time-varying environment position and stiffness. In the first case, the finger is desired to exert the desired force f_d in x direction while tracking a reference trajectory, y_d in y direction, described by

$$f_d = \begin{cases} 0 & 0\,\text{s} < t < 0.08333\,\text{s} \\ 618(t-0.0833)\,\text{N} & 0.08333\,\text{s} < t < 0.13333\,\text{s} \\ 25+10\sin\left(\dfrac{2\pi(t-0.0833)}{0.5}\right)\text{N} & t > 0.1333\,\text{s} \end{cases} \tag{34}$$

$$y_d = -60\times10^{-3}t + 15\times10^{-3}\,\text{m} \tag{35}$$

The true environment position and stiffness have been set as

$$k_e = 25000 + 10000\sin\frac{2\pi(t-0.0833)}{0.5}\,\text{N/m} \tag{36}$$

$$x_e = 0.004\sin\frac{2\pi(t-0.0833)}{2/3} + 0.0375\,\text{m} \tag{37}$$

However, these values are assumed to be unknown earlier. They have been initially estimated as $x_e^{'} = 0.042$ cm and $k_e^{'} = 50000$ N/m in (6). The update rates have been tuned as $Q_{kddot}^{-1} = 10I_{11}, Q_{kd}^{-1} = 10^{-1}I_{11}, Q_{kxdot}^{-1} = 10I_{11}, Q_{kx}^{-1} = I_{11}$, $Q_k^{-1} = 10^{-1}I_{11}, Q_{kxx} = I_{11}$. Fig. 1 - 3 illustrate the force tracking response in x direction, position tracking response in y direction and position response in Cartesian space for the first case respectively. It can be seen from the figures that the proposed controller has successfully control the robotic finger to exert the desired force on the environment although the accurate knowledge of the time-varying environment position and stiffness are unknown a priori. The position tracking performance in y direction is excellent. It can also be observed that no force overshoot occurs in the first case since the reference trajectory in constraint space, x_d is smooth although it is time varying.

In the second case, the finger is desired to track the reference trajectory, y_d in (35) while at the same time exert the desired force f_d in x direction is described by

$$f_d = \begin{cases} 0 & 0\,\text{s} < t < 0.08333\,\text{s} \\ 538(t-0.0833)\,\text{N} & 0.08333\,\text{s} < t < 0.13333\,\text{s} \\ 25+5\sin\left(\dfrac{2\pi(t-0.0833)}{0.8}\right)\text{N} & t > 0.1333\,\text{s} \end{cases} \tag{38}$$

The true environment position and stiffness for the second case have been set as

$$k_e = 25000 + 5000\sin\frac{2\pi(t-0.0833)}{0.8}\,\text{N/m} \tag{39}$$

$$x_e = \begin{cases} 0.02941t + 0.0385\,\text{m} & 0<t<0.25333\,\text{s} \\ -0.03033t + 0.0487\,\text{m} & t>0.25333\,\text{s} \end{cases} \tag{40}$$

These values are assumed to be unknown in advance and $x_e^{'}$ and $k_e^{'}$ in (6) have been set as 0.050 m and 50000 N/m respectively. The update rates have been tuned as $Q_{kddot}^{-1} = 10I_{11}, Q_{kd}^{-1} = 10I_{11}, Q_{kxdot}^{-1} = 10I_{11}, Q_{kx}^{-1} = I_{11}$, $Q_k^{-1} = I_{11}, Q_{kxx}^{-1} = 10I_{11}$.

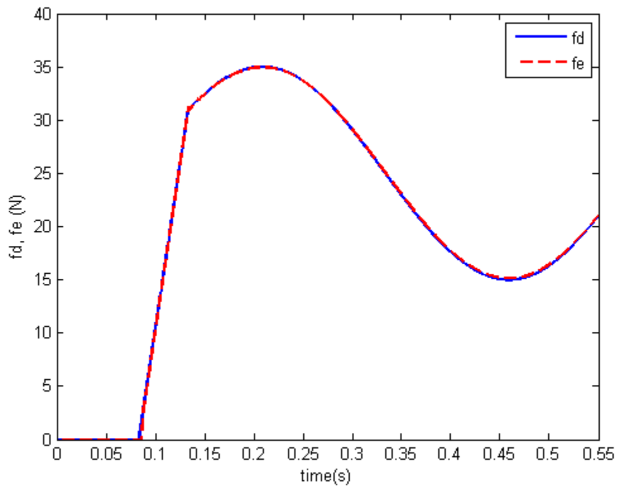

Fig. 1 Force tracking response in x direction for the first case

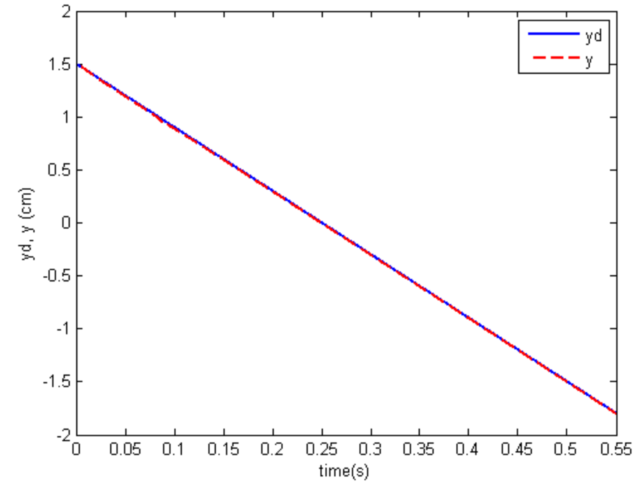

Fig. 2 Position tracking response in y direction for the first case

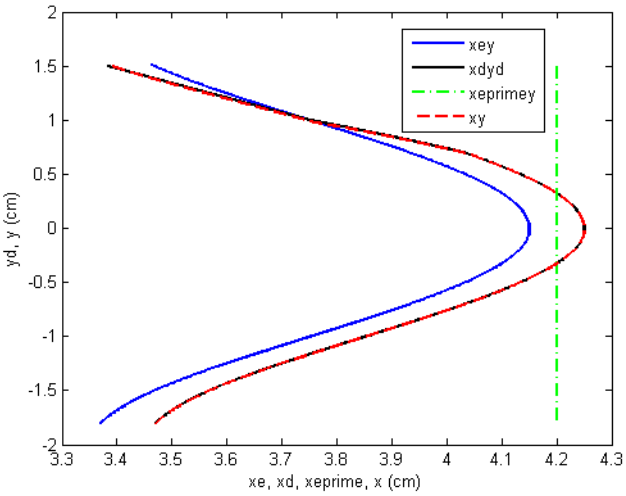

Fig. 3 Position response in Cartesian space for the first case

The force tracking response in x direction and position response in Cartesian space for the second case are illustrated in Fig. 4 and 5 respectively. The figures demonstrate that the proposed control strategy has successfully compensate for unknown time varying environment position and stiffness, where the robotic finger has accurately exerted the desired force on the environment while tracking the desired trajectory. However it can be observed that a force overshoot occurs between $0.24 < t < 0.26$ s. This is due to robotic finger's movement while tracking the desired force at the corner or the triangular-shaped environment.

The simulation results verify that the proposed control strategy is effective in providing the necessary force and position control under unknown time-varying environment position and stiffness.

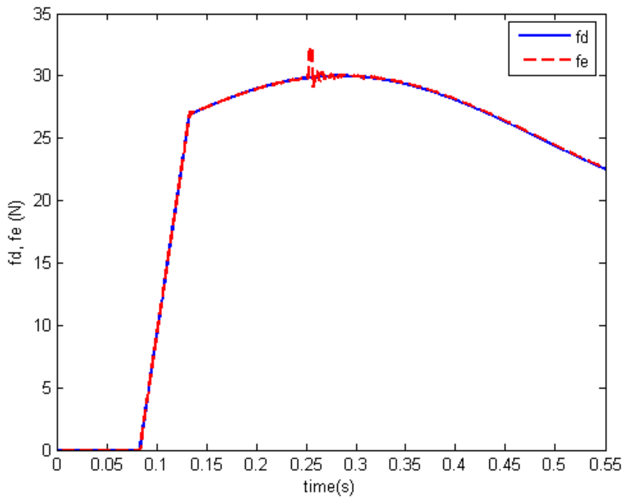

Fig. 4 Force tracking response in x direction for the second case

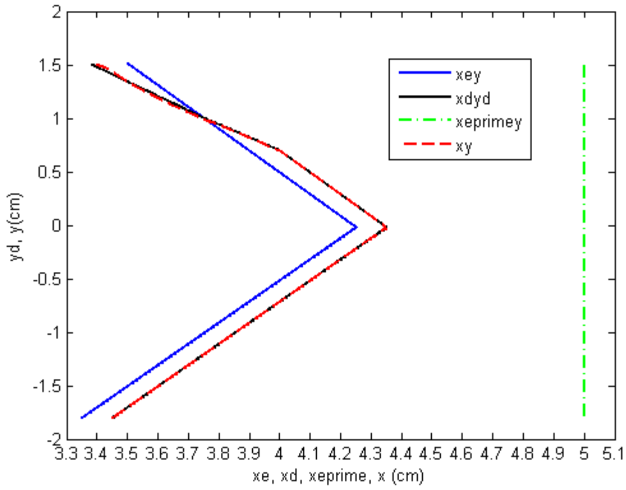

Fig. 5 Position response in Cartesian space for the second case

IV. Conclusion

This paper presents a new FAT-based adaptive impedance control to compensate for unknown time-varying environment position and stiffness. The uncertain terms are represented by FAT, allowing the update laws of the weighting functions to be derived easily using Lyapunov stability theory. The simulation results have proven that the controller is effective in controlling the robotic finger to exert the desired force in the force controllable direction, while tracking the desired position in the position controllable direction in spite of the time-varying uncertainties in the environment position and stiffness. The proposed control law also does not require any noisy derivative force error feedback signal, which makes it practical for implementation.

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